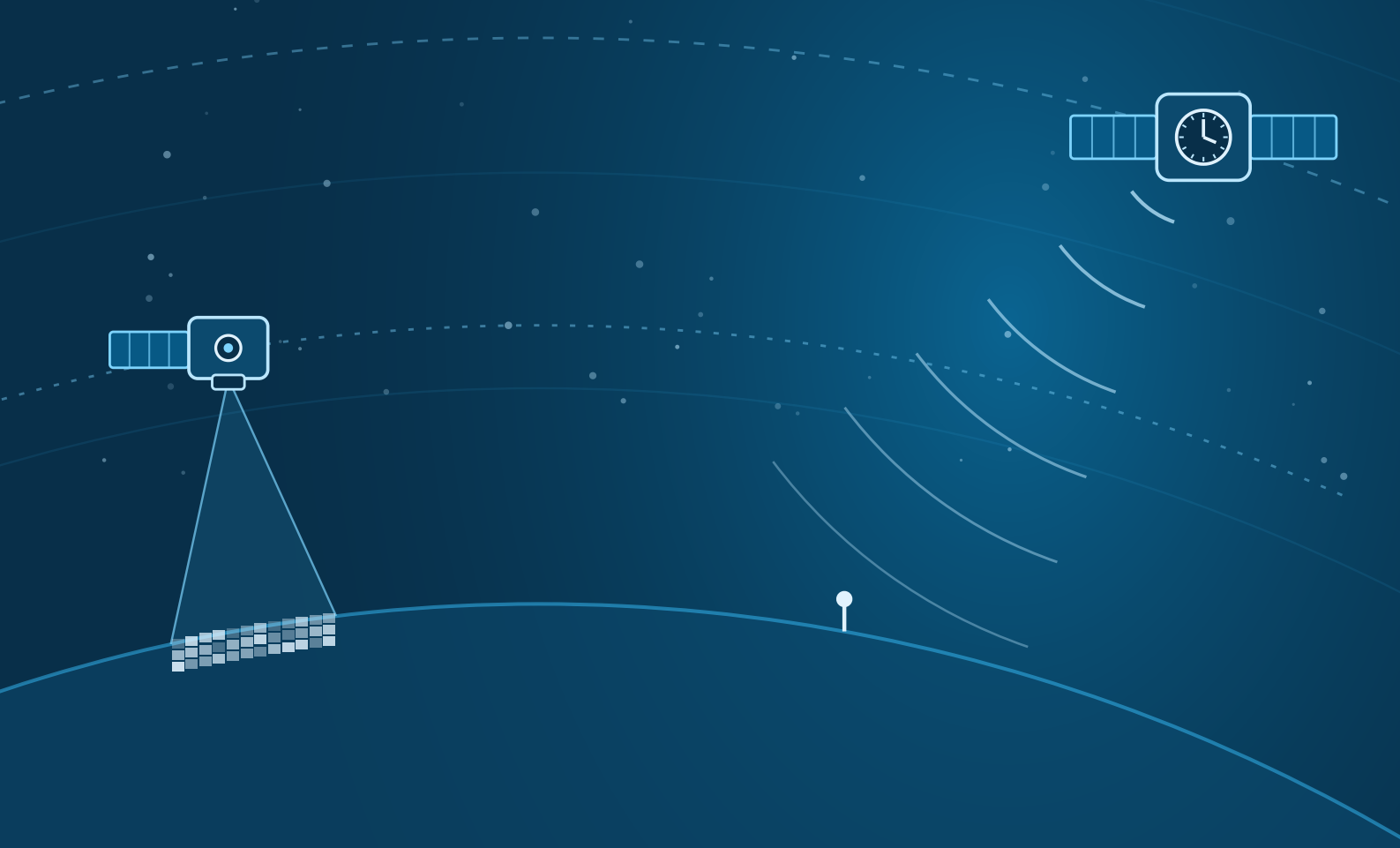


THE SATELLITE SERIES, SIGNAL BY SIGNAL

Eyes and Clocks

Satellite data and positioning

Two of the most used satellite services need nothing from the user: clocks overhead that let a receiver find its position and time, and sensors overhead that measure the Earth. A buyer of either buys a measurement, not a link, so the questions are what is measured, with what quality, how fast it arrives, who stands behind the promise, and what happens when the signal is denied or falsified.

Juan Cardena

Enterprise AI & Agentic Systems Architect · blog.jcardena.com

CONTENTS

BEFORE THE SERVICES

Reader's Brief: The Link Is Necessary, Not Sufficient

Prologue: A Clock Overhead, a Camera Overhead

01 Two Kinds of Service That Need Nothing From You

PART I: CLOCKS

02 How a Receiver Finds Itself

03 The Systems: Four Global, Two Regional

04 Accuracy and Integrity: Augmentation, Corrections and Monitoring

05 Time as a Service

06 What a One Way Signal Can Promise: Jamming, Spoofing and Fallback

PART II: EYES

07 The Buyer's First Questions: Observable, Resolution, Revisit, Latency

08 Optical, Thermal and Hyperspectral Sensing

09 Radar Sensing

10 Weather and Climate Data: Imagers, Sounders and the Products Built on Them

11 Other Sensors a Buyer Meets: Listening, Microwave, Altimetry and Gases

PART III: BUYING THE DATA

12 From Photon to Product: Tasking, Downlink, Processing, Delivery, Acceptance

13 Open Programs and Commercial Suppliers: Licenses, Prices, Platforms and Rules

14 Writing the Requirement and Reading the Offer

Epilogue: What Moves Next

APPENDICES

A The Forms: Link Ledger, Positioning and Timing Sheet, Data Sheet, Latency Template, Index of Ledgers

B Formulas and Check Values

C Glossary

D Dated Register: Systems, Fleets, Service Status, and Systems Sought and Not Sourced

E Sources

BEFORE THE SERVICES

Reader's Brief: The Link Is Necessary, Not Sufficient



A GPS satellite does not hear from the phone that uses it, and an imaging satellite does not hear from the analyst who buys its pictures. Both services still end in a purchase decision: a receiver, a correction subscription, a data license, a contract for tasking. This book is for the people who make those decisions. It asks what you buy when the satellite never hears from you, and how to tell a good offer from a confident one.

The question of the series, asked of a measurement

Every book in this series asks the same question of each system: how was the work divided between the user's end, the satellite and the ground, what limits drove that split, and did it work? Three verdicts are kept apart: the link, the service and the business. A link can work while the service fails, and a service can work while the business fails.

Navigation and Earth observation answer the first part in an unusual way. The ranging service needs no user uplink. A navigation satellite broadcasts its time and its orbit to every receiver in view, and the receiver does the rest. An imaging satellite measures the Earth, stores what it saw and sends it to a few ground stations; the user meets the result as a file, often days later. In both cases the radio link is necessary, and it is not sufficient. What the buyer needs is a **measurement**: a position and a time of known quality, or an observation of a known quantity, with its uncertainty, delivered in time and under a license that allows the intended use.

Four kinds of promise

Most confusion in this field comes from mixing four kinds of promise that look alike on a sales page. This book keeps them apart in every chapter.

- **A public performance commitment.** A state publishes what its signal in space will do: accuracy at a stated percentile, availability, the geometry it maintains. It is a commitment about the signal, not about your receiver or your result, and it is not a

contract with you.

- **A service contract.** A correction service, a data subscription or a tasking order, with its terms and sometimes a service level. This is where a buyer has a counterparty.
- **An equipment warranty.** What the maker of a receiver or an antenna stands behind.
- **A downstream managed service.** Someone else's product built on the signal or the data, with its own terms.

No legal right, and no absence of one, is inferred from how a signal is broadcast. Where a promise exists, the chapter names the document that makes it.

Positions: accuracy, uncertainty, integrity

Three words are kept apart in Part I. **Accuracy** is how close the reported position or time is to the truth, stated at a percentile (95 percent, say) under stated conditions. **Reported uncertainty** is what the receiver says about its own error; it is an estimate, not a guarantee. **Integrity** is the ability to warn in time when a position should not be used; it is stated as a tolerable error (the alert limit), a risk of exceeding it without a warning, and a time to alert. A position can be accurate to centimeters and have no integrity at all. The reference frame and the time scale are part of the answer: a coordinate without its frame and epoch is not yet a measurement a second system can use.

Data: the observable first

Part II starts from the **observable**, the physical quantity or the decision sought: reflectance, temperature, radar backscatter, height, a gas column, a ground displacement. Only then come the four screening questions: resolution (spatial, spectral, radiometric and temporal, four different things), revisit, latency, and the license. Latency is measured on two clocks, from request to accepted product and from collection to accepted product, because a buyer of archive data and a buyer of urgent tasking live on different ones.

How this book writes numbers

Every number carries its source and its date. Each one is marked with one of the series' seven classes: measured (by a named party, on a date), calculated, simulated, operator claim, standard, assumption (printed as "assumption, to verify") and published history. A provider's published performance standard is cited by edition and table; the text calls it what it is, a commitment about the signal in space. An operator's figure is never restated as measured.

Counts are written with their date and who counted. Announced, launched, in service and usable are four different states, and a status needs a source that speaks for the book's date. Where no such source was read, the book says so; Appendix D lists what was sought and not found. Nothing in this book was measured, received or ordered by the author: where a step needs equipment, the book says what the step requires and cites other people's published results.

The tools, and where they stop

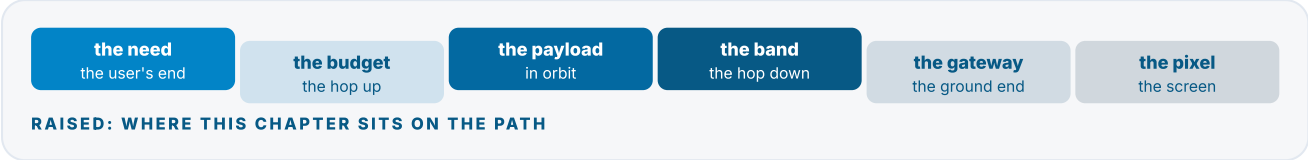
The series' tool is the two-page Link Ledger: page 1 describes the service in ten fields, page 2 adds up one hop in decibels. It fits the navigation broadcast, a correction broadcast and a satellite's payload downlink, and this book prints page 1 where a buyer's decision depends on it. None of its ledgers prints a page 2: the inputs a budget needs were not published, or the budget is printed in the book that owns the ledger. It does not fit what most of this book is about. A position's quality depends on geometry and on the receiver's measurement model; an image's fitness depends on the sensor, the cloud, the calibration and the processing chain. For those, the book uses three forms of its own, all blank in Appendix A: a positioning and timing requirement sheet, a data requirement sheet, and a latency budget on the two clocks. Chapter 1 says where the ledger fits and where it does not.

Each chapter ends with a **Monday rule**: one sentence a reader can act on next week. These rules are the author's practice, not a standard. The security notes stay with public sources and conditions; they give no operational detail.

Two other books of this series carry what this one leans on. The first book of this series, *The Bit's Path*, carries the link theory: decibels, hop budgets, how a spread signal is acquired. The second, *From Telstar to the Phone in Your Pocket*, carries the history. This book refers to both and does not retell them.

The record behind this book leans on sources that could be read when it was written: United States, European and Indian documents, and the operators' own pages. Several systems a specialist would expect are therefore thin or absent: Japan's QZSS, the interface documents of Galileo and BeiDou, Sentinel-2, the Japanese, Canadian and Indian radar missions, the Asian weather fleets, and the tasking terms of the optical operators. Each was sought; Appendix D lists them with the date sought, and the chapters say where a row would have stood. A missing row is a gap in the record, not a judgment of the system. The book is a method for buying, with dated examples, not a catalog of every offer.

Prologue: A Clock Overhead, a Camera Overhead



On 1 April 1960 the United States launched TIROS-1, a satellite of about 270 pounds carrying two television cameras, into an orbit about 450 miles up. It worked for 78 days and sent down more than 19,000 usable pictures of clouds, by the count of NOAA, the agency that runs the country's civil weather satellites. Twelve days later, on 13 April 1960, Transit 1B reached orbit. It was the first satellite of the Navy's Transit navigation program to get there (Transit 1A had failed to reach orbit the year before), and it operated for 89 days, according to the program's own history from the Johns Hopkins Applied Physics Laboratory, which designed it.

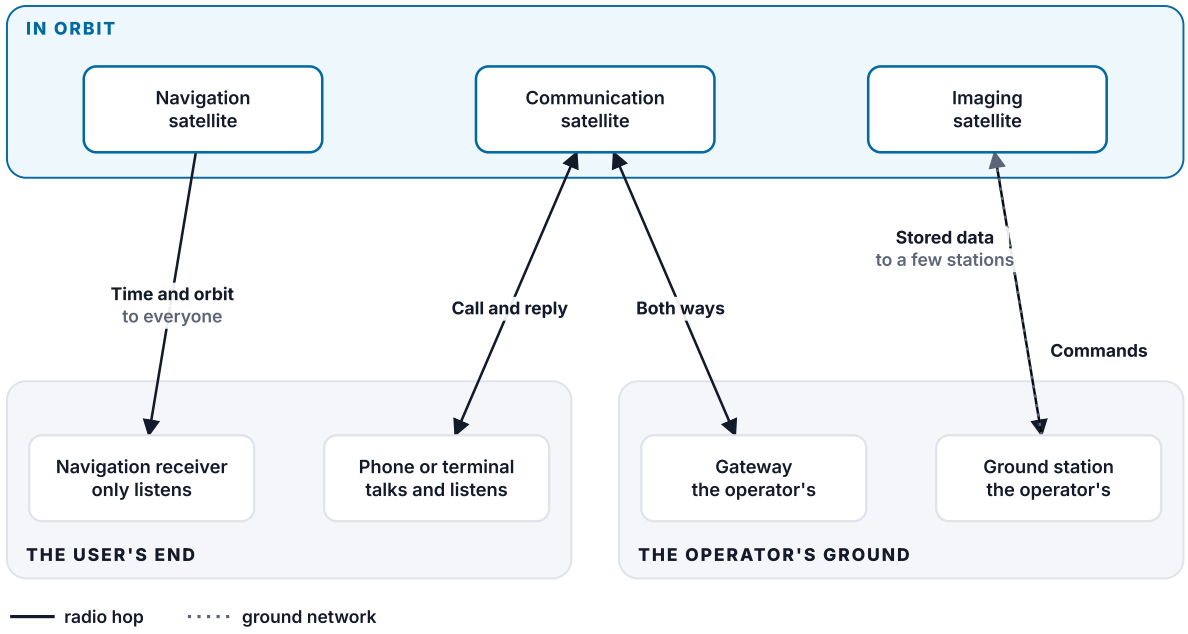
Two satellites that only speak

Neither satellite listened to its users. TIROS-1 looked down, recorded what it saw and sent it to ground stations, which turned it into pictures for forecasters. Transit broadcast two radio tones and a description of its own orbit; a ship's receiver measured how the tones shifted as the satellite passed and computed where the ship was. The satellite did not know the ship existed. The telephone satellites of the same years, which the second book of this series, *From Telstar to the Phone in Your Pocket*, follows, had to carry a conversation both ways. These two carried no conversation at all.

That difference changes almost every question a buyer asks. A telephone link has a far end that can complain, a gateway that can be billed and a counterparty that can be held to a contract. A clock overhead and a camera overhead have none of those at the moment of use. The receiver simply listens. The analyst receives a file.

FIGURE P.1

Three kinds of link: a conversation, a clock and a camera



A telephone satellite carries traffic both ways between a user and a gateway; a navigation satellite broadcasts one way to any receiver and never hears it; an imaging satellite sends stored data one way to a few stations and takes commands from its own ground.

Author's diagram based on the Johns Hopkins APL Technical Digest 19(1), 1998 (Transit), and NOAA NESDIS (TIROS-1).

Sixty-six years later

In 2026 the pattern is the same and the scale is not. Four systems broadcast navigation signals worldwide: GPS, GLONASS, Galileo and BeiDou. Two more serve regions: Japan's QZSS and India's NavIC. On 21 April 2026 the last GPS III satellite was launched, by its builder's account, and the European Space Agency announced that Galileo satellite 34, by its numbering, entered service on 23 July 2026. Any compatible receiver may use the open signals, with no uplink, no subscription and no license to transmit.

The eyes multiplied too. Europe's Copernicus program flies radar satellites, the Sentinel-1 series, at 693 km, imaging in C band at 5.405 GHz through cloud and darkness; Sentinel-1D was launched on 4 November 2025, according to the program's mission page. NOAA's current geostationary weather satellites image the full disk of the Earth every 10 minutes. Commercial operators sell optical and radar imagery, and analysis built on it, beside these public programs; Part II names them, each with a date. None of these satellites knows who uses what they send.

The question

So this book asks: what can be promised to someone the system cannot see, and by whom? The navigation user gets a signal whose quality is a policy of its provider and a published commitment about the signal in space, not about the user's position. The data user gets an observation whose fitness depends on physics, weather, calibration and a license. Between the satellite and a decision lie a receiver, a correction service, a processing chain, a delivery interface and several contracts, each with its own owner.

Part I follows the clocks: how a receiver finds itself, who runs the systems and what they commit to, how accuracy becomes integrity, how time is delivered, and what a one way signal can promise when someone jams or imitates it. Part II follows the eyes: what to measure, with which sensor, and what the numbers on a data sheet do and do not say. Part III follows the data from the photon to a file a buyer accepts, and ends with the sheet the buyer writes.

CHAPTER ONE

Two Kinds of Service That Need Nothing From You



A few minutes past midnight, Eastern Daylight Time, after the end of 1 May 2000, the United States stopped degrading the open GPS signal on purpose, a practice called Selective Availability, and no receiver had to change; the failure box at the end of this chapter tells the case. The radio link did not change; the policy behind it did. This chapter asks what a one way service is, who stands behind which of its promises, and what the series' tool, the Link Ledger, shows about such a service and what it misses.

Broadcast to everyone, or collect, store and forward

The satellites of most other books in this series carry traffic: a call, a message, a stream of packets, with a user at one end and a gateway or another user at the other. This book is about two families that carry no traffic for the user at all.

A **navigation satellite** broadcasts one way to everyone. It sends a signal timed by an atomic clock on board, and with it a description of where the satellite is and how its clock is running. A receiver that hears several such satellites can work out its own position and the time. The satellite does not know the receiver exists, and one more receiver takes nothing from anyone else.

An **Earth observation satellite** works the other way round. It collects: a camera, a radar or another instrument measures the Earth as the satellite passes. A satellite in low orbit stores the data on board and forwards it when a ground station, or a relay satellite, is in view; a geostationary weather satellite, always in view of its ground station, sends its data down continuously (Chapter 10). Copernicus's Sentinel-1 radar satellites, for example, can hold 1,410 gigabits on board and unload them by an X band downlink or through a laser relay; the program's mission page gives 520 Mbit/s (two channels of 260 Mbit/s) for the payload data, without saying in that passage which route carries which rate. The user meets the result later, as a file.

Figure 1.1 sets the three kinds of service side by side. The telephone link is the contrast: it has a direction both ways, a far end that answers, a modest rate per user, and a ground end owned by a carrier that bills someone. The navigation signal goes one way to anyone, at a very low data rate: the legacy civil GPS signal carries its navigation message at 50 bits per second, by its interface specification. The imaging downlink goes one way to a few stations, at hundreds of megabits per second, with a small command link in the other direction.

FIGURE 1.1

Three kinds of satellite service, and the promise behind each

	Telephone link	Navigation signal	Imaging downlink
Direction	Both ways, through the satellite	One way, satellite to everyone	One way to a few stations; a small command link up
The far end	One caller, through a gateway	Any receiver; the satellite does not know it exists	The operator's own stations, or a relay satellite
Rate, one example	Modest per user	50 bit/s of navigation data (GPS L1 C/A)	520 Mbit/s of payload data (Sentinel-1)
What the user sends	Speech or data, and signaling	Nothing	Nothing at collection; an order to the operator
Who runs the ground infrastructure	A carrier that bills the user	The state's control segment; the receiver is the user's	The space agency or the operator
Public performance commitment	Not usual	Yes: a provider's performance standard for the signal in space	For open programs, a data policy; not a delivery commitment
Service contract	The subscription	Only for corrections or managed services	Data, subscription or tasking order
Equipment warranty	The handset or terminal	The receiver and antenna	The buyer's own receiving or processing equipment, if any
Downstream managed service	Applications on the network	Products built on positions and time	Platforms and analytics built on the data

The telephone link is the contrast; the navigation broadcast and the imaging downlink need nothing from the user at the moment of use, and their promises come from different parties.

Author's table based on IS-GPS-200N (2022) clause 20.3.1; Copernicus SentiWiki, S1 Mission (read 2026-11-22); GPS SPS Performance Standard, 5th edition (2020), section 3.1.

What a one way service asks of the user, and what it does not

For the user of an open navigation signal there is no uplink, no subscription and no license to transmit, because the user transmits nothing. That is a large part of why such receivers are so common. It does not make the user's end trivial. A receiver is real engineering: an antenna that sees enough of the sky, a front end that keeps a signal weaker than its own noise from being drowned, a correlator that finds and follows each satellite's code, a clock, and software that turns the measurements into a position and states how good that position is. Chapter 2 walks through each of these. The cost of the service has moved, not vanished: into the receiver, the integration and the public budget that pays for the satellites.

Nor is the system itself one way. Every navigation system has a **control segment** that tracks the satellites, computes their orbits and clocks, and uploads the message each satellite will broadcast. For GPS, the government's Standard Positioning Service Performance Standard (fifth edition, April 2020) describes a master control station at Schriever, Colorado, an alternate master control station, four ground antennas for commanding and a network of monitor stations worldwide; the Space Force's briefing to civil users of 21 April 2026 counts 6 monitor stations of its own and 11 more run by another agency. The satellites need that loop, but not continuously: the interface specification states that every GPS satellite can operate for at least 60 days without contact from the control segment. The user's receiver is outside the loop and has no way to ask a satellite anything.

An imaging service also asks nothing of the user at the moment of collection. The commands go up from the operator's ground, not from the buyer. A buyer who wants a particular place imaged at a particular time sends an order to the operator, and the operator decides whether and when to command the satellite. Chapter 12 follows that order end to end.

Other services on the same spacecraft

Some navigation and weather spacecraft carry more than one payload. Messaging services, relays for distress beacons, and the collection of readings from ground platforms such as river gauges and buoys ride on some of them. Those are communication services: the user's device transmits, the satellite relays the message or reading to a receiving system, and some services send a reply. They belong with the communication systems of the third book of this series, *The Sky as a Network*, and are not treated here. This book keeps to the signal that needs nothing from the user and to the data that a sensor collects without being asked.

The eyes: sensor, recorder, downlink, processing

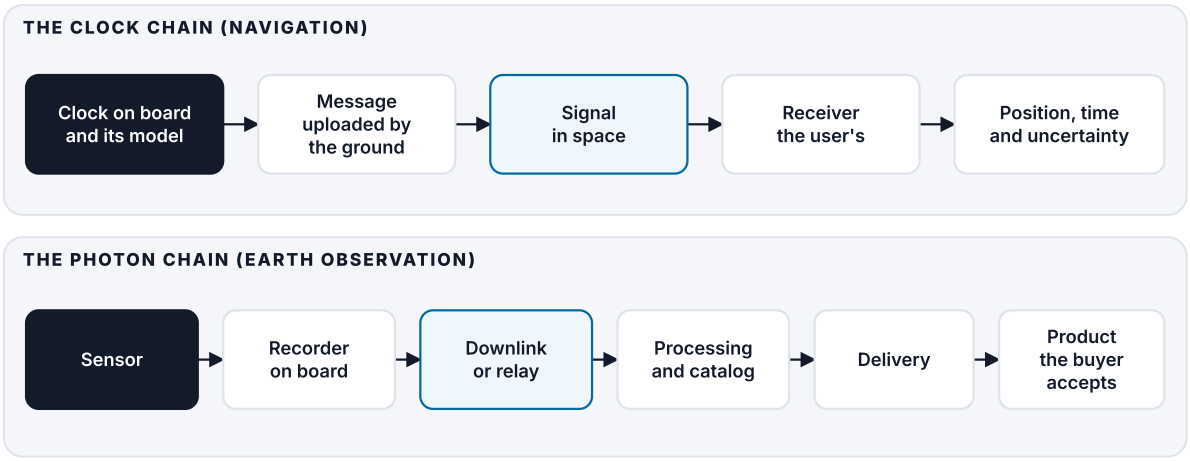
An Earth observation satellite is a measuring instrument with a radio attached. Its chain has four stages before a buyer sees anything. The **sensor** turns light, heat or a radar echo into numbers; Landsat 9's Operational Land Imager records each sample with 14 bits, according

to the US Geological Survey. The **recorder** holds those numbers until a station is in view. The **downlink** empties the recorder during a pass; official pages give Landsat 9's daily acquisitions as "more than 700", 740 and "about 750" scenes, and all of them have to come down. On the ground, **processing** turns raw counts into calibrated, located products, and a delivery system hands them to the buyer.

Figure 1.2 draws both chains in the same form. The clock chain ends in a receiver the user owns; the photon chain ends in a file the user accepts. In both, the radio hop is one stage of several, and usually not the one that decides whether the buyer gets what was needed.

FIGURE 1.2

Two product chains: from a clock to a fix, and from a photon to a product



In both chains the radio hop is one stage of several, and the stages that decide fitness for use are mostly on the ground and in the user's hands.

Author's diagram. The radio hop is the shaded stage in each row.

Four kinds of promise, and who pays

A navigation provider's main written promise is a **public performance commitment**. The GPS performance standard says plainly what it covers. Its signal-in-space standards "do not include any element not under the direct control of the GPS Control/Space Segments", and they "do not directly represent the end performance users will experience". The document lists the errors it excludes: ionospheric and tropospheric scintillation, residual atmospheric correction errors in the receiver, receiver noise and interference, receiver faults, multipath, antenna effects and user error. What it commits to is the signal arriving from space, and the geometry of the constellation. The rest is the user's.

A **service contract** appears when a buyer pays someone: for corrections that, with suitable receivers and antennas, can bring meters down toward centimeters (Chapter 4), for a data subscription, for tasking. An **equipment warranty** covers the receiver or the antenna. A **downstream managed service** is a product built by someone else on top of the signal or the data, with its own terms. A buyer who reads the four as one ends up holding the wrong party to the wrong promise.

Who pays differs by family. The navigation systems in this book are paid for by states; the user pays nothing at the point of use, and pays instead for a receiver and, if needed, for corrections. Weather satellites and the open Earth observation programs are also paid for by states, and their data are free or nearly free to obtain, under terms that differ by program (Chapter 13 reads them). Commercial Earth observation is paid for by customers, and governments are prominent among them: ICEYE reported in July 2026 that seven European governments had procured sovereign radar systems from it, and Planet's results release for its quarter ended 31 July 2026 reports a sovereign reconnaissance satellite launched for Sweden in May 2026. Chapter 13 gives the dated cases. Zero access charge is not zero cost.

Where the Link Ledger fits, and how it reads for a broadcast

The series' Link Ledger has two pages: page 1, the service in ten fields, and page 2, the hop budget in decibels. It fits four links in this book: a navigation satellite's broadcast to a receiver, a correction broadcast from an augmentation satellite, an imaging satellite's payload downlink, and a weather satellite's direct broadcast. For a broadcast, several fields read differently from a telephone service, and they should be filled in that reading rather than marked "does not apply":

- **Field 1, requirement:** "let any receiver compute position and time to a stated quality", not "deliver this message".
- **Field 5, capacity:** one more receiver uses no airtime, but the message rate and the age of the data still matter, and corrections sent over a network do have a per-user capacity.
- **Field 6, who owns each end:** the operator owns the transmitting end; the user owns or controls the receiver; a correction or data provider is a third party with a contract.
- **Field 9, cost shape:** no charge at the point of use for the open signal; the receiver, the corrections, the integration and public funding carry the cost.
- **Field 10, evidence:** lists the numbers that carry the argument, each with its class, source and date; the other numbers on the page name their source in the field; the sources behind every number are listed by chapter in Appendix E.

Where the ledger does not fit, this book says so. A position's quality depends on the geometry of the satellites in view and on the receiver's model of its errors; no single hop budget shows either, so Chapter 2 gives that model separately. An Earth observation product is a chain of stages, of which the radio hop is one; Part III uses a latency budget on two clocks instead. Radar and passive sensing are measurement models, not message delivery, and are described as such. A ledger page in this book is a structured first assessment of one link. It does not show that a position or a product is fit for a purpose.

THE SYSTEM'S FAILURE

Selective Availability, until 2000: an open signal degraded by policy. Until 2 May 2000 the open GPS signal was deliberately degraded. The government's GPS site records that the degradation ended a few minutes past midnight Eastern Daylight Time after the end of 1 May 2000, at the direction of President Clinton, and that in September 2007 the government announced that the GPS III satellites would be built without the feature. Nothing failed in the satellites or the radio link. What the civil user could do was set by a decision of the provider, applied to the whole constellation at once, and changed by another decision. What the record supports is narrow and durable: the quality of an open signal is a policy of its provider, and the published performance standard of the day is the document that states it.

SECURITY NOTE

Who can interfere or command. Anyone with a compatible receiver may use an open navigation signal; only the system's control segment is authorized to command the satellites and upload their messages. For an imaging satellite, only the operator is authorized to command; a buyer orders, the operator decides. A transmitter near a receiver, of sufficient power in the band, can interfere with the signal it hears, because that signal is very weak (Chapter 6). **How it is seen.** The open signal is public, so confidentiality is not what is at stake; anyone can record it. What matters is whether the receiver notices that what it hears is wrong. The interface specification of the legacy GPS civil signal defines no authentication of its navigation message, so the receiver cannot prove where a message came from; Chapter 6 covers the newer signals that add it. **How it is recovered.** By the user's own system, because the provider cannot see the user: a second source of position or time, a check against other sensors, and a decision about what to do when the position is absent or wrong.

Monday rule: list every place where your product takes a position or a time from a satellite, which promise stands behind it, and who would notice if it were wrong.

CHAPTER TWO

How a Receiver Finds Itself



The GPS interface specification, in its revision of August 2022, sets the satellite clocks to run slow on purpose: their rate is offset by a fractional -4.4647 parts in ten billion, to compensate for relativity, so that the nominal rate of the satellite's 10.23 MHz reference, as it appears to an observer on the ground, is exact. Left uncompensated, that fraction would add up to about 38.6 microseconds a day; light covers about 11.6 km in that time (calculated), which is the size of the clock error expressed as a range, not a prediction of a position error. The specification also tells the receiver to apply one more relativistic correction of its own, for the shape of each orbit. A position from satellites is built from measurements of time, so most of its error budget is written in clocks and in the path the light took. This chapter asks how clocks in orbit become a position and a time on the ground, in which frame, and with what uncertainty, so that a buyer can ask the right questions of any position a system receives.

Transit's idea: one satellite and a Doppler curve

The method began with Transit, the US Navy's navigation satellites, designed by the Johns Hopkins Applied Physics Laboratory and in operation from 1964. The second book of this series, *From Telstar to the Phone in Your Pocket*, tells its history; this book keeps only the idea. A Transit satellite broadcast two coherent tones, at 150 and 400 MHz, and a description of its own orbit loaded from the ground. A ship's receiver measured how the tones shifted in frequency as the satellite passed, the **Doppler shift**, and from that curve, the broadcast orbit and an allowance for the ship's own motion during the pass computed where the ship was. The design goal was 0.1 nautical mile per fix, and the laboratory's requirement was a usable pass on average within 4 hours, anywhere: between passes, by design, the navigator waited.

Two of Transit's choices are still in every navigation system. The receiver never transmits; the work of knowing where the satellite is moves to the ground, which tracks the satellites and uploads their orbits. And two frequencies are broadcast because the ionosphere delays them differently: comparing them removes most of its error. Transit was released for civil use in 1967 and terminated on 31 December 1996, according to the laboratory's history. Its one page ledger follows, as the second book prints it.

LINK LEDGER · LL-1964-01 · SERVICE LEDGER

1964 System: Transit (Navy Navigation Satellite System): a position fix at sea **Retired**

Class: service only

1 Requirement	Positions for ballistic missile submarines several times a day, 0.1 nautical mile per fix, from passive receivers. Later: a usable pass on average within 4 hours anywhere on Earth.
2 Ends and path	A passive receiver on a ship or submarine. It measures the Doppler shift during one pass and computes its own position. At the other end, the Navy's ground control system. **Path:** One-way broadcast to any receiver in view. A separate control loop: the ground tracks the satellites, predicts their orbits and loads the navigation message into satellite memory.
3 Orbit and time	Operational satellites in polar orbits near 1,000 km; the experimental Transit 2A flew 626 by 1,078 km (1960). By 1988, 12 satellites, 7 or 8 operational. **Time:** One fix per pass; between passes the user waits, by design.
4 Band and permission	**Satellite to receiver.** 150 and 400 MHz, two coherent carriers; operated by the US Navy; frequency authorization not in the source read **Ground to satellite.** Not in the source read
5 Capacity	**Up.** None. The user never transmits; there is no user uplink and no subscription. **Down.** One navigation message, repeated to every receiver in view; rate not in the source read. Users unlimited: a receiver takes nothing from another.
6 Who owns each end	**Space segment.** US Navy; designed by APL; built by a Navy facility, APL, then RCA **Ground segment.** US Navy, designed by APL **Customer relationship.** None; open to civil ships from 1967; receivers bought from makers **The exit.** Terminated 31 December 1996
7 Trust	Only the Navy's ground system loads and commands the satellites. The sources describe no authentication of the broadcast; a receiver cannot ask the satellite anything.
8 How it fails, and how we would see it	Early operational satellites ran days to weeks. For the user: no satellite in view, no fix; drag that spoils the predicted orbit degrades the fix. **How we would see it:** The Navy, in tracking and telemetry; the navigator, as a long wait or a fix that disagrees with dead reckoning.
9 Cost shape	Program cost not in the source read. Scout launches, chosen for the lowest cost per pound. Civil users paid only for a receiver: about 1,000 dollars some years after 1974 (no exact year given).
10 Evidence	Operational 1964 published history APL Technical Digest 19(1), 1998, pp. 21, 25, 2026-11-23 150 and 400 MHz; later 3 W and 5 W published history Same, pp. 20, 22 to 23, 25, 2026-11-24 0.1 nmi per fix; 4 h mean wait published history Same, pp. 18 to 19, 2026-11-23 Near 1,000 km (Transit 2A 626 by 1,078 km); 12 by 1988, 7 or 8 operational published history Same, pp. 20, 24, 25, 2026-11-24 Civil use 1967; receivers about 1,000 dollars after 1974; ended 31 Dec 1996 published history Same, pp. 19, 25, 2026-11-24

Service only, no hop budget: the source read gives the transmitter power of the later satellites (3 W at 150 MHz, 5 W at 400 MHz) but no receiver figures, and this book prints no budget without both ends.

Ranging to clocks

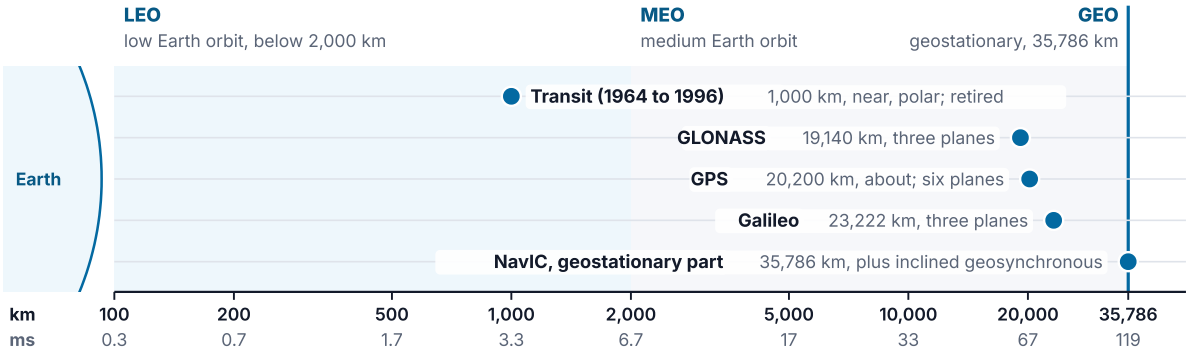
GPS and its successors replaced the Doppler curve with timing. Each satellite sends a signal whose timing comes from its atomic clock, and in that signal its own time and orbit. The receiver measures when each signal arrives by its own clock. The difference, times the speed of light, is a range to the satellite, but not a true one, because the receiver's clock is not set exactly to the system's time. The measured quantity is called a **pseudorange**: the true range, plus the receiver's clock error and minus the satellite's, both converted to distance, plus the delays of the atmosphere and the hardware, multipath and noise. The broadcast clock correction removes an estimate of the satellite's part. Both positions must also be put in one Earth-fixed frame, allowing for the Earth's turn during the light's flight (the specification uses the WGS 84 rotation rate); left out, it would add tens of meters.

The scale is unforgiving. A GPS satellite straight overhead is about 20,200 km away, according to the government's GPS site, which light crosses in about 67 ms (calculated). One nanosecond of timing error is about 30 cm of range (calculated). A receiver's own quartz clock can be off by far more than a nanosecond, so the receiver treats its clock error as an unknown to solve for, along with its three coordinates.

That is where the familiar "four satellites" comes from, and it holds for one case: a receiver that knows nothing in advance, using one system, solving for three coordinates and one clock error. Even then it needs at least four independent pseudoranges from satellites spread well enough across the sky; four in a line give no usable answer. The count changes with what the receiver already knows. A timing receiver at a surveyed position solves for time alone, and can work from one satellite at a time. A receiver with a good enough constraint on its height needs one satellite fewer. A receiver whose clock is held by another accurate source can drop the clock unknown instead. A receiver that uses two or more systems has, in general, one more unknown for each additional system's time scale: the offset between that system's time and the first one's, plus the receiver's own bias between the two, unless both are known. More satellites help the geometry, and add more ways to be wrong.

FIGURE 2.1

Most navigation clocks fly 19,000 to 23,000 km up, 64 to 78 ms of light straight overhead



km: altitude above the surface (log scale). ms: light time straight up, one way (altitude divided by the speed of light).

The receiver measures that light time with a clock of its own, so with no prior knowledge and one system it solves for four unknowns, three coordinates and its clock error; a known position or height, or a steered clock, removes some of them, and each extra system can add one.

Source: APL Technical Digest 19(1), 1998 (Transit); NASA ILRS, GLONASS page; GPS.gov archive, Space Segment; ESA, What is Galileo?; ISRO, Satellite Navigation Services; all read 2026-11-22. Light time straight up, calculated from the altitude; a satellite near the horizon is farther away. BeiDou and QZSS are not drawn: no primary page giving their altitudes was readable.

What a navigation satellite carries, and what its message says

A navigation satellite is not only a clock with a transmitter. The GPS performance standard describes the chain on board: an atomic frequency standard generates the stable time base; a synthesizer derives a 10.23 MHz reference and the code and carrier timing from it; a mission computer receives the navigation data uploaded by the control segment; a baseband unit generates the ranging codes and adds the navigation message to them; and an L band subsystem modulates the result onto the carriers. The standard's assumptions name rubidium and cesium clocks.

The message itself is small and slow. On the legacy civil signal it runs at 50 bits per second, in a frame of 1,500 bits made of five subframes of 300 bits each, by the interface specification. At that rate a subframe takes 6 seconds and a frame 30 seconds (calculated). The satellite's own clock correction and precise orbit, the **ephemeris**, repeat in every frame. Two subframes are shared out across 25 pages, so the full message, including the **almanac**, a coarse orbit for every satellite, takes 25 frames, 12.5 minutes (calculated). A first fix does not need the whole almanac, only each satellite's own clock and ephemeris, which repeat every frame; but a receiver that starts with no stored data must first find the satellites and

then wait for those subframes. This is why such a receiver can take a while before its first fix, and why many phones take that data from the mobile network instead of waiting for the sky (*The Bit's Path*, chapter 6, has the acquisition search).

The message also carries the time scale's relation to UTC and a week number. GPS time began at midnight between 5 and 6 January 1980 and is continuous, while UTC is adjusted from time to time by a whole leap second; the specification requires the control segment to keep GPS time within one microsecond of UTC as kept by the US Naval Observatory, UTC(USNO), apart from those whole seconds, and the message carries the data a receiver needs to relate the two. The week number in the legacy message is ten bits, a count modulo 1,024 weeks: every 1,024 weeks, about 19.6 years (calculated), it returns to zero, and a receiver must know which cycle it is in. How a receiver handles the wrap is covered in *The Bit's Path*, chapter 7.

The one way broadcast from a GPS satellite is the one hop in this chapter that a Link Ledger can describe. Its page 1, from *The Bit's Path*, where its budget is worked, is printed here.

LINK LEDGER · LL-2000-02 · SERVICE LEDGER

2000-05-02 System: GPS L1 C/A, satellite to any receiver (civil signal after Selective Availability)

In service | Class: full | Budget: page 2 not printed in this book

1 Requirement	Deliver time and the satellite's orbit to any number of receivers wherever a satellite is in view, with no uplink and no subscription; the receiver usually needs four satellites to solve for position and its own clock.
2 Ends and path	A GPS satellite and any receiver with an antenna, a correlator and a clock. The receiver never answers. **Path:** One way broadcast, one hop. The satellite generates the signal; the ground control segment uploads orbit and clock data.
3 Orbit and time	About 20,200 km, six planes, two orbits a day (GPS.gov), one every half sidereal day. Slant range 25,247 km at 5 degrees elevation (calculated). **Time:** About 84 ms one way at 5 degrees elevation (calculated); the receiver measures this delay as a pseudorange that includes its own clock error.
4 Band and permission	**Satellite to receiver.** L1, 1575.42 MHz, right-hand circular (IS-GPS-200N); transmitted by a United States government system
5 Capacity	**Up.** None: no uplink from the user. **Down.** 50 bit/s of navigation data per satellite, the same to every receiver. Unlimited users: a receiver only listens, so users do not share capacity.
6 Who owns each end	**Space segment.** United States government **Ground segment.** The same operator's control segment; the user's receiver is the user's **Customer relationship.** None: no subscription **The exit.** Other navigation systems broadcast nearby; a receiver must support them
7 Trust	Today the United States Space Force commands the satellites from a master control station at Schriever Space Force Base. The receiver transmits nothing and holds no keys. The civil message carries no authentication (none in IS-GPS-200N), so a receiver cannot prove a signal genuine.
8 How it fails, and how we would see it	Jamming: lock lost, or output degraded or stale, not always flagged. Spoofing: output present and wrong while locked. A wrong broadcast parameter, as in the UTC error of January 2016, leaves positions right and time wrong. Blockage and a week number wrap also fail it. **How we would see it:** Jamming: gain control and C/N0 fall on many satellites at once. Spoofing and bad data: by disagreement with an independent source (another system on another band, inertial sensors, a stable clock). The GPS performance standard (2020) allows a UTC data alert up to six hours late.
9 Cost shape	Free at the point of use; the receiver is the user's cost. The space and ground segments are a government budget not assessed here.
10 Evidence	-158.5 dBW minimum, above 5 degrees (standard) IS-GPS-200N Table 3-Va, 2026-11-23 1.023 Mchip/s; 50 bit/s (standard) IS-GPS-200N 3.2.1.3, 3.2.2, 2026-11-23 C/N0 45.5 dBHz; system 290 K to verify (calculated) Page 2, 2026-11-23 Selective Availability off, 2 May 2000 (operator claim) GPS.gov, 2026-11-22 15.5 dB after 1 ms of correlation (calculated) C/N0 over 1 ms, 2026-11-23 Control segment in operation (status) (operator claim) US Space Force briefing to the CGSIC, 2026-04-21, 2026-11-22

With an assumed 20 dB obstruction loss, the hop is 3.6 dB short (calculated). The open-sky margin covers demodulating the data, not acquiring or tracking the signal.

The error sources, and what the provider commits to

Every term between the satellite's clock and the receiver's measurement adds error. Figure 2.2 lists them with who can reduce each and whether the provider's commitment covers it.

- **Satellite clock and orbit.** The broadcast clock correction and ephemeris are predictions, uploaded by the ground and aging until the next upload. The clock correction includes the relativistic term, which the specification requires the receiver to compute.
- **Group delay.** Each signal leaves the satellite's hardware with its own small delay; the message carries corrections for them.
- **Ionosphere.** To first order, the ionosphere delays the code and advances the carrier phase by an amount that falls with the square of the frequency. A single frequency receiver uses a broadcast model; a dual frequency receiver estimates and removes most of the effect, leaving hardware biases, noise and smaller terms.
- **Troposphere.** The lower atmosphere delays all navigation signals almost alike, so a second frequency does not remove it; receivers model it.
- **Multipath and the antenna.** Reflections from buildings, ground and the vehicle arrive late and bias the measurement; the antenna's own phase and delay pattern adds more.
- **Receiver noise, interference and inter-channel biases.** These depend on the receiver, its signal to noise ratio and the environment.

The errors add up in each measurement, but their uncertainties do not simply add: some are correlated between satellites, some vary slowly and some quickly, and each has its own statistical model. What the provider commits to is the part in its control. The GPS performance standard (fifth edition, April 2020) commits to a **user range error** of the signal in space of 7.0 m or less at 95 percent, as a global statistic in normal operations over all ages of the uploaded data; on the same basis, 3.8 m at zero age of data and 9.7 m at any age, each for a single satellite's signal; for the ensemble of satellites in the constellation's slots the same table gives 2.0 m (Table 3.4-1). It lists what it excludes: atmospheric scintillation, the residual errors of the receiver's ionospheric and tropospheric corrections, receiver noise and interference, receiver faults, multipath, antenna effects and operator error (section 2.4.5).

FIGURE 2.2

Where a position's error comes from, and which part the provider commits to

Error source	What causes it	Who reduces it	In the provider's commitment?
Satellite clock	The on-board clock drifts from system time; relativity	The control segment's uploaded correction; the receiver applies the relativistic term	Yes, within the user range error
Orbit (ephemeris)	The broadcast orbit is a prediction that ages	The control segment's uploads	Yes, within the user range error
Group delay	Each signal's own delay in the satellite's hardware	Broadcast corrections	Yes, within the user range error
Ionosphere	Free electrons delay the signal, more at lower frequency	A second frequency, or the broadcast model for one frequency	No: residual errors and scintillation excluded
Troposphere	At navigation frequencies, the lower atmosphere delays all signals almost alike; a second frequency does not remove it	The receiver's model	No: residual errors excluded
Multipath and antenna	Reflections arrive late; the antenna's own delay pattern	Antenna design and siting, receiver processing	No: excluded
Receiver noise and interference	Weak signal, the receiver's noise, local transmitters	Receiver design; the environment	No: excluded
Geometry	Where the satellites sit in the sky	The constellation; more systems	Yes: PDOP of 6 or less 98 percent of the time, global average

Error source	What causes it	Who reduces it	In the provider's commitment?
The provider's figure for the signal in space	The rows marked yes, except geometry		7.0 m or less at 95 percent, global, all ages of data

The provider's commitment covers the signal in space and the constellation's geometry; every local term is the user's, and the errors add in each measurement while their uncertainties combine through their variances and correlations.

Source: GPS Standard Positioning Service Performance Standard, 5th edition, April 2020, section 2.4.5 and Tables 3.4-1 and 3.8-1; IS-GPS-200N (2022), clause 20.3.3.3.3.1.

The range error becomes a position error through the **geometry**. If all the satellites in view sit in one part of the sky, a small range error moves the solution a long way; if they are spread out, it moves little. **Dilution of precision** is the factor that turns the range error into the position error: the root-sum-square of the position error's standard deviations along each axis, divided by the standard deviation of the range error, under the assumption that the range errors are independent and equal; PDOP is its three dimensional form, and GDOP adds the clock. Appendix B gives the matrix form. The GPS standard commits to a PDOP of 6 or less for at least 98 percent of the time averaged over the globe, and 88 percent at the worst site, each over a sidereal day, with a 5 degree elevation mask (Table 3.8-1).

The standard states that these commitments, with its receiver assumptions, support its position accuracy standards: 8 m or less horizontal and 13 m or less vertical, at 95 percent, averaged over the globe; 15 m and 33 m at the worst site; and a time transfer error of 30 ns or less, 95 percent of the time, for the signal in space only (Table 3.8-3). Every one of those figures is defined for a **representative receiver**: built to the interface specification, tracking all satellites above 5 degrees with no local obstruction, in a nominal noise environment, computing in the current realization of WGS 84, excluding unhealthy signals (section 3.8). The standard says outright that its signal-in-space figures "do not directly represent the end performance users will experience". A buyer's receiver, under trees, in a city or in a vehicle, rarely meets those assumptions. The local terms need the receiver's own test results.

Why two and three frequencies

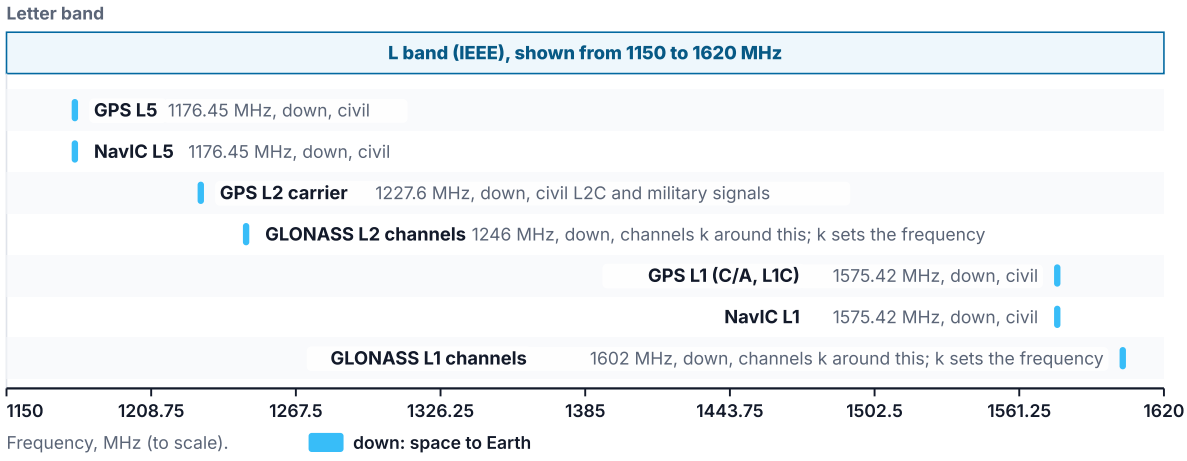
Because the ionosphere's delay falls with the square of the frequency, two signals on different carriers are delayed by different amounts, and the difference reveals the delay. Transit used 150 and 400 MHz. GPS broadcasts on L1 at 1575.42 MHz and L2 at 1227.6 MHz (IS-GPS-200N); the specification gives the ratio of their squares, $(77/60)^2$, for exactly this

use. L5 at 1176.45 MHz (IS-GPS-705J) and the newer L1C signal on the L1 carrier (IS-GPS-800J) add civil signals; the performance standard of 2020 calls L2C and L5 pre-operational and their use "at the users' own risk", with no commitment until they are declared operational. No later declaration was read for this book, so a buyer should check the current status before relying on either. L1C is another signal on L1, not another frequency; a third frequency mainly helps precise receivers (chapter 4) and guarantees no accuracy by itself.

Figure 2.3 places the navigation signals whose interface documents or official pages were read for this book. GLONASS broadcasts on a set of channels around 1602 MHz and 1246 MHz (the channel number sets each satellite's frequency), according to NASA's laser ranging service. India's NavIC uses 1176.45 MHz and a new civil signal at 1575.42 MHz, according to ISRO, plus a signal in S band near 2.5 GHz. Galileo, BeiDou and Japan's QZSS also broadcast in L band; their signals are not printed here, as Chapter 3 explains. A second frequency also helps against interference confined to one band, though both signals are weak and a wideband or multi-band interferer reaches both (Chapter 6).

FIGURE 2.3

The navigation signals crowd into a few parts of L band



Several systems share center frequencies, which helps receivers use them together and also means one interferer can reach them together.

Source: IS-GPS-200N clause 3.3.1.1; IS-GPS-705J; IS-GPS-800J (all 2022); NASA ILRS, GLONASS page (L1 = 1602 + 0.5625k MHz, L2 = 1246 + 0.4375k MHz); ISRO, Satellite Navigation Services; read 2026-11-22 and 2026-11-23. Galileo, BeiDou, QZSS: not drawn (Chapter 3).

The receiver as engineering

A receiver does four jobs before it reports a position. Its **antenna** has to see as much of the sky as possible and reject reflections from below. It has to **acquire** each satellite: search over the code's timing and the Doppler shift until a correlation peak appears. It has to **track**

code and carrier as they drift, and **decode** the message to learn the satellite's clock and orbit. Then it solves for position and time and, if it is a good receiver, estimates its own error. *The Bit's Path*, chapter 6, works through acquisition; this book only names its consequences.

How long the first fix takes depends on what the receiver already knows. A **cold start** knows nothing: it must search the whole range of codes and Doppler shifts and then wait for each satellite's clock and orbit. A **warm start** knows roughly where and when it is and has a recent almanac. A **hot start** still holds valid ephemerides. An **assisted start** receives the satellites' data, and often a rough position and time, over a mobile network, which is why a phone can fix quickly in conditions where a standalone receiver would wait. The rules that require phones to report a location for emergency calls are law, and are treated in the fourth book of this series, *Who Owns the Sky*.

A phone and a survey receiver are both receivers, and they differ in almost every part that matters for quality: antenna size and pattern, number of frequencies, whether raw measurements are available, how multipath is rejected, and whether the receiver reports an honest estimate of its own uncertainty. A buyer cannot read those differences from the chipset's list of supported systems. They show only in test results under the conditions of use.

Where the answer is expressed: frame, height and time scale

A position is three numbers in a **reference frame**. GPS works in WGS 84, the World Geodetic System 1984, in its current realization, and the performance standard's representative receiver computes in it. Other systems define their own frames, and national mapping agencies define theirs. The difference between frames, and between epochs of the same frame, can be larger than the accuracy a buyer is paying for. A coordinate without its frame and epoch (the date its coordinates refer to, since the ground moves with the plates) is incomplete.

Two height quantities are common. A satellite receiver computes **ellipsoidal height**, above a mathematical surface. Maps and engineering in many countries use **orthometric height**, roughly height above mean sea level, which needs a **geoid model** to convert (others use related quantities with their own models); the difference changes from place to place, and the model used is part of the answer.

Time has the same problem. Each system keeps its own **system time** with its own defined relation to UTC; GPS time is continuous and does not include leap seconds, and its message carries the data to relate it to UTC. Chapter 3 names the other systems' time scales where the

documents read do. A receiver's timestamp is in the scale and at the instant its output interface states, and an application that mixes scales without the offsets is wrong by whole seconds or by the steering error (Chapter 5).

THE SYSTEM'S FAILURE

How a GPS satellite fails, in its operator's own standard. The GPS performance standard of 2020 describes the defenses against a satellite that starts sending bad data. The first line of defense is the satellite: it removes itself from service when it detects certain on-board failures, by switching to non-standard ranging codes or default navigation data, which a receiver will not use. The second is the control segment: when a fault is not covered by that automatic removal, the control segment removes the satellite "in a prompt manner, subject to" its monitor stations and ground antennas having the satellite in view and its own equipment working. The same document states that the Department of Defense "does not currently monitor and assess SPS SIS performance in real time"; it monitors the military signals as an adequate surrogate for the civil one.

Kept to that document, the point is this: between a fault in the sky and the satellite's removal there is a window, set by visibility and by the operator's response, in which a receiver can use a signal that is wrong. Detecting that inside the receiver, by comparing satellites against each other, is the user's job, and Chapter 4 describes how.

SECURITY NOTE

Who can interfere or command. Any compatible receiver may use the open signal; only the system's control segment is authorized to command the satellites and uploads the message. The received signal is far weaker than the receiver's own noise in its band, so a nearby transmitter can disturb it (Chapter 6). **How it is seen.** A receiver can raise doubt by checking the satellites against each other, against another system or against its own clock and motion, but such consistency checks are not authentication: they show that measurements disagree, not where a signal came from. **How it is recovered.** By the receiver's own checks, by another system, but only after checking that the two do not fail together because they share an antenna, a receiver, a band or an environment, and by holdover on an inertial sensor or a clock for as long as its error bound allows.

Monday rule: ask of any position in your system how many satellites it used, from which systems and on which frequencies, in which frame, and whether the receiver reports its own uncertainty.

CHAPTER THREE

The Systems: Four Global, Two Regional



On 21 April 2026, according to its builder, Lockheed Martin, the tenth and last satellite of the GPS III block was launched from Cape Canaveral. On the same day, a US Space Force briefing to the civil users' committee listed the satellites of the next block, GPS IIIF, on orbit as of 13 April: none. A buyer reading those two lines learns something no data sheet says. The constellation a receiver depends on is renewed one launch at a time, by a government budget, on a schedule the user does not control. This chapter reads the six systems a receiver can use in 2026 the same way, one table shape for each, and asks of each the question a buyer should ask before choosing a chipset: who operates the clocks, what do they publish, and what do they commit to in writing?

One shape for every system

Comparisons of navigation systems usually rank them. This one does not, because the right system depends on where the receiver is, which signals it can track, and what the product needs (chapter 2 and chapter 4). Instead every system gets the same columns, and a column that could not be filled from a primary source says so.

- **Operator and owner:** who runs the control segment and who funds it.
- **First launch and declared service:** dates, and what each declaration meant. "Initial" and "full" capability are different promises.
- **Orbit and design:** the altitude, the planes and the number of satellites the design calls for.
- **Count on a date:** how many satellites are usable, on which date, and who counted. A count without a date and a counter is not printed (Appendix D).
- **Open signals:** as the system's interface document gives them.
- **Written commitment:** the public document in which the provider states the performance of its signal, if one was read.
- **Other services:** what else the same spacecraft carry.

Figure 3.1 is that table, filled as far as the primary sources read on 22 and 23 November 2026 allow. The sections below explain each row.

FIGURE 3.1

Six systems in one shape: what was read, and what could not be

System and operator	Key dates (first launch, declarations, recent launches)	Orbit and design	Count, date, who counted	Open signals (interface document)	Written commitment	Other services on the satellites
GPS; US Space Force	First launch 1978; initial capability 8 Dec 1993; full capability 27 Apr 1995	About 20,200 km; six planes; 24-slot baseline, three slots expanded (2011)	31 operational as of 3 Jul 2023 (GPS.gov); 2026 total not printed (Appendix D)	L1 C/A 1575.42, L2C 1227.6, L5 1176.45 MHz (IS-GPS-200N, IS-GPS-705J); L1C 1575.42 (IS-GPS-800J)	SPS Performance Standard, 5th ed., 2020: position accuracy 8 m H, 13 m V, 95%, global average, from signal-in-space errors only	Military signals; other payloads not covered here
GLONASS; Russia	First satellites 12 Oct 1982; declared operational 1993; 24 satellites 1995	About 19,140 km; three planes; 64.8 degrees; 24 satellites	Not read (status page did not answer 2026-11-23)	Legacy L1 and L2 by frequency division: 1602 + 0.5625k and 1246 + 0.4375k MHz (NASA ILRS); code-division signals not read	Not read	Not read
Galileo; European Union	GIOVE-A 2005; initial services 15 Dec 2016	23,222 km; three planes; full constellation of 30 planned (2016)	Satellite 34 in service 23 Jul 2026 (ESA); in-orbit count not dated on the page read; usable count not read	Not read (interface document not reached)	Open Service definition not read	High Accuracy Service; navigation data authentication since July 2025; Public Regulated Service; search and rescue with return link
BeiDou (BDS-3); China	Constellation complete June 2020; commissioned 31 Jul 2020	24 medium orbit, 3 geostationary, 3 inclined geosynchronous	30 satellites at completion (white paper, 2022); current count not read	Triple-frequency; names and frequencies not read	White paper (policy, no percentile stated): better than 9 m H, 10 m V; timing under 20 ns	Short messages; augmentation; precise positioning; search and rescue
NavIC; ISRO, India	NVS-02 launched 29 Jan 2025, left in transfer orbit; NVS-03 launched 30 Oct 2026	Design: 3 geostationary and 4 inclined geosynchronous	Usable count not stated in the ISRO pages read	L5 1176.45 MHz; S band 2492.028 MHz (ICDs; ISRO web page reads 2498.028); L1 1575.42 MHz from 2023 satellites	ISRO page: designed for better than 20 m and 50 ns (two sigma), India and 1,500 km beyond	Safety-of-life alerts (IRNSS-1A); one way messaging (IRNSS-1F)
QZSS; Japan	Not read	Not read	Not read	Not read	Not read	Not read

Every cell is from a source read on 22 or 23 November 2026 (the operator, its government or a national agency), or says not read; no count is printed without its date and who counted.

Sources: GPS SPS Performance Standard (2008, 2020), IS-GPS-200N, IS-GPS-705J, GPS.gov Space Segment, US Space Force briefing to the CGSIC (agency presentation, 2026-04-21); NASA ILRS GLONASS page; Russian Information and Analysis Center for PNT; European Commission IP/16/4366, MEMO/16/4382; ESA (2026-07-24); State Council Information Office, BeiDou white paper (2022-11-04); ISRO Satellite Navigation Services, ISRO SPS ICD 1.1 (2017) and L1 ICD 1.0 (2023), ISRO notices (2025, 2026).

GPS, United States

The US Department of Defense launched the first NAVSTAR satellite in 1978. Two declarations followed, and they are easy to confuse. The government's performance standard for the civil service records that initial operational capability for the civil signal was declared on 8 December 1993. Its 2008 edition records full operational capability, "achieved on 27 April 1995 when the GPS satellite constellation met all of its specified requirements", and announced to the public on 17 July 1995. NASA's history page, read for this book, says the 24 satellite system "became fully operational in 1993", a wording that matches the initial, not the full, declaration. The performance standard is the document that defines the terms, and this book follows it: initial capability in 1993, full capability in 1995.

The satellites fly at about 20,200 km in six orbital planes and circle the Earth twice a day. GPS.gov describes the design as a baseline of 24 slots and notes that "three slots were expanded in June 2011", which lets more than 24 satellites contribute. How many do contribute changes with every launch and retirement. The GPS.gov space segment page, as read on 23 November 2026, still gave its count "as of July 3, 2023": 31 operational satellites. A Space Force briefing to the Civil GPS Service Interface Committee on 21 April 2026 listed, as of 13 April 2026, 5 satellites of block IIR-M, 11 of block IIF and none of block IIIF on orbit; its other cells did not survive text extraction, so this book prints no total for 2026 (Appendix D).

The civil signals arrived block by block. The original civil signal, L1 C/A at 1575.42 MHz, is on every satellite. L2C at 1227.6 MHz came with block IIR-M (launched 2005 to 2009), L5 at 1176.45 MHz with block IIF (2010 to 2016), and L1C with GPS III (from 2018). The frequencies are from the interface specifications IS-GPS-200 (revision N, 2022) and IS-GPS-705 (revision J, 2022); L1C has its own specification, IS-GPS-800 (revision J, 2022), which gives it on the L1 carrier at 1575.42 MHz. A receiver that tracks L5 is therefore using a signal only part of the constellation sends, and the 2020 edition of the performance standard, the edition read for this book, states that L2C and L5 "are pre-operational and their use is at the users' own risk", with no commitment of availability until they are declared fully operational.

The control segment, run by the US Space Force, has a master control station at Schriever Space Force Base, 6 monitor stations and 11 monitor stations of another US agency. Lockheed Martin, the builder, states that it is under contract for 12 GPS IIIF satellites; the Space Force briefing describes a plan for up to 22. The first IIIF launch date was not stated in a primary source read for this book.

GLONASS, Russia

The first GLONASS satellites were placed in orbit on 12 October 1982. The design is 24 satellites in three orbital planes at about 19,140 km, inclined at 64.8 degrees, with a period of 11 hours 15 minutes 44 seconds (NASA's laser ranging service, which tracks the satellites, gives these figures). The Russian information center for the system records that GLONASS was formally declared operational in 1993 and reached 24 satellites in 1995.

GLONASS differs from the other systems in how its legacy signals share the band. GPS, Galileo and BeiDou give each satellite its own code on a shared carrier. The legacy GLONASS signals put each satellite on one carrier channel from a set of channels, so that satellites in view of a user differ in frequency: 1602 MHz plus 0.5625 MHz times the channel number on L1, and 1246 MHz plus 0.4375 MHz times the channel number on L2. A receiver that tracks them needs a wider front end and must handle a delay through its hardware that differs from channel to channel, an inter-channel bias (chapter 2).

The current number of satellites in operation, the code-division signals of the newer satellites, and the dates of the system's return to a full constellation could not be read from a primary source for this book: the Russian information center's status page did not answer on 23 November 2026. They are listed in Appendix D as sought and not read. The system broadcasts and is in use; what this book cannot print is a dated count.

Galileo, European Union

Galileo is a program of the European Union, presented to the public by the European Commission. The first test satellite, GIOVE-A, was launched in 2005, and the first operational satellites in 2011 (ESA). The European Commission announced that Galileo "will start offering" initial services on 15 December 2016, with 18 satellites in orbit and a full constellation of 30 planned.

The satellites fly at 23,222 km in three planes. ESA's overview, read on 22 November 2026, gives an in-orbit figure without the date of its count, so it is not printed. More useful to a buyer is the dated news of entry into service: ESA reported on 24 July 2026 that satellite 33 had been authorized for service in May 2026 and satellite 34 on 23 July 2026, after the launch of the pair on 17 December 2025, and that four first generation satellites remained to be launched. The number of satellites usable on a given day is published on the service center's constellation page, which did not answer on 23 November 2026; no count is printed here.

Galileo offers several services on the same satellites, each with its own promise:

- **Open Service:** "a free mass-market service for positioning, navigation and timing" (European Commission, 2016).

- **High Accuracy Service:** corrections broadcast on the satellites' own signal, free of charge, whose entry into service the Commission announced on 24 January 2023. ESA states 20 cm horizontal accuracy, with no percentile or conditions in the page read; chapter 4 places it among the correction services.
- **Open Service Navigation Message Authentication:** authentication of the navigation data (the orbit, clock and status the satellites broadcast), in service "since July" 2025 in the words of a Commission statement of 10 September 2025. Chapter 6 explains what it proves and what it does not.
- **Public Regulated Service:** "a particularly robust and fully encrypted service for government users" (European Commission, 2016). A Commission speech of 27 January 2026 still described its initial services as upcoming. Galileo is a civil program with a governmental service inside it.
- **Search and rescue:** the satellites relay distress beacons, and the European Commission announced in April 2021 a return link that tells the person in distress that the alert was received. The acknowledgment says the alert arrived, not that help is on its way.

The frequencies of the open signals, the current issue of the interface document and the performance figures of the Open Service definition document were sought on the service center's site and could not be read; they are not printed.

BeiDou, China

BeiDou's third generation, BDS-3, uses three orbit types in its core constellation. The State Council's white paper of 4 November 2022 records that in June 2020 China "completed the entire constellation deployment of 24 MEO satellites, three Geostationary Earth Orbit (GEO) satellites, and three Inclined Geosynchronous Orbit (IGSO) satellites", 30 in all, and that on 31 July 2020 BDS-3 was "officially commissioned", the start of global service. The white paper ties the global services to the medium orbit satellites and several regional services, for "China and neighboring areas", to the 3 geostationary satellites.

The white paper is a policy document, not an interface specification, and the reader should know what it does and does not give. It states the global open service as "better than 9 meters horizontally and 10 meters vertically", with timing "accurate to less than 20 nanoseconds", and gives no percentile or conditions for either, so the figures cannot be compared with the GPS standard's. It says the system uses triple-frequency signals but names no signal and no frequency. The interface documents and the open service performance standard are published by the China Satellite Navigation Office; its site did not answer on 23 November 2026, so signal names and frequencies are not printed here.

What sets BeiDou apart for a buyer is the range of services on the same spacecraft, all described in the white paper:

- **Short messages:** a global service "to specific users" through 14 medium orbit satellites, up to 560 bits a message, and a regional service through the 3 geostationary satellites, up to 14,000 bits. These are communication services and belong to the third book of this series, *The Sky as a Network*.
- **Satellite-based augmentation:** through the 3 geostationary satellites, "a Category I precision approach service" for China and neighboring areas, in the white paper's words; flying such an approach needs the aviation authority's approval of the service, the equipment and the procedure (chapter 4).
- **Precise point positioning:** for users in China and neighboring areas, through the same 3 satellites, "a cost-free high-precision positioning augmentation service", better than 30 cm horizontally and 60 cm vertically, with convergence in less than 30 minutes; no percentile is stated (chapter 4).
- **Search and rescue:** a global distress alert service through 6 medium orbit satellites, with a return link designed in.

The white paper calls the system's time "BDS time" and says its coordinate system "will remain aligned with the International Terrestrial Reference Frame". Those are the facts a receiver integrator needs for the time scale and frame lines of chapter 2; the realization of the frame, its epoch and the time offsets come from the interface documents, which were not read for this book.

Regional systems: NavIC and QZSS

NavIC (India). The Indian Space Research Organisation (ISRO) describes NavIC as a constellation of 7 satellites: 3 geostationary, at 32.5, 83 and 129.5 degrees east, and 4 in inclined geosynchronous orbits. Its service area is India and "a region up to 1500 km beyond Indian boundary", and ISRO states that its signals "are designed to provide user position accuracy better than 20m" and timing better than 50 ns, both at two sigma. NavIC broadcasts its standard positioning service on L5 at 1176.45 MHz, the same center frequency as GPS L5, and in S band; ISRO states that satellites from 2023 onward add a civil signal on L1 at 1575.42 MHz.

The S band frequency is a disputed number, and the book prints it only after reading both documents. ISRO's services page, read on 22 and 23 November 2026, gives 2498.028 MHz. The standard positioning service interface document (version 1.1, August 2017, section 3.3.1 and table 1) and the L1 interface document (version 1.0, August 2023, table 1) both give 2492.028 MHz, inside a band from 2483.5 to 2500 MHz that they name; 2492.028 MHz is

near the middle of that band and 2498.028 MHz is near its upper edge. The interface documents are the specification a receiver is built to, so this book uses 2492.028 MHz and notes the difference.

A design count is not a usable count, and ISRO's own notices show why. NVS-02, launched on 29 January 2025, was left in its transfer orbit because "the orbit raising operations from the elliptical to circular orbit could not be carried out" (ISRO). On 13 March 2026 ISRO reported that IRNSS-1F had completed its ten-year design life and that its atomic clock had stopped; the satellite continues only for one way messaging. NVS-03 was launched on 30 October 2026 and reached its final orbit, with "satellite health ... normal", according to ISRO on 4 November 2026. How many NavIC satellites provide positioning on the book's date was not stated in the ISRO pages read.

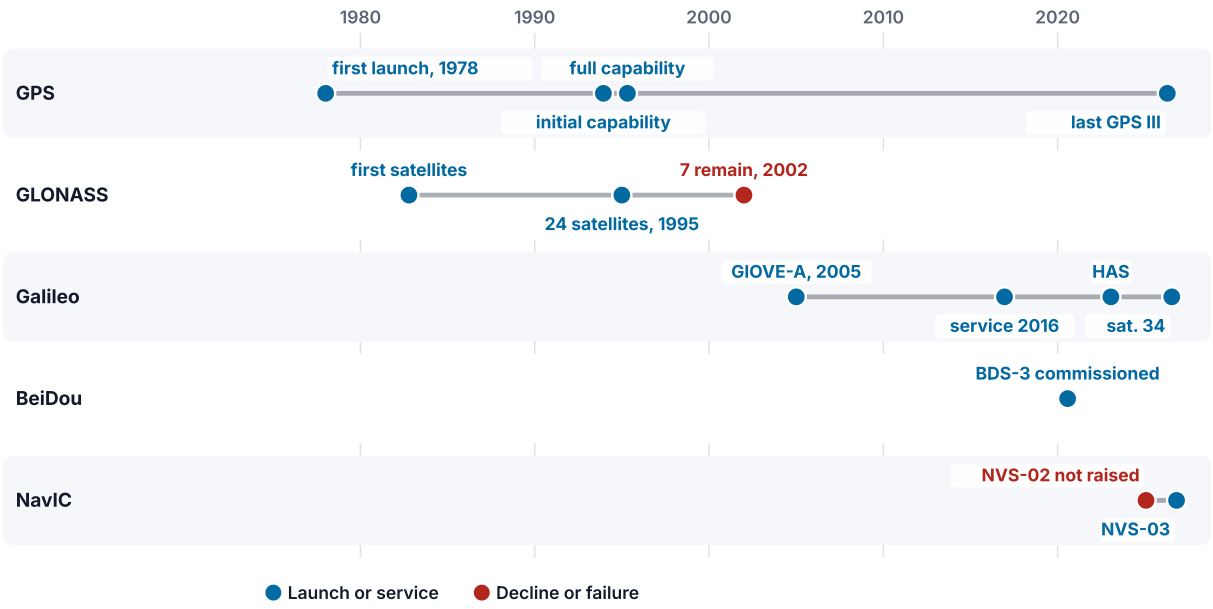
QZSS (Japan). Japan operates a regional system, the Quasi-Zenith Satellite System, which published research lists beside the global systems (for example arXiv 2401.01304, a 2024 study of spoofing detection for vehicles, a preprint, not peer reviewed). Its operator's pages and the space agency's releases did not respond when sought on 23 November 2026, so no QZSS date, orbit, count, signal or service figure is printed. Appendix D lists what was sought.

Sought, not read. This book also sought the status of a Korean regional system, the Korean Positioning System. Its agency and ministry pages could not be read, so no plan, date or status is printed; it appears only in Appendix D.

Figure 3.2 puts the dates of this chapter on one axis. It shows what a table hides: the systems were built decades apart, and each has had its own years of decline or delay.

FIGURE 3.2

Declared service, decline and renewal, system by system



Dates of first launch, declared service and decline from the sources of figure 3.1; a year without a day is placed at the start of that year.

Sources as figure 3.1. Author's diagram.

Interoperability: more satellites, more ways to be wrong

The systems were designed to be used together where it suits their owners. Several share center frequencies: GPS L1 and NavIC's new L1 signal both use 1575.42 MHz, and GPS L5 and NavIC L5 both use 1176.45 MHz, according to their interface documents. A shared frequency lets one antenna and one front end receive several systems. It does not make them one system. Each keeps its own time scale and its own realization of the terrestrial reference frame, so a receiver combining them must estimate the offset between system times (one more unknown per system, or a broadcast offset between system times) and still estimate or calibrate the receiver's own delays between signals, which no broadcast removes (chapter 2).

More satellites in view improve geometry and availability, especially in cities and valleys where buildings hide part of the sky. They also add ways to be wrong. Each system has its own control segment, its own faults and its own policy. A fault in one system can pull a combined solution off unless the receiver detects and excludes it (chapter 4). And satellites of several systems share the same band, so a local jammer in that band can deny all of them at once: a second constellation is a second source of satellites, not an independent backup (chapter 6).

The buyer's question is therefore not "how many systems does the chipset support" but "which signals does the receiver actually track and use in the solution, with which settings, and how does it treat a system that disagrees with the others". Ask too whether any constellation or frequency is disabled by default or sold as a separate option.

What each provider commits to in writing

The only performance standard read in full for this book is the one for GPS; the other providers may publish equivalents that could not be read. The GPS *Standard Positioning Service Performance Standard*, fifth edition, April 2020, states that "the U.S. Government is committed to meeting and exceeding the minimum levels of service specified" in it. Three of its numbers show how such a document is written:

- A signal-in-space user range error of 2.0 m or less at 95 percent for the ensemble of satellites in the constellation's slots (7.0 m for any one satellite's signal, chapter 2), a global statistic in normal operations, leaving out the errors of the single-frequency ionospheric model (table 3.4-1).
- A global average position accuracy of 8 m or less horizontally and 13 m or less vertically, at 95 percent, for a representative receiver with a 5 degree elevation mask and no local obstructions; at the worst site, 15 m and 33 m (table 3.8-3).
- For comparison, the same document reports that in 2018 the service gave "horizontal accuracy of 3 meters or better and vertical accuracy of 5 meters or better 95% of the time". The commitment is the floor; the performance the operator reports for 2018 is better.

As chapter 2 shows, the standard excludes every error source outside the control and space segments: it commits to the signal, not to the position a particular receiver computes.

The other systems publish statements of different kinds: BeiDou's figures above come from a policy white paper; NavIC's are a design statement on ISRO's site; Galileo's Open Service definition document could not be read. None of these documents is a contract with the user. A navigation user of an open signal has no subscription and no individual service agreement with remedies; remedies for a degraded open signal come from the user's own design, not from the provider. Where a contract exists, it is with a correction provider or a receiver supplier (chapter 4).

THE SYSTEM'S FAILURE

What failed: the size of the constellation. GLONASS reached its full 24 satellites in 1995. By 2002, according to Russia's own information center for the system, only 7 remained. The decline came in the years after the dissolution of the Soviet Union. The source records the count, not the decisions or the budgets behind it, and this book does not supply them. The consequence follows from the numbers alone: with 7 satellites spread over three planes, a receiver can no longer expect four in view at any time and place, so GLONASS alone could not give continuous positioning. The record supports one useful conclusion: a constellation exists only as long as launches keep replacing the satellites that wear out, and a receiver's service life can outlast that commitment.

SECURITY NOTE

Who can interfere or command. Each system's satellites are commanded by its state operator's control segment, the only party authorized to do so; the restricted governmental services (the GPS military signals, Galileo's Public Regulated Service and their equivalents) are named here only; their current operational status was not checked. The open signals are public by design, so receiving them reveals nothing secret (a connected receiver can still reveal its user's position through its own network link); interference by a local transmitter is the concern, and it affects every system that shares the band (chapter 6). **How it is seen.** Whether a receiver can tell a genuine message from a forged one depends on the system and signal: the GPS legacy civil message carries no authentication (the word does not appear in IS-GPS-200 revision N); Galileo's open signal carries authentication of its navigation data since July 2025; for BeiDou, GLONASS, NavIC and QZSS no authentication of the open signal was stated in the sources read. **How it is recovered.** A one way broadcast gives the provider no link back to an individual user, so recovery is the user's design: a receiver that tracks more than one system and more than one frequency, with the shared dependencies listed (one antenna, one band, one front end), and an alternative for time and position. In some countries which systems a receiver may use is itself a regulatory matter, covered in depth later in this series.

Monday rule: find out which constellations and signals your receivers actually use in their solution, with today's firmware and settings, not which the chipset could use.

CHAPTER FOUR

Accuracy and Integrity: Augmentation, Corrections and Monitoring



In July 2003 the US Federal Aviation Administration commissioned the Wide Area Augmentation System, WAAS: a network of reference stations on the ground and a broadcast from geostationary satellites that corrects GPS and warns of its faults. By 27 November 2025, according to the FAA, 4,219 published approach procedures at 2,035 US airports were built on it, with minimums as low as 200 feet. A guidance receiver on a tractor can decode the same broadcast on the same frequency; the FAA's worldwide summary notes that the European system's use in surveying, agriculture and shipping is increasing. The pilot and the farmer receive the same bits and buy different things: the pilot's avionics are certified to use the integrity part of the message, and a published procedure, crew training and a check that the service is available for that approach stand behind it. This chapter separates the qualities a position can have and what stands behind each.

Three different things: accuracy, reported uncertainty, integrity

A buyer who asks for "an accurate position" has asked for one of three things without saying which. They are measured differently, often stated by different parties, and bought separately.

Accuracy is how far the reported position is from the true one, described over many fixes. It is a statistic, so it needs a percentile and conditions: "2 m horizontal, 95 percent, open sky, over 24 hours" says something; "2 m" does not. For an error in one dimension with a normal distribution, the 95 percent value is about twice the one sigma value; for a horizontal error the conversion depends on how the two components are defined, and a root mean square figure is something else again. Two data sheets with the same number may describe different receivers.

Reported uncertainty is what the receiver says about its own fix, usually as an estimated error in meters. A phone's map draws it as the circle around the blue dot. It is the receiver's model of its own errors; when its assumptions hold, the circle is useful. When they do not (a reflected signal taken for a direct one, a satellite with a fault the receiver cannot see), the circle can be small and wrong at the same time.

Integrity is the ability of a system to warn the user in time when its output should not be used. It is stated as a probability over a stated exposure (per approach, per hour): the probability that the true error exceeds a stated limit without the user being told within a stated time. Aviation states it with three numbers: the *integrity risk* (the probability allowed, over the exposure, that the error exceeds the alert limit with no warning in time), the *alert limit* (the largest error the operation can tolerate) and the *time to alert* (how quickly the user must be warned). A system that provides integrity computes, for each fix, a *protection level*: a bound on the error at that integrity risk under its stated fault models. When the protection level exceeds the alert limit, the position is declared unusable for that operation.

The three come apart in practice. A centimeter-level correction service can deliver excellent accuracy with no integrity statement at all. An aviation receiver can provide strong integrity with an accuracy of a meter or more. Integrity matters wherever a wrong position is worse than none: a vehicle in its lane, a rail signal, a geofence that releases a payment. Figure 4.1 sets the three side by side.

FIGURE 4.1

Accuracy, reported uncertainty and integrity are three different promises

Quality	What it is	Who states it	How it is written	How a buyer tests it
Accuracy	How far the reported position is from the truth, as a statistic over many fixes	A provider for the signal in space; a receiver maker or integrator for the result	A value with its percentile and conditions: 95 percent, open sky, over a stated period	Occupy a surveyed point in the conditions of use and compute the percentile
Reported uncertainty	The receiver's own estimate of the error of each fix	The receiver, fix by fix, from its error model	An estimated error in meters, often one sigma; the method is rarely published	Compare the reported value with the true error over many fixes, including in bad conditions
Integrity	A bound on the error that holds with a stated probability, with a warning when it cannot be met	A service provider with certified equipment, or a receiver with a stated monitoring algorithm and fault assumptions	Integrity risk, alert limit and time to alert; a protection level per fix	Through the domain's safety case and certification (aviation, rail, road): analysis, fault models and testing; a field trial alone cannot show a very small integrity risk

Each quality is often stated by a different party and is tested a different way; a data sheet that gives one says nothing about the other two.

Author's table based on the FAA's WAAS pages and Performance Analysis Report 98 (2026) and the GPS Standard Positioning Service Performance Standard (2020), read 2026-11-23.

Monitoring: in the receiver, on the ground, overhead

Something has to watch the signals for faults the satellites do not announce: in the receiver, on the ground, or from space.

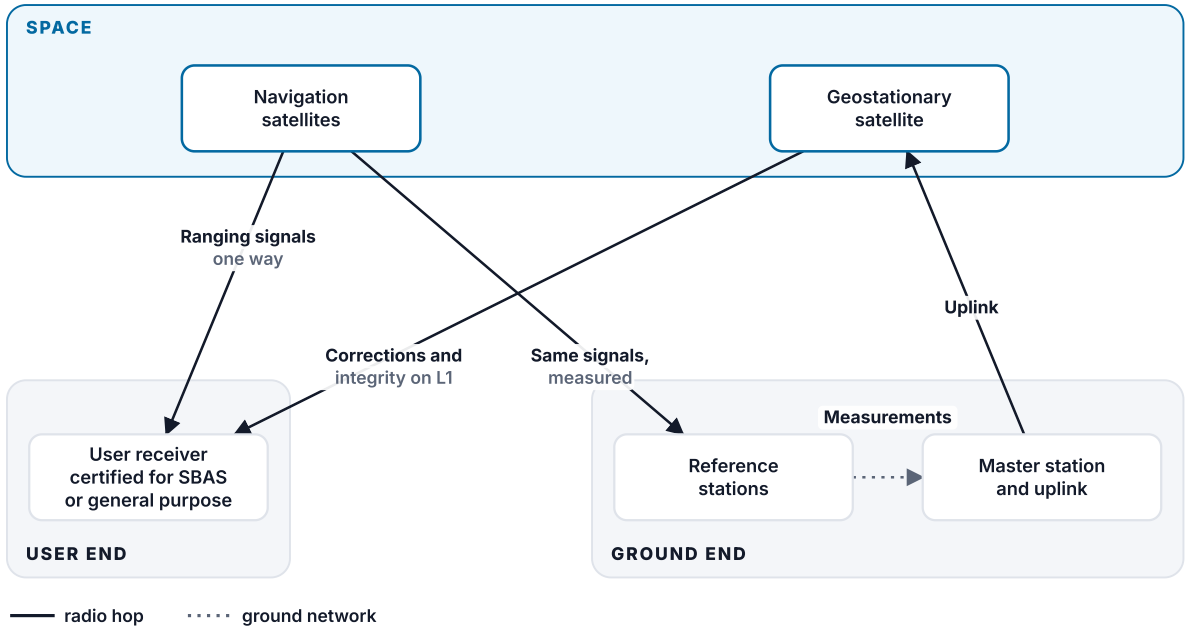
In the receiver. Receiver autonomous integrity monitoring (RAIM) uses redundancy: with more satellites in view than a fix needs (and more still to exclude a fault than to detect one), the receiver checks whether the measurements agree, detects a fault when they do not, and in its fuller form excludes the faulty satellite (fault detection and exclusion). Advanced RAIM (ARAIM) extends the idea to several constellations and two frequencies, with assumptions about the faults of each constellation supplied from the ground in an integrity support message (FAA Technical Center, 2021). The FAA's technical center publishes analyses of its performance; no approval of ARAIM for operations was read for this book. RAIM needs no infrastructure beyond the satellites; it is limited by geometry, because a fault can only be detected if enough independent measurements remain to see it.

On the ground, near the user. A ground-based augmentation system (GBAS) serves one airport: reference receivers at surveyed positions compute corrections and integrity data and broadcast them locally to aircraft on approach. Its coverage is local by design.

From a wide-area network, broadcast from space. A satellite-based augmentation system (SBAS), in its conventional single-frequency form, spreads reference stations over a continent, sends their measurements to a master station that computes corrections for satellite orbits, clocks and the ionosphere together with integrity information, and uplinks the result to a geostationary satellite. The geostationary satellite broadcasts it on the GPS L1 frequency, in a format a certified receiver decodes alongside the GPS signals. The broadcast is one way and open, like the core signal. Figure 4.2 shows the chain.

FIGURE 4.2

Conventional single-frequency SBAS, illustrated by WAAS: a second broadcast, built on the ground



Reference stations measure the navigation signals, master stations compute corrections and integrity data, uplink stations send them to geostationary satellites, and the satellites broadcast them on L1; dual-frequency SBAS and correction services delivered over the internet differ.

Author's diagram based on the FAA's description of WAAS.

Receiving the broadcast is not the same as being allowed to depend on it: an approach also needs certified avionics, an approved procedure, a trained crew and the service available at that time. A receiver that applies the corrections but is not certified to use the integrity information may gain accuracy without the protection; it must still obey the message's flags and age limits that mark a correction unusable.

The world's augmentation services

WAAS shows what such a service is made of, in the FAA's own description. Precisely surveyed reference stations across the airspace (38 of them in the FAA's 2021 program overview) receive the GPS signals and send their measurements to master stations. The master stations generate "a WAAS User Message every second", which uplink stations send to navigation payloads on geostationary communications satellites; the payloads broadcast it "on a GPS-like signal". In the third quarter of 2026 the FAA's technical center evaluated the broadcasts of three such satellites, PRN 131, 133 and 135, leased on Eutelsat 117 West B,

SES-15 and Galaxy 30. The FAA states that users "are notified within six seconds" of hazardously misleading information. Its performance reports quote the system's requirement for vertically guided approaches: 1.5 m horizontal and 2 m vertical accuracy at 95 percent, and a probability of hazardously misleading information below one in ten million per approach. The ledger below reads the service in the series' ten fields.

LINK LEDGER · LL-2003-01 · SERVICE LEDGER

2003-07 (into service)

System: WAAS: GPS augmentation broadcast on L1 from geostationary satellites (FAA) **In service**

Class: service only

1 Requirement	Let any equipped receiver correct its GPS fix and be told within a stated time when it is unsafe; for aviation, guidance to 200 feet with certified avionics and an approved procedure.
2 Ends and path	FAA reference, master and uplink stations; any GPS/WAAS receiver in view (TSO-C145c or TSO-C146c avionics for approaches). **Path:** Corrections computed on the ground, relayed one way by a leased geostationary payload.
3 Orbit and time	Geostationary; PRN 131, 133 and 135 in July to September 2026. **Time:** A message every second; a hazardous error flagged within six seconds (FAA).
4 Band and permission	**Broadcast.** GPS L1, 1575.42 MHz; ICAO Annex 10 SBAS standard; FAA
5 Capacity	**Up.** None from the user. **Down.** One message stream per satellite, 500 symbols a second. One more receiver costs nothing; the limit is message content and age.
6 Who owns each end	**Space segment.** Payloads leased on Eutelsat 117 West B, SES-15, Galaxy 30 **Ground segment.** FAA: 38 reference stations (2021), master and uplink stations **Customer relationship.** None; avionics certified to FAA standards **The exit.** GPS with receiver integrity monitoring: a degraded mode without guidance to 200 feet
7 Trust	The FAA's master stations generate the messages and its uplinks send them. No authentication of the message is stated in the sources read. Interference on L1 can deny GPS and the corrections together.
8 How it fails, and how we would see it	A ground or satellite fault or an ionospheric storm can withdraw vertical guidance over part of the area. **How we would see it:** The receiver flags the service unavailable; the FAA publishes coverage and quarterly reports.
9 Cost shape	Free to the user; the FAA funds stations and payload leases; the user pays for certified avionics (assessment from the FAA's description).
10 Evidence	Commissioned July 2003 operator claim FAA, SBAS fact sheet, 2025-11-27, 2026-11-23 LPV: 1.5 m H, 2 m V (95%); misleading information below 1e-7 per approach standard FAA-E-2892, quoted in FAA report 98, table 1-4, 2026-11-23 PRN 131, 133, 135 broadcasting, Q3 2026 measured FAA Technical Center, report 98, 2026-11-23 L1 1575.42 MHz, 500 symbols/s standard ICAO letter 2021-07-06, Annex 10 App. B, 2026-11-23

Service only, no hop budget: the WAAS Performance Standard and the payloads' transmit figures were not read.

WAAS is one of a family. Every satellite-based augmentation system is built to the same international standard, the Standards and Recommended Practices in Annex 10 of the Chicago Convention, maintained by the International Civil Aviation Organization (ICAO), so

that certified avionics can move from one system's area to the next. Figure 4.3 lists the systems with their status in the words of a primary source and its date. Most of the status lines come from the FAA's worldwide summary of November 2025, because the other providers' own pages could not be read for this book; where a provider's page was read (India's GAGAN, China's white paper), it is cited instead.

FIGURE 4.3

Augmentation and correction services, as a primary source stated them

Service	Provider and region	Signal or transport	Status as stated, with date	Source
WAAS	FAA; North America	GPS L1 from geostationary satellites PRN 131, 133, 135	Commissioned July 2003; dual-frequency service in development, 2027; broadcasting July to September 2026	FAA fact sheet; FAA report 98
EGNOS	European Union; Europe	SBAS on L1 (ICAO); satellites not read	Commissioned for aviation March 2011; dual-frequency multi-constellation service in development, 2028	FAA fact sheet; provider page not read
MSAS	Japan	Not read	Commissioned 2007; provides LNAV service, establishing LPV	FAA fact sheet; provider page not read
GAGAN	ISRO and Airports Authority of India; India	Not read	Certified by India's civil aviation regulator for RNP 0.1 on 30 December 2013 and APV-1 on 21 April 2015	ISRO
KASS	South Korea	Not read	Commissioned 2024	FAA fact sheet; provider page not read

Service	Provider and region	Signal or transport	Status as stated, with date	Source
SouthPAN	Australia and New Zealand	Not read	Early services 2022; aviation services 2028	FAA fact sheet; provider page not read
SDCM	Russia; GPS and GLONASS	Not read	Under development	FAA fact sheet; provider page not read
BDSBAS	China and neighboring areas	Three geostationary satellites	White paper (2022): a Category I precision approach service; FAA (2025): in test, undergoing certification	White paper; FAA fact sheet
Galileo HAS	European Union; coverage not read	The Galileo satellites' own signal; internet delivery not read	Entry into service announced 24 January 2023; "up to 20 centimetres" (percentile and conditions not stated)	European Commission
BeiDou precise point positioning	China and neighboring areas	Three geostationary satellites	Free; better than 30 cm horizontal, 60 cm vertical; convergence under 30 minutes (2022; percentile not stated)	White paper
QZSS services	Japan; region	Not read	Sought, not read	Provider pages not read
Trimble RTX	Trimble; worldwide	Internet over cellular, or satellite	Surveying tier 2 cm; as fast as one minute in its fast-start areas (operator claim)	Trimble RTX page

Service	Provider and region	Signal or transport	Status as stated, with date	Source
Swift Skylark	Swift Navigation; coverage map	Internet (NTRIP, RTCM)	1 cm to 1 m by tier; 99.9 percent service availability, tier and conditions not stated (operator claim)	Swift Skylark page

Status is in the words of the source named, on the date given; for most SBAS rows that source is the FAA's worldwide summary, not the provider. A footprint is not a service area, and an aviation status is not a status for other uses.

Sources: FAA, SBAS worldwide fact sheet (rev. 2025-11-27) and WAAS Performance Analysis Report 98 (October 2026); ISRO, Satellite Navigation Services; European Commission, SPEECH/23/341 and MEX/25/3110; State Council Information Office, BeiDou white paper (2022-11-04); Trimble, Trimble RTX; Swift Navigation, Skylark; all read 2026-11-23. Rows marked not read were sought on the provider's site.

Three cautions apply to every row. First, a broadcast footprint is not a service area: a geostationary satellite's signal reaches far beyond the region where the reference stations can measure the ionosphere. The ionospheric corrections hold only inside the region the message itself marks as monitored, and a receiver must obey the message's masks, flags and age limits, not the fact that it can hear the satellite. Second, an aviation status is a status for aviation, not a commitment for other uses. Third, several systems are moving to a second frequency and several constellations (dual-frequency multi-constellation service, which the FAA lists for WAAS in 2027 and for EGNOS in 2028); a receiver bought today should state which generation of the message it decodes.

Corrections: from meters to centimeters

An SBAS improves a fix to a meter or a few meters: the FAA states "position accuracy of a few meters" for WAAS across US airspace, and the tighter requirement for vertically guided approaches quoted above. Getting to centimeters needs a different measurement and a different service. Four methods are on the market, and they differ in what they need, how long they take, and where they work (figure 4.4).

Code differential. A reference receiver at a known position measures the error in each satellite's code range and sends a correction; a user nearby applies it. Errors that both receivers share (satellite clock and orbit, most of the atmosphere) cancel, and the cancellation weakens with distance from the reference. An SBAS works differently: instead of one station's range errors, it models the satellites' orbit and clock errors and the ionosphere over a continent from many stations, and adds integrity data. Both reach meter level.

Real-time kinematic (RTK). The receiver measures not only the code but the phase of the carrier wave itself, whose wavelength at L1 is about 19 cm. The phase is very precise, and once the receiver locks on it counts the whole cycles as they pass; what it cannot know is the whole number of cycles between it and the satellite at the moment it locked on, and a cycle slip, a jump in that count by whole cycles, often after tracking is interrupted, opens that question again. With a base station's measurements sent over a data link, the rover solves for those whole numbers. When it has resolved them as integers, the solution is called *fixed*, and with the right integers, good geometry and little multipath it reaches centimeters; while it is still estimating them as real numbers, the solution is *float*, and its error can be decimeters or more. A wrong set of integers gives a fixed solution that looks good and is not. A buyer should read "RTK" on a data sheet as "centimeters when correctly fixed", and ask how often and how fast it fixes, how a wrong fix is detected, and how often one happened in the supplier's tests.

Network RTK. Instead of one base, a network of permanent reference stations models the errors over a region and sends each rover corrections that work as if a base were nearby (one common implementation computes a virtual base near the rover). The buyer does not operate a base; they subscribe to the network and need a data connection, usually a mobile data link, inside the network's coverage.

Precise point positioning (PPP). A global network of stations computes precise satellite orbits and clocks (and, in some services, biases), and a provider sends them to the user by satellite or over the internet. The user needs no nearby station. Without nearby reference measurements, the receiver must estimate the atmosphere and the carrier ambiguities on its own, and that takes time: the solution *converges* over minutes to tens of minutes before it reaches its stated accuracy. Some services also send the satellite biases a receiver needs to resolve the ambiguities as integers. **PPP-RTK** adds regional atmospheric corrections, which shortens convergence where a regional network exists.

FIGURE 4.4

Four correction methods differ in what they need, how long they take and where they work

Method	Accuracy class	Time to reach it	Where it works	What the user needs	Usual transport
Code differential; SBAS	A meter to a few meters	No convergence wait once valid corrections are received	Code differential: near the reference. SBAS: inside the monitored service area	A receiver that decodes the corrections	SBAS: geostationary broadcast on L1. Code differential: radio or data link
RTK, own base	Centimeters when correctly fixed; decimeters or more while float	Not stated in a source read; ask the supplier	Near the base: shared errors cancel only at short distance	A base on a known point, a data link, a carrier-phase receiver	Radio or mobile data link
Network RTK	Centimeters when correctly fixed	Not stated in a source read; ask the supplier	Inside the network's coverage	A subscription and a data connection; no own base	Internet over mobile data (NTRIP)

Method	Accuracy class	Time to reach it	Where it works	What the user needs	Usual transport
PPP and PPP-RTK	Decimeters to centimeters after convergence	Stated by providers: under 30 minutes (BeiDou, 2022); one minute in regional fast-start areas (Trimble)	Global (PPP); a region (PPP-RTK)	A carrier-phase receiver that decodes the format; a subscription or an open service	L-band satellite, the navigation signal itself, or the internet

Accuracy here is the order of magnitude each method reaches in good conditions; a buyer takes the value, its percentile and its conditions from the provider's own service definition (figure 4.3).

Author's table. Accuracy classes as stated by the providers in figure 4.3 (FAA, European Commission, State Council Information Office of China, Trimble, Swift Navigation), read 2026-11-23.

Public precise positioning services. Two navigation systems whose documents were read for this book broadcast precise corrections free of charge on their own satellites; Japan's QZSS services could not be read (below). The European Commission announced the entry into service of Galileo's High Accuracy Service on 24 January 2023, and describes it as reaching "up to 20 centimetres". China's white paper of 2022 describes a "cost-free high-precision positioning augmentation service" through BeiDou's three geostationary satellites, "better than 30 centimeters horizontally and 60 centimeters vertically", with a convergence time "less than 30 minutes". Neither statement gives a percentile or conditions, and both are public statements of performance, not contracts. Japan's QZSS services were sought and could not be read for this book (Appendix D).

Commercial services, by what they sell. A commercial correction service sells a subscription defined by coverage, accuracy tier, convergence and delivery. Two examples, as their operators state them on 23 November 2026: Trimble describes its RTX family as "available via IP/cellular or satellite delivery worldwide", with a surveying tier at 2 cm and initialization "as fast as one minute in RTX FAST areas", and lower tiers from 10 cm to 50 cm for mapping and agriculture. Swift Navigation describes its Skylark service as ranging "from 1 centimeter to 1 meter" by tier, delivered over the internet in the open RTCM formats, so that "a GNSS receiver needs to be connected to the Internet". Neither page states a global convergence time, and neither states the percentile behind every tier. A service availability

figure, such as Swift's 99.9 percent, describes the correction stream, not whether a receiver at the buyer's site reaches the tier's accuracy. Those are the first two questions for the sales engineer, and the answers belong in the contract.

Integrity is a separate product even here. Swift Navigation describes, for its automotive customers, positioning that "alerts you in the event that it is unreliable" under a functional safety rating; its general correction page states no integrity figure. A buyer who needs integrity asks for it by name, with the integrity risk, alert limit and time to alert, and the certification behind them.

Transport is a separate question from method

The same corrections can reach the receiver in several ways: on a navigation satellite's own signal, on a separate communications satellite in L band, or over the internet, most often through a mobile data connection. The transport decides where the service works (a mobile data connection ends where the network ends), what else it depends on, and how old a correction is when it is applied. Correction age matters because the errors being corrected drift; a provider should state the age limit its corrections assume, and a buyer asks for it if it does not.

Corrections also travel in formats: the open RTCM version 3 standard of the Radio Technical Commission for Maritime Services, carried over the internet by its companion protocol NTRIP, and other published formats built for broadcast. A buyer checks that the receiver decodes the format the service sends, in the firmware the buyer will run.

Buying a usable solution, not only a correction

A correction subscription alone does not deliver centimeters. The result depends on a chain, and each link is a line on the order:

- **The correction service itself:** coverage, tier, percentile, convergence, the availability of a usable solution and its continuity through an operation, transport, format, age limit and status notices, in the contract.
- **The receiver and its firmware:** which constellations and frequencies are enabled (some are licensed features), which correction formats it decodes, and whether it reports fixed or float status and its own uncertainty.
- **The antenna and cable:** a survey antenna whose phase center is calibrated, with the calibration model the receiver uses; a phone's antenna is not one.
- **Raw observations:** whether the buyer can log the receiver's measurements for later checking and post-processing.

- **The frame:** corrections deliver coordinates in the provider's reference frame and epoch. A centimeter position in one frame can differ by decimeters or more from the same point expressed in a national frame, because the ground itself moves with the tectonic plates (chapter 2). The provider states its frame; the buyer states the frame the product needs.
- **The acceptance test:** a known point, surveyed independently, occupied in the conditions of use, with the time to fix and the share of fixed solutions recorded; for a moving or obstructed use, a reference trajectory from an independent system of known uncertainty, aligned in time, with correction outages, reacquisition after loss of lock and wrong fixes counted. A high share of fixed solutions is not evidence of integrity.

What none of these fix

Every method in this chapter improves the measurement of signals that are genuine. Corrections alone do not keep a receiver working when the signals are drowned by a nearby transmitter (jamming), and they do not establish that a signal the receiver accepts is genuine (spoofing). Some monitoring and cross-checks can raise doubt; none guarantees detection. A spoofed fix with valid-looking corrections applied to it is a precise wrong answer. Chapter 6 treats both, and what message authentication does and does not add.

THE TRADE-OFF: GLOBAL REACH AGAINST A LOCAL NETWORK

What is traded: coverage against time to accuracy. Network RTK and precise point positioning both sell positions far better than a standalone receiver's, down to centimeters in some tiers, and fall short in different places. Network RTK can fix quickly, but only inside the network and only while its correction data link, usually a mobile connection, holds: a tractor at the edge of the coverage map or a survey crew in a valley without signal works on aging corrections only until the receiver's age limit, then falls back to whatever it had before. Precise point positioning needs no nearby station and works inside the coverage its provider declares, which the reach of the satellite or internet delivery does not define, but needs time: China's white paper states under 30 minutes for BeiDou's service; Trimble states one minute only "in RTX FAST areas", where regional data exists. The operators' published figures above support only this much: the buyer pays either in coverage or in waiting, and the requirement sheet decides which is affordable.

SECURITY NOTE

Who can interfere or command. The augmentation or correction provider generates the corrections and is the authorized party to command the broadcast; any equipped receiver may use an open broadcast, while a paid stream is access-controlled by the vendor's subscription and login. A satellite broadcast on L1 shares the core signal's exposure: a jammer in the band can remove both at once. An internet stream adds the mobile network and the provider's servers to the list of things that can fail or be attacked. **How it is seen.** No authentication of the WAAS message, or of the commercial streams' content, is stated in the sources read; a receiver checks the integrity flags and the age of the corrections, and an operator sees service status in the provider's notices. **How it is recovered.** Falling back to an uncorrected solution is a recovery only if that solution still meets the requirement for degraded operation; otherwise the system must raise an alarm, withhold the output or stop the operation.

Monday rule: write down whether you need accuracy, integrity or both, at which percentile and in which frame; they are bought separately.

CHAPTER FIVE

Time as a Service



In late January 2016, ground software uploaded to the GPS control segment on 26 January threw the system's coordinated universal time message "off by 13 microseconds", in the words of a trade press report published three days later (Inside GNSS, 29 January 2016). The same report says the problem "did not appear to have affected" positioning. Positioning, in that report's cautious words, did not appear to suffer; some timing receivers did not keep the right time. This chapter changes one decision: a timing user is a different customer from a navigation user, with a different promise, a different failure and a different test.

Three things called time

A buyer who writes "we need GPS time" has not yet written a requirement. Three different quantities hide behind the word, and equipment is specified, tested and sold separately for each:

- **Frequency:** how fast a clock ticks. A radio transmitter or a network link may need its oscillator held to a stated fraction of its nominal rate, with no interest in what time it is.
- **Phase:** whether two clocks tick together. Two base stations that share a frequency band in turns must start their frames at the same instant, within a stated error, relative to each other.
- **Time of day:** which second it is, against a named time scale. A log entry, a trade record or a fault recording must carry a timestamp that can be compared with records made elsewhere.

The time scale matters as much as the accuracy. Coordinated Universal Time (UTC) is the civil time scale; national laboratories each keep a real-time version of it, such as UTC(USNO), kept by the United States Naval Observatory. Each navigation system runs its own system time and publishes its relation to UTC. GPS time started at midnight between 5 and 6 January 1980, counts in weeks of 604,800 seconds, and is not adjusted for leap seconds; its interface specification keeps it within one microsecond of UTC(USNO), apart from a whole number of seconds (IS-GPS-200N, section 3.3.4). UTC(USNO) is the Naval

Observatory's real-time realization of UTC; how far it is from UTC itself is a separate, published quantity. That whole number counts the leap seconds added to UTC since GPS time was aligned with it at its start; it is not the offset between TAI and UTC. The GPS performance standard records that the offset between GPS time and UTC "transitioned from 17 to 18 sec" at the last second of 31 December 2016 (GPS Standard Positioning Service Performance Standard, 5th edition, April 2020; this book calls it the SPS standard). A receiver that reports GPS time where UTC was asked for is wrong by that count; one that applies the count late is wrong by a second.

The broadcast tells the receiver how to convert. Each satellite carries offset parameters that relate its system time to UTC, and the receiver applies them after it has solved for its own clock. The 2016 event in the lead was an error in those parameters, not in the ranging signal, which is why positioning need not suffer while time goes wrong.

What the provider commits to, in its own words

The SPS standard is the United States government's public performance commitment for the civil GPS signal (chapter 1 sets it beside the other three kinds of promise). Its timing lines are specific, and each comes with its conditions:

- **Accuracy of the offset data:** 30 nanoseconds, 95 percent, global statistic, "during Normal Operations at Any AOD" (age of data), for "any trackable and healthy" signal (Table 3.4-4).
- **Integrity of the offset data:** a probability of 1 in 100,000 over any hour that the instantaneous offset error exceeds a not-to-exceed tolerance of 120 nanoseconds without a timely alert; "Worst case for delayed alert is 6 hours" (Table 3.5-4).
- **Time transfer accuracy:** 30 nanoseconds, 95 percent of the time, marked "SIS only" (signal in space), for a solution that meets the standard's representative user conditions (Table 3.8-3). Those conditions include a receiver "operating at a surveyed location (for a time transfer receiver)".

Three phrases in the same document set the limits of these numbers. The standards "do not include any element not under the direct control of the GPS Control/Space Segments". They "do not directly represent the end performance users will experience". And the user's UTC error is built by "root-sum squaring the UTCOE with a receiver's solution accuracy for GPS time" (Table 3.4-4, note 2). In plain terms: the government commits to the time in the sky; the antenna, the cable, the receiver, the network and the server clock are the buyer's.

Two more points follow from the text. The 120 nanosecond tolerance with alerts up to six hours late describes the broadcast's integrity, not an alarm that reaches a server: a timing receiver has to notice, and the buyer's system has to act. And the standard is a performance

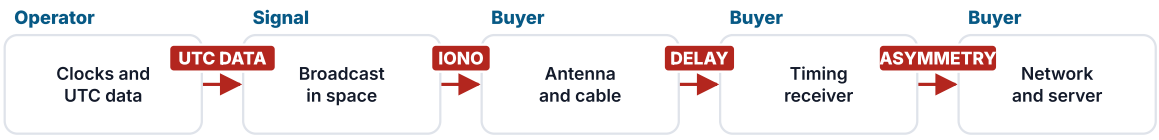
commitment, not a contract. It creates no service level the user can claim against, which chapter 6 takes further.

From the antenna to the timestamp

A timing receiver is a navigation receiver used differently. Fixed at a surveyed position, it no longer needs to solve for position, so every satellite in view helps estimate one unknown, its clock offset. It steers a local oscillator, often an oven-controlled crystal or a rubidium cell, to the satellite time it computes, and hands out a pulse per second, a frequency output and a time-of-day message. The receiver's data sheet states how well its outputs follow satellite time. The data sheet does not state how well a log entry on a server three network hops away follows UTC. That number is built along a chain, and each link adds error (Figure 5.1):

FIGURE 5.1

A timestamp is built along a chain, and only the first link is the provider's



Red chips: the main error each step adds. The first step is the operator's; the rest are the buyer's.

From the clocks in orbit to a timestamp on a server: the provider's commitment covers the signal in space; every error after it is the buyer's to calibrate, budget and watch. The diagram shows the path, not the size of each error.

Author's diagram based on the GPS Standard Positioning Service Performance Standard, 5th edition (April 2020), Tables 3.4-4 and 3.8-3 and equation B-7; RFC 5905, section 8; NASPI-2017-TR-001 (March 2017), page 23.

- **The signal in space:** the provider's share, bounded by the commitment above while the system is healthy.
- **The propagation:** the ionosphere and troposphere delay the signal; a receiver that uses one frequency corrects the ionosphere with a broadcast model, two frequencies remove most of it (chapter 2).
- **The antenna installation:** the antenna position, if surveyed wrongly, turns directly into time error, about 3.3 nanoseconds for each meter of error along the line to a satellite; reflections from nearby structures add a varying error.

- **Cable and receiver delay:** the antenna cable, amplifiers and the receiver's internal path delay the signal before it is timestamped. Each nanosecond of uncompensated delay is a nanosecond of time error, so these delays are calibrated and entered into the receiver, or measured against a reference at installation.
- **Distribution:** the time travels from the receiver to its users over a network protocol, usually the Network Time Protocol (NTP) or the Precision Time Protocol (PTP, standardized as IEEE 1588).
- **The end clock:** the server or device applies the time with its own resolution, servo and software path.

Distribution has a trap that the timing exchange cannot see by itself; only a calibration or an independent measurement of the path reveals it. Both NTP and PTP estimate the delay of the path by timing a message out and back, and assume the two directions are equal: the clock offset formula in the NTP specification is half the sum of the two one-way differences (RFC 5905, section 8). If the outbound path is slower than the return path, half of that difference appears as a clock offset (calculated; Appendix B gives the formula). The grid's time synchronization task force puts the consequence plainly: asymmetry "can result in a constant bias in the time transfer value that can only be measured with an independent time transfer system" (NASPI Technical Report NASPI-2017-TR-001, March 2017, page 23). A buyer who needs a timestamp to a stated accuracy needs a budget for the asymmetry of every network segment the time crosses, and a way to check it.

The telecommunications standards show what an engineered chain looks like. ITU-T Recommendation G.8272 (July 2025) defines the primary reference time clock that sits at the head of an operator's timing network. Its clause 6.1 says the output of the class A clock "should be accurate to within 100 ns or better when verified against the applicable UTC time signal source", and the class B clock "to within 40 ns or better". The enhanced clock of G.8272.1 (January 2024) is held to 30 nanoseconds. Those numbers apply at the clock's output, before the network: a separate recommendation, G.8271, budgets what remains for the network and the radio.

Who depends on it, document by document

Statements of the form "everything depends on satellite time" do not help a buyer. What helps is a sector's own document, which gives the requirement, the reference and the kind of time. Figure 5.2 collects the ones read for this chapter; the rows show how far apart the requirements are.

FIGURE 5.2

Who needs which time: the requirement, its kind and the document that sets it

Use	Requirement	Kind of time	Document
Head of a telecom timing network (class A, B; enhanced)	100 ns; 40 ns; 30 ns	Time, against the applicable UTC source	ITU-T G.8272 (07/2025) clause 6.1; G.8272.1 (01/2024) clause 6.1
Time division radio: LTE-TDD small cell, NR TDD	1.5 microseconds (class 4)	Time error against a common reference	ITU-T G.8271 (03/2020) Table 1
Some LTE carrier aggregation features	260 ns (6A); 130 ns (6B)	Time error against a common reference	ITU-T G.8271 (03/2020) Table 2
Grid phasor measurement units	Better than 1 microsecond	Time of day against UTC	NASPI-2017-TR-001, Table 2, page 22
Grid traveling wave fault location	100 ns	Time of day against UTC	NASPI-2017-TR-001, Table 2, page 22
Grid protective relays	1 ms or better	Time of day against UTC	NASPI-2017-TR-001, Table 2, page 22
US market event records (computer clocks)	50 ms	Time of day against NIST	FINRA Rules 4590 and 6820
US member firm business clocks, general	1 second	Time of day against NIST	FINRA Rule 4590

Requirements span more than seven orders of magnitude, and each names its own reference; values as written in each document, read in November 2026.

Source: the documents named in each row, read 2026-11-23.

Mobile networks. ITU-T G.8271 (March 2020) groups time and phase requirements into classes. Class 4, 1.5 microseconds, is listed for time-division radio systems including LTE-TDD small cells and NR TDD; class 6A, 260 nanoseconds, and 6B, 130 nanoseconds, for some carrier aggregation features (Tables 1 and 2). The requirement is "expressed in terms of time error with respect to a common reference" (Table 1, note 1): what matters is that neighboring cells agree, and a satellite receiver at each site is one way, not the only way, to make them agree.

Power grids. A phasor measurement unit samples voltages and currents and stamps each measurement so that measurements across a grid can be compared. The NASPI report explains the standard's link between accuracy and time: a 1 percent angle error, meaning a 1 percent total vector error from phase alone, "at 60 Hz ... corresponds to a timing error of 26.5 μs", while "the standard suggests a maximum timing uncertainty of 1 μs" to leave room for other errors (page 10). Its table of grid uses runs from 15 minute intervals for time-of-use meters to 100 nanoseconds for traveling wave fault location (Table 2, page 22). It also says that "the most common means of time distribution that is able to synchronize to the IEEE C37.118 requirement of 1 μs is via GNSS; GPS is the primary constellation used in North America" (page 23).

Financial records. Requirements here are set by market rules; the United States rules read for this chapter are looser than those of grids and radio networks. In the United States, FINRA Rule 4590 requires member firms' business clocks to be synchronized to within one second of the time kept by the National Institute of Standards and Technology (NIST), and computer clocks that record events in national market system securities to within 50 milliseconds; Rule 6820 sets the same 50 millisecond tolerance for reports to the consolidated audit trail. The European business clock rule of 2017 was sought for this chapter but its official text could not be opened, so its values are not printed. The European Space Agency lists time-stamping of "financial transactions for online banking" among the system's uses (European Space Agency, What is Galileo?, read 2026-11-22), which shows a use, not a requirement.

Policy. A United States executive order of 12 February 2020 (Executive Order 13905, Federal Register vol. 85, page 9359) names "the electrical power grid, communications infrastructure and mobile devices, all modes of transportation, precision agriculture, weather forecasting, and emergency response" as users of space-based positioning, navigation and timing, and asks critical infrastructure owners for "responsible use", defined as use "such that disruption or manipulation of PNT services minimally affects" national security, the economy and public health. It sets a direction; it does not set a tolerance.

Holdover: how long the clock can coast

When the satellite signal is lost, a timing receiver keeps going on its local oscillator, and its error grows. How fast it grows depends on the oscillator's frequency error at the moment of loss, its drift with age and temperature, how long the receiver had been locked and learning the oscillator's behavior, and the steering algorithm. That is why a holdover figure without its conditions means little. A constant frequency error of one part in 100 billion (1e-11), held for a day, gives 864 nanoseconds; one part in a billion gives 3.6 microseconds in an hour (calculated; Appendix B). Real oscillators do not hold a constant error, so these are arithmetic, not product figures.

The telecommunications standard shows how a holdover requirement is written when it is written properly. For the class A enhanced clock, G.8272.1 says that after a locked period of L days the output should stay within "a value increasing linearly from 30 ns to 100 ns over a holdover period of H days"; for L under 6 days H is 70,000 seconds, or 0.81 days, between 6 and 40 days H equals L, and above 40 days H is 40 days (clause 8.2.1). It also states what the clock leans on while it coasts: "an autonomous primary reference clock (PRC) frequency reference input". A holdover requirement therefore names a time error bound, a duration, the locked history and the frequency reference behind it, which may be outside the clock itself. A buyer should ask for all four.

Other ways to carry time

A second source matters only if its dependencies are known. Each option below has a different failure domain and a different status, and none is a drop-in replacement:

- **Another satellite system.** A receiver that tracks two or more constellations can compare them. They share the band, the antenna and often the receiver, so a local jammer can take both at once (chapter 6). The constellations and their time scales are in chapter 3.
- **Terrestrial radio.** NIST's station WWVB near Fort Collins, Colorado, "continuously broadcasts digital time codes on a 60 kHz carrier", and "if the path delay is removed, WWVB can provide UTC with an uncertainty of about 100 microseconds" (NIST, Radio Station WWVB, updated 17 December 2025). That serves a wall clock or a meter; it is far too coarse for the microsecond phase requirements of the radio networks above. The NASPI report also describes eLoran, a terrestrial low frequency system whose timing accuracy "is strongly dependent on the distance from the transmitter", and a NIST proposal for a differential WWVB service (page 30); the status of each in a given country is a dated fact to check, not assumed here.

- **Fiber and network time.** Time carried over the operator's own network from a protected master clock, with PTP and with each segment's asymmetry calibrated. The source of that master clock is usually a satellite receiver too; the gain is that it is one well-protected receiver instead of many exposed ones.
- **Low orbit signals.** Iridium has offered a position and time service called Satellite Time and Location, named in a peer-reviewed paper as a service that requires a subscription (Oligeri, Sciancalepore and Di Pietro, ACM WiSec 2020). Its current name, performance and terms were sought from the operator's page on the date of writing and could not be read, so none is printed. Chapter 6 lists such services by status.
- **Planned services.** The European Space Agency lists a future "Timing Service Monitoring" that "will provide timing and synchronisation information to users" (European Space Agency, What is Galileo?). It is announced, not in service.

THE SYSTEM'S FAILURE

January 2016: right positions, wrong time. A trade press report written three days after the event (Inside GNSS, "GPS Glitch Caused Outages, Fueled Arguments for Backup", 29 January 2016) says that ground software uploaded on 26 January, when the satellite SVN 23 was being removed from service, put the system's UTC message off by 13 microseconds; it attributes the explanation to a spokesman of the Air Force's 50th Space Wing, without a direct quotation, and quotes a timing supplier who said that at affected sites "it lasted for about 12 hours". The same report says positioning did not appear to be affected. The grid's task force later recorded that "the 2016 GPS UTC transmission error" caused "real PMU data errors" (NASPI-2017-TR-001, page 23). No operator statement was read for this chapter, so the number of satellites that broadcast the error is not printed.

The leap second, a planned event. The NASPI report says that during the leap second of 2015 an independent grid operator, ISO New England, "reported that none of the online streaming PMUs in its system applied the 2015 leap second properly, taking from one sample to one full second to add the leap second" (page 25). Nothing in the satellite system failed: the announced correction was handled badly downstream.

The sources support a narrow conclusion. A timing user can be harmed by an error in the time data that a navigation user never sees, and by planned events in the time scale itself. A receiver's alarm, a second source and a test of leap second handling are the user's to provide.

What to ask of a timing receiver and a timing service

A short list turns the chapter into a purchase. Ask for the answers in writing, with the document each comes from:

- Which systems and frequencies the receiver uses for time, and what it does when they disagree: alarm, exclude, average, or follow one.
- Which alarms it raises (loss of signal, holdover entry, a jump in time, a change in the UTC parameters, a leap second announcement), and how those alarms reach the system that uses the time.
- The holdover specification with its four parts: error bound, duration, locked history, and the oscillator or frequency reference it relies on.
- The calibration record of the installation: antenna position and how it was surveyed, cable and receiver delays, and who measured them on which date.
- The distribution budget: protocol, number of hops, the asymmetry assumed or measured on each, and the error at the end application.
- The test: how leap seconds, week number rollover (chapter 2) and a change of UTC parameters were tested, and with what result; whether a leap second is stepped or smeared over an interval downstream, and whether every client does the same; and an end-to-end check of the timestamp at the application against an independent reference, through signal loss, holdover, source switching and recovery.

For a timing service sold over a network rather than a receiver, the same questions apply to the provider, plus the contract: which time scale, which traceability chain, which service level, and what the provider does when its own satellite source fails.

> **SECURITY NOTE**
>
> **Who can interfere or command.** The system operator sets system time and uploads the UTC offset data; nobody else is authorized to command it. The open signal is public, so there is nothing to intercept. Anyone near a fixed antenna can interfere with it: a timing receiver at a known site is exposed to local interference, and how exposed a fleet of receivers is depends on where and how each is installed, case by case. The legacy open signals carry no authentication of their data; message authentication where it exists is chapter 6. **How it is seen.** A drop in signal to noise, loss of lock, entry into holdover, a jump in the computed time, or disagreement with a second, independent source. A receiver that is not watched has no way to tell anyone. **How it is recovered.** Holdover within its stated bound, then a second source whose dependencies are documented; then the decision, made in advance, to stop or flag the operations that need the time.

Monday rule: for each system that needs time, write its tolerance at the end point (time, phase or frequency, against which reference) and its holdover in hours with the error bound, and ask who would see an alarm.

CHAPTER SIX

What a One Way Signal Can Promise: Jamming, Spoofing and Fallback



On 10 September 2025 European Commissioner Kubilius opened a debate in the European Parliament by thanking the pilots of an aircraft that had carried him and the Commission's president to Bulgaria "when our satellite navigation on board was jammed". Later in the same statement he told the Parliament that "since July this year" Galileo's message authentication "protects against spoofing attacks by certifying the authenticity of the Galileo signal" (European Commission, SPEECH/25/2072). A buyer needs to read the two sentences together and precisely: authentication cannot restore a signal that has been denied, since a jammed receiver has nothing to check, and what it certifies is narrower than "the signal". This chapter changes one decision: what a system that depends on satellite positions or time does when the position is absent, and when it is wrong.

The promise as written

A navigation provider can promise only what it controls: the signal in space and the performance of a representative receiver under stated conditions, not the result at an installed receiver. The GPS performance standard says so in its own words. Its standards "do not include any element not under the direct control of the GPS Control/Space Segments", and it describes the receiver's part plainly: receivers "cannot always monitor the broadcast NAV message data since interruptions may be caused by temporary signal blockages, abnormal receiving antenna orientation, RFI (particularly jamming), and intermittent environmental effects", and "the GPS receiver is responsible for taking appropriate action" when that happens (GPS Standard Positioning Service Performance Standard, 5th edition, April 2020, sections 3.1 and 2.4.4). Interference at the user's antenna is, in the provider's own document, the user's problem.

That is the first of the four kinds of promise of chapter 1, a public performance commitment. It is not a contract and it offers no remedy. A correction service bought under contract (chapter 4) or a managed timing service (chapter 5) may add a service level, but read its terms: a provider of corrections can no more stop a jammer near the buyer's antenna than the satellite operator can. The rest of this chapter is about what happens between the satellite and the receiver, where nobody but the user is in a position to act.

Why a small transmitter wins

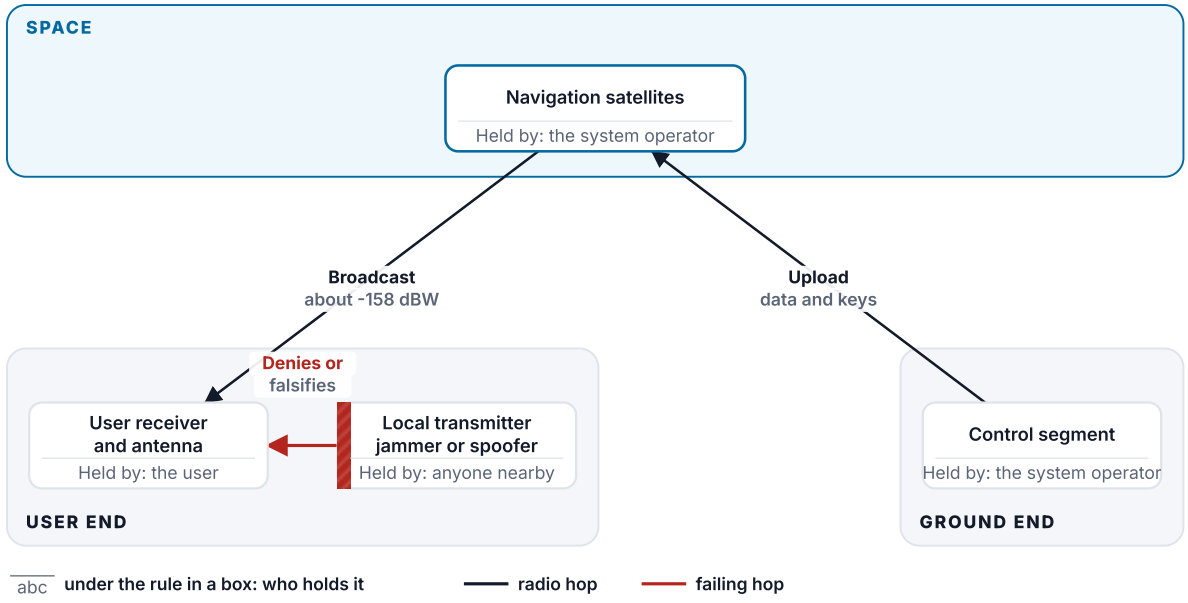
The received navigation signal is weak by design. The GPS L1 C/A signal is specified at a minimum of minus 158.5 dBW at the user's antenna for satellites above 5 degrees of elevation (IS-GPS-200N, Table 3-Va, as the first book of this series, *The Bit's Path*, works through in its ledger for that signal), and a 2025 conference paper tabulates Galileo's open signal on E1 at minus 157 dBW (Yan and colleagues, Engineering Proceedings 88, 17, Table 1, a peer-reviewed conference paper; the Galileo interface document itself was not read). The two figures come from different documents, each with its own antenna conditions, so they are levels to know, not a like-for-like comparison. Those levels are below the receiver's own noise in its band; the receiver recovers the signal only by correlating it against a known code over time. A transmitter nearby, even a weak one, can easily arrive stronger, depending on its power, its antenna and the path. *The Bit's Path* gives the arithmetic of interference as a budget line and the band neighbors that can cause it without intent; this book does not repeat it, and it gives no powers, methods or settings for any source.

Two kinds of attack follow from the same weakness, and they look different to the user (Figure 6.1 and Figure 6.2):

- **Jamming** drowns the signal, usually by raising the noise, until the receiver loses it. The output is absent, degraded or stale, and not always flagged to the application.
- **Spoofing** provides false signals that the receiver accepts. The output is present and looks normal, but the position or the time is wrong.

FIGURE 6.1

Interference reaches a civil user at the receiver, not at the satellite



The satellite broadcast arrives below the receiver's noise; a local transmitter, jammer or spoofer, can arrive far stronger, and nobody but the user is placed to act.

Author's diagram based on IS-GPS-200N, Table 3-Va (minimum received power of GPS L1 C/A above 5 degrees elevation, minus 158.5 dBW) and the GPS SPS Performance Standard, 5th edition (2020), section 2.4.4.

The Commission's statement describes the two in the same terms: jamming "aims to blind satellite navigation signal receivers", while spoofing "aims to deceive navigation signal receivers with counterfeit satellite signals. They appear as a normal service to most GNSS signal receivers" (SPEECH/25/2072). Unintentional interference, from faulty equipment or a neighbor in the band, acts like jamming.

Jamming: where it is documented, and what it looks like

Regions and periods of interference are dated facts with a named source. Two are used here, one of them only through trade press. The European Union Aviation Safety Agency's bulletin on navigation outages, SIB 2022-02 in its third revision, names "conflict zones, as well as the south and eastern Mediterranean, Black Sea, Middle East, Baltic Sea, and Arctic regions", and recommends contingency procedures, keeping conventional ground navigation aids in service, and reporting; it concludes that "the current conditions do not warrant immediate safety directives or airworthiness actions" (as reported by Inside GNSS, trade press, 8 July 2024; the bulletin itself could not be opened for this chapter). The

Commission's 2025 statement says that "today 40% of European air traffic operates in regions strongly affected by radio frequency interference" and that "since the start of Russia's full-scale invasion of Ukraine, interference has gotten worse" (SPEECH/25/2072). The Commission's sentences are its own words; the bulletin's are quoted as the trade press reported them.

At the receiver, jamming tends to show in a few ways. A survey of interference management for aircraft receivers describes a common front end check: a jammer forces the automatic gain control to reduce the receiver's gain, and "this change of the AGC level can be used to detect an interferer" (Morales-Ferre and colleagues, IEEE Communications Surveys and Tutorials, 2020, as quoted in *The Bit's Path*). How a given receiver reports that gain, and whether its number rises or falls, is in its own interface documentation. The carrier to noise density, C/N0, often falls on many satellites at once, then lock is lost. None of these signs is conclusive alone: a blocked antenna, a failed cable and a heavy storm can produce some of them. A system that logs gain control and C/N0 per satellite, and compares them with a second site, can often tell a local cause from a wider one, though two sites can share a regional source or a common fault; a system that logs only "fix" or "no fix" cannot.

Spoofing: the wrong answer that looks right

Spoofing is the harder problem, because the receiver keeps reporting. A position may jump, or drift away slowly; a time may step, or walk. Possible signs include a jump or drift that the platform's own motion cannot explain, signal strengths that are too uniform or too high for the geometry, satellites that disagree with each other, a receiver clock that steps, and disagreement with other sensors. None of these is necessary and none is sufficient: a careful spoofer avoids some of them, and ordinary multipath produces others. The useful test is disagreement with a source the spoofer is unlikely to control at the same time.

FIGURE 6.2

Jamming takes the answer away; spoofing gives a wrong one

	Jamming	Spoofing
Effect	No output, a degraded or stale output, not always flagged	Normal-looking output with a wrong position or time
Who can do it	Anyone with a transmitter in the band near the receiver	A better equipped party near the receiver; relaying real signals needs no keys
Possible signs	The front end reduces its gain; C/N0 falls on many satellites at once; loss of lock	Unexplained jump or drift; signal strengths too uniform or too high; clock step; disagreement between satellites
Corroborate with	A second site; a spectrum check; weather and antenna faults ruled out	Another system on another band, inertial sensors, a stable local clock, expected motion
Recovery	Fallback source, holdover, or a planned stop	Stop trusting first, then the same; a wrong answer already used must be traced

Possible signs are neither necessary nor sufficient; each needs corroboration from a source the attacker does not control.

Author's table based on the European Commission, SPEECH/25/2072 (10 September 2025); Morales-Ferre and colleagues, IEEE Communications Surveys and Tutorials 22(1), 2020; arXiv 2204.11641 and 2010.12502 (preprints, not peer reviewed).

The research record shows why disagreement, not cryptography alone, is the test. A paper of 2022 by Motallebighomi and colleagues at Northeastern University and the CISPA Helmholtz Center (arXiv 2204.11641, a preprint, not peer reviewed as posted) reports that in their evaluation "it is possible to spoof a victim receiver to locations as far as 4000 km away from the actual location", "without breaking any cryptographic operation", and concludes that broadcast positioning has "fundamental limitations … even if all communications are cryptographically protected". *The Bit's Path*, chapter 11, tells that study in full; what matters here is its consequence for a buyer, which the next section draws.

What authentication proves, and what it does not

Galileo's Open Service Navigation Message Authentication (OSNMA) adds authentication data to the navigation message of the open signal on E1. The European Space Agency's description is careful: it "allows regular users to verify the authenticity of Galileo GNSS information, making sure that the data they receive has not been modified" (European Space Agency, What is Galileo?). A trade press report of January 2026 puts it the same way: receivers "verify that the broadcast ephemeris and clock data truly originate from Galileo satellites" (Inside GNSS, 21 January 2026). The service entered operation in July 2025, in the Commission's words; Inside GNSS gives the day as 24 July 2025 (trade press, 24 July 2025); the declaration on the operator's own site could not be opened for this chapter.

The scheme behind it is called TESLA: the satellite sends message authentication codes with the data, built with one-way hash functions, and discloses the key that checks them later (arXiv 2204.11641). That design has two consequences a buyer must know. First, a check can complete only after the key arrives, at the earliest in a later 30 second subframe; a receiver starting cold also needs time to gather the key material, and until then the data are unverified. Second, the check is meaningful only if the receiver already knows the time loosely, well enough to be sure the key was not yet public when the data arrived: "loose time synchronization at the receiver is critical and directly affects the scheme's effectiveness" (arXiv 2204.11641). A receiver that takes its only notion of time from the signal it is trying to check has a circular argument. A preprint co-written with a Commission engineer describes the budget: the authentication fields use 600 bits every 30 seconds of the E1-B message (Seco-Granados and colleagues, arXiv 2010.12502, preprint, not peer reviewed; the OSNMA interface document was not read).

So OSNMA, correctly implemented, with trusted key material and a passing time check, proves that the orbit, clock and status data came from Galileo and were not changed, and the time check guards against accepting a message after its key became public. It does not prove that the ranging signal is genuine, or that it arrived when it appears to have arrived: a relay of real signals carries valid authentication data. A receiver should report three states, not two: verified, failed, and not yet or not possible to verify. The same preprint by Seco-Granados and colleagues proposes detectors that use the unpredictable authentication bits to catch some replay attacks "for receivers already tracking real signals with relatively good visibility conditions"; that is a receiver technique, not a property of the service. The Commission has announced a Signal Authentication Service "from 2027" (SPEECH/25/2072), which the European Space Agency describes as "authenticated positioning"; it is announced, not in service. The governmental Public Regulated Service, with encrypted signals, was expected "in the coming weeks" in January 2026 (European Commission, SPEECH/26/228); its status on this book's date was not checked. The GPS

legacy civil signal carries no authentication of its message (chapter 3). Figure 6.3 puts the distinctions side by side; the service ledger that follows records the authenticated open signal as a buyer meets it.

FIGURE 6.3

Message authentication proves where the data came from, not where the signal came from

Question	Legacy open signal (GPS L1 C/A)	Galileo open signal with OSNMA	Galileo signal authentication (announced)
Status, with the date of the last source read	In service; no message authentication (IS-GPS-200N)	In service since July 2025 (Commission, September 2025 and January 2026)	Announced "from 2027" (Commission, September 2025)
Data came from the system, unchanged?	Not provable	Yes, when the receiver has trusted key material, its time check passes and the data's codes verify	Not stated in the sources read
Message received before its key was public?	Not applicable	Checked by the receiver's own time check; needs loosely known time	Not stated in the sources read
Ranging signal and its arrival time genuine?	No	No: a relay of real signals carries valid codes	The European Space Agency describes "authenticated positioning"; terms not read for this book
Stops jamming?	No	No	No
What the receiver needs	Nothing extra	Key material, a loosely known time, compliant software; reports of failed, pending and unavailable states	Not stated in the sources read

What a pass means for the authenticated open signal, set against the legacy open signal and the announced next step; statuses are the last ones read, with their dates.

Source: European Space Agency, What is Galileo? (read 2026-11-22); European Commission SPEECH/25/2072 (2025-09-10); IS-GPS-200N; arXiv 2204.11641 and 2010.12502 (preprints, not peer reviewed).

LINK LEDGER · LL-2016-02 · SERVICE LEDGER

2016-12-15

System: Galileo Open Service on E1 (since 15 December 2016), with message authentication (OSNMA) since July 2025

In service | Class: service only

1 Requirement	Let any receiver compute position and time from Galileo's open signal, and let an equipped receiver check that the navigation data it uses came from Galileo unmodified.
2 Ends and path	A Galileo satellite and any receiver that tracks E1. The check needs the system's public key and a loosely known time. The receiver never answers. **Path:** One way broadcast, one hop; the control segment uploads data and authentication material.
3 Orbit and time	23,222 km, three planes (European Space Agency). **Time:** A check completes at the earliest when its key arrives in a later 30 second subframe; a cold start takes longer (arXiv 2204.11641, preprint).
4 Band and permission	**Satellite to receiver.** E1, 1575.42 MHz (peer-reviewed conference paper, 2025; interface document not read). European Union system
5 Capacity	**Up.** None: no uplink from the user. **Down.** 600 bits every 30 seconds of the E1-B message for authentication, about 20 bit/s (calculated from the preprint's figure). Unlimited receivers.
6 Who owns each end	**Space segment.** The European Union's Galileo program **Ground segment.** Galileo control centers; the receiver is the user's **Customer relationship.** None: no subscription, no contract **The exit.** Other systems; the authentication covers Galileo only
7 Trust	The system authenticates; the receiver verifies. A pass, with trusted key material and a passing time check, shows the data came from Galileo unchanged, not that the ranging signal is genuine: a relay of real signals carries valid codes (arXiv 2204.11641, preprint).
8 How it fails, and how we would see it	Jamming: signal lost, nothing to check. Forged data: rejected once the key arrives and verifies. Relay, or replay within the time check: not detected; older replay fails the check. No valid key material or trusted time: no authentication. **How we would see it:** A failed or missing check is reported if the receiver exposes it; a pass shows only the data's origin. Range manipulation shows only through cross checks: clock jumps, other systems or sensors.
9 Cost shape	No charge or subscription. The user pays for a receiver that implements the check, its key updates and its alarm handling; public funding is not assessed here.
10 Evidence	In service since July 2025 (operator claim) European Commission, SPEECH/25/2072, 2026-11-23 Fully operational, January 2026 (operator claim) European Commission, SPEECH/26/228, 2026-11-23 E1 1575.42 MHz; -157 dBW minimum (standard) Interface document value in Yan et al. 2025, Table 1 (peer reviewed); document not read, 2026-11-23 600 bits per 30 s (assumption) arXiv 2010.12502 (preprint, not peer reviewed); settle with the OSNMA interface document, 2026-11-23 Moved 4000 km, authentication intact (measured) arXiv 2204.11641 (preprint, by its authors), 2026-11-23

Service only, no hop budget: The hop is an open broadcast like GPS L1 C/A, budgeted in the first book of this series; authentication adds no power line.

Defenses in plain terms

A receiver's defenses are engineering choices with costs, and each rests on an assumption about the attacker. They are named here so a buyer can ask about them, not described as instructions.

- **Several systems and frequencies,** with a dependency analysis. Two constellations through one antenna, one front end and one band are not independent: a jammer in the band can take both (chapter 3). Diversity helps against a failure in one system's ground or space segment, as the next box shows, more than against a local transmitter.
- **Antenna techniques,** such as antennas that reduce gain toward the horizon, where ground transmitters usually are, or arrays that steer nulls toward a source. They are named in this book and not detailed.
- **Cross-checks with other sensors:** an inertial unit, wheel speed, a barometer, a stable local clock, the expected motion of the vehicle. A spoofer must stay consistent with all of them at once, which is harder, though thresholds and sensor uncertainty leave room for small errors.
- **Monitoring:** logging gain control, C/N0 and the receiver's own alarms; comparing sites; reporting to the authority that collects reports. The power grid's timing task force recommends that timing-dependent systems "should use multiple timing sources to improve timing redundancy and reliability" (NASPI-2017-TR-001, page 24).

Fallback: what to use when the signal is absent or wrong

A fallback is useful only with its status, its country and its date. Figure 6.4 lists the ones read for this chapter. Two rules apply to all of them. A fallback needs its own failure domain, or it fails with the thing it backs up. And a fallback must be tested in representative conditions, for example a controlled loss of signal; a fallback that has never been exercised is a hope. Detection of interference is listed apart: it tells the user something is wrong, it does not supply a position or a time.

FIGURE 6.4

Fallbacks by status: in service, offered, announced

Option	Gives	Status	Country, source and date
Inertial sensors, clocks in holdover	Position or time for a bounded period	Equipment	Any; bound depends on the unit and its conditions (chapter 5)
Another satellite system on another band	Position and time	In service	Chapter 3; shares the antenna and often the receiver
WWVB radio time code, 60 kHz	Time, about 100 microseconds with the path delay removed	In service	United States; NIST page updated 2025-12-17
eLoran	Time and position	Not checked	Described in NASPI-2017-TR-001 (March 2017); no current status read
Iridium Satellite Time and Location	Position and time, by subscription	Not checked	Named in a 2020 peer-reviewed paper; operator page not read
EU interference monitoring service	Detection of interference, not a source of position or time	Announced	European Union; SPEECH/25/2072, 2025-09-10, for 2026 to 2027
EU low orbit positioning constellation	Position and time	Announced	European Union; SPEECH/25/2072, 2025-09-10, mid term

Each option carries its country, its status and the date of the source; detection is listed apart from sources, and a fallback covers only the failures it does not share with satellite navigation.

Source: the documents named in each row; statuses as read on 2026-11-23.

The European Union has announced, for the short term, "a Radio Frequency Interference monitoring service, capable of detecting and localising GNSS interference", and, in the mid term, a low orbit positioning constellation to work with Galileo's medium orbit satellites (SPEECH/25/2072). Both are announced; the first is detection, not a fallback source. Other

low orbit timing and positioning services exist or are announced by private operators; each enters a register only with its own dated statement, and none was read for this chapter except through the third-party paper on Iridium cited in chapter 5.

THE SYSTEM'S FAILURE

Galileo, July 2019: a week without the open service. Notices to users published by the European agency then responsible for Galileo's services announced a potential degradation on 11 July 2019, an outage on 13 July and recovery on 18 July, with the cause given as "an equipment malfunction in the Galileo ground infrastructure, affecting the calculation of time and orbit predictions", and the agency said it would set up an independent inquiry board (as reported by Inside GNSS, trade press, 18 July 2019). Two months later a Commission spokesperson said "the technical issue was solely related to the ground infrastructure in a Galileo control centre, not to the Galileo satellites"; the same later report dates the total failure from 10 to 17 July (Inside GNSS, 19 September 2019). The two reports disagree on the dates, and the notices themselves and the inquiry's findings could not be opened for this chapter, so both ranges are printed as reported and no root cause beyond those words is given.

What failed was the ground segment, and through it the service; the satellites and the radio link did not fail. What the sources support: an open service can stop for days, and the performance commitment gives its users no remedy. Whether a receiver kept a usable solution depended on whether it used other systems and how it treated the Galileo satellites while their data were unusable. That is a design decision for the user, made before the event.

SECURITY NOTE

Who can interfere or command. Only each system's operator is authorized to command its satellites and to authenticate its messages. Anyone with a transmitter near the receiver can deny the signal; a better equipped party can falsify it. Interception is not a concern for open signals: they are public by design. **How it is seen.** Jamming shows as lost lock and falling signal quality, best seen in logs and across sites. Forged navigation data can be caught by message authentication where it exists; a relayed genuine signal, or one replayed soon enough to pass the time check, shows only through receiver checks or disagreement with something the attacker does not control; a failed authentication check is reported if the receiver exposes it, and a passed one proves the data's origin only. **How it is recovered.** By the user: fallback to a source with a different failure domain, holdover within its bound, or a planned stop. The table answers the five questions for three kinds of signal.

Five questions for three kinds of navigation signal (as of November 2026)

Question	Open signal without authentication	Open signal with message authentication	Augmented or corrected signal
Who is authorized to use, and to command?	Anyone uses; the system operator commands	Anyone uses; the operator commands and authenticates	Anyone equipped (open broadcast) or the subscriber (paid stream); the provider commands
Who can intercept?	Not applicable: public	Not applicable: public	Open broadcast public; paid streams access-controlled by the vendor (chapter 4)
Who can interfere?	Anyone near the receiver	Anyone near the receiver: authentication does not stop jamming	As the core signal, plus the network path of an internet stream
How is it authenticated?	Not at all (GPS legacy civil message)	Navigation data: yes, after key disclosure, with loose time. Ranging signal: no	Differs by service (chapter 4)
How is service recovered?	By the user's design	By the user's design; the user's policy decides what a failed or missing check does	By the user's design; fall back only if the uncorrected result still meets the requirement

Monday rule: decide what your system does when the position or time is absent and when it is wrong; these are two different tests, and the second is the one usually missing.

CHAPTER SEVEN

The Buyer's First Questions: Observable, Resolution, Revisit, Latency



Landsat 9 was launched on 27 September 2021 and now flies a 705 kilometer sun-synchronous orbit, eight days out of step with Landsat 8, as the US Geological Survey describes it. Each satellite repeats its ground track every 16 days; together they cover each ground track every 8, with some extra looks where neighboring swaths overlap toward the poles. That single dated fact settles more for a buyer than any catalog page: a question that needs a fresh look every few days at mid latitudes cannot be answered by these two satellites alone, however good their pixels, and cloud removes some of the looks they do get. The decision this chapter changes is the order of the questions. First the physical quantity you need and its uncertainty; then resolution in four senses, revisit and latency; the supplier last.

Start from the observable

A satellite sensor records radiation, or for a radar the strength, timing and phase of its own echo; each kind of sensor is built to reach one physical quantity from that record. An optical camera measures the sunlight reflected from the ground, after the atmosphere has added and removed some of it; once corrected, this becomes **reflectance**, the share of the incoming sunlight returned toward the sensor in each band, which depends on the sun and view angles (it is not albedo, the share returned in all directions). A thermal sensor measures emitted infrared radiation, which a model turns into a **surface temperature**. A radar measures how much of its own pulse comes back, the **backscatter** (chapter 9). An altimeter measures a travel time and so a **height**; a spectrometer tuned to absorption lines records spectra from which a model retrieves a **gas column**, the amount of a gas between the sensor and the ground (chapter 11). Two radar passes compared by interferometry give a relative **displacement** along the radar's line of sight, once the phase cycles have been counted and the effects of terrain, orbit and atmosphere have been estimated and removed (chapter 9).

Everything else is inferred. "Crop health", "flood extent", "roof damage" and "illegal mining" are decisions, not measurements. Each is reached from one of the quantities above through a model, a threshold or an analyst, and each step adds its own error. The first line of a data requirement therefore names two things: the decision the data must support, and the observable that would support it, with the uncertainty the decision can tolerate. "A field is irrigated if its surface temperature at midday is clearly lower than its unirrigated neighbors" is a hypothesis a supplier can test, and the requirement then adds how often the rule may be wrong (false alarms and misses) and how it will be checked on the ground. "Monitor irrigation" is neither.

The observable also decides the sensor class before any supplier is named. A question about surface temperature usually needs a thermal band; a question asked through cloud at night needs a microwave sensor, an active radar or a passive radiometer, at a scale that fits the question; a question about a gas needs a spectrometer with the right absorption lines. A buyer who starts from a supplier's catalog tends to buy what the supplier sells and then look for a question it answers.

Resolution is four things

"Resolution" said alone means nothing a buyer can test. There are four kinds, and a sensor is good at some of them only by giving up others.

- **Spatial.** The number usually printed is the **ground sample distance** (GSD): the distance on the ground between the centers of two neighboring pixels. It is a sampling interval. It is not the optical resolving power, which depends on the telescope and the atmosphere, and it is not the size of the smallest thing an analyst can identify, which also depends on contrast, shape and context. Two products with the same pixel size can contain different information.
- **Spectral.** How many bands, how wide, and where in the spectrum. A broad panchromatic band gives sharp shape; many narrow bands give material and chemistry.
- **Radiometric.** How finely the signal is quantized. Landsat 9's imager records 14 bits per sample, according to the US Geological Survey. Bit depth is the size of the ruler's smallest mark, not the accuracy of the ruler. Accuracy comes from calibration and from the signal to noise ratio, and a supplier who quotes bits without a calibration statement has answered a different question.
- **Temporal.** How often a useful look at the same place is possible. This is revisit, the next section.

FIGURE 7.1

Resolution is four numbers, and each trades against another

Kind	What it is	What it does not say	Public example (source date)	Trades against
Spatial	Ground sample distance: spacing of pixel centers on the ground	Optical resolving power; the smallest thing an analyst can identify	Landsat 9: 30 m multispectral, 15 m panchromatic, 100 m thermal (USGS, read 2026-11-23)	Swath, data volume
Spectral	Number, width and position of bands	Whether a material can be told apart in the buyer's scene	Landsat 9: nine reflective bands, one of them panchromatic, and two thermal bands (USGS)	Signal to noise per band, swath
Radiometric	Quantization: bits per sample	Calibration accuracy; signal to noise	Landsat 9: 14 bits, up from 12 on Landsat 8 (USGS)	Data volume
Temporal	How often a useful look is possible	Cloud-free success; delivery time	Landsat 9: 16 day repeat, 8 days with Landsat 8 (USGS); GOES-R series: full disk every 10 minutes (NOAA)	Spatial detail, area

The four kinds of resolution, what each does not tell the buyer, and one dated public example of each.

Source: US Geological Survey, Landsat 8 and Landsat 9 pages (read 2026-11-23); NOAA NESDIS, Celebrating 50 Years of GOES (read 2026-11-22). Author's table.

Figure 7.1 sets the four against the observable. The point of the table is the last column: no sensor class wins on every row. A geostationary weather imager wins on time and loses on detail; a 30 cm class camera wins on detail and loses on area and on how often it can look; a hyperspectral instrument wins on spectrum and gives up swath.

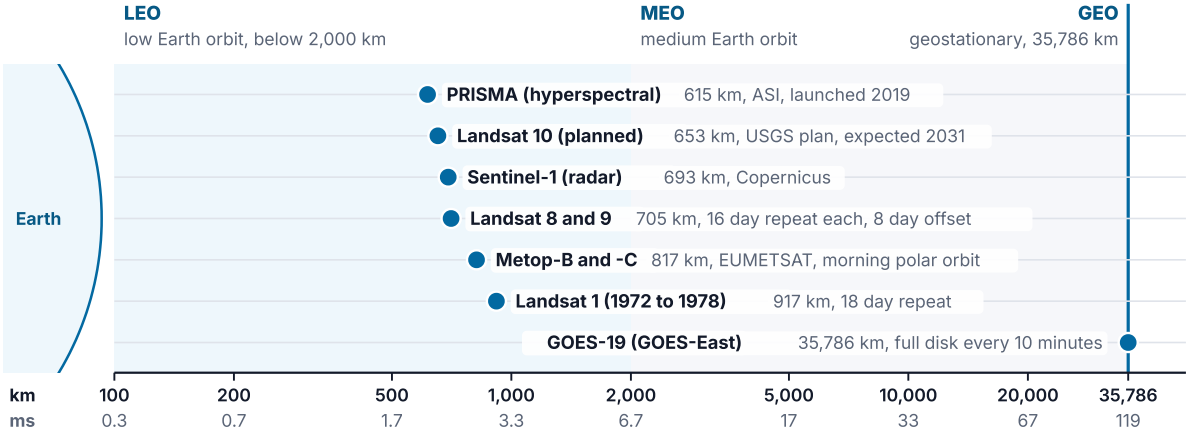
Revisit: three numbers with one name

Suppliers use "revisit" for at least three different quantities, and the buyer needs to know which is meant.

The **repeat cycle** is a property of the orbit: the number of days after which the satellite flies over the same ground track again. For Landsat 9 it is 16 days. The **revisit** is how often a given place can be imaged, which can be shorter than the repeat cycle for three reasons: neighboring ground tracks overlap, more so near the poles than at the equator; the satellite can point its camera to the side; and several satellites can share the work, as Landsat 8 and 9 do with their eight day offset. The **successful collection** is what actually happened: a scene taken, not lost to cloud, not displaced by another customer's priority, and accepted.

FIGURE 7.2

Land imagers fly low and sun-synchronous; weather imagers also stare from geostationary orbit



km: altitude above the surface (log scale). ms: light time straight up, one way (altitude divided by the speed of light).

Altitudes of the public missions named in Part II, with repeat cycle or role as each agency states it; the swath is not drawn.

Source: USGS Landsat 1, 8, 9 and Landsat 10 pages; Copernicus SentiWiki S1 Mission; ASI PRISMA page; EUMETSAT Metop series page; NOAA OSPO GOES status (all read 2026-11-22 or 2026-11-23). Geostationary altitude about 35,786 km is calculated (Appendix B).

Pointing to the side, "off nadir", shortens the wait but changes the product. The ground is seen at a slant, so the pixel on the ground grows and becomes longer in one direction than the other; tall objects lean; terrain shifts features sideways unless an elevation model corrects it; and the light comes back at a different angle, which changes the brightness of the same surface. A revisit figure that depends on large off-nadir angles is a revisit for a different, coarser product. The buyer should ask for the revisit at the off-nadir angle that the requirement's geometry and resolution can tolerate.

Most land-imaging satellites fly **sun-synchronous** orbits: the orbit plane turns once a year with the Earth's path around the Sun, so the satellite crosses the equator at about the same local mean solar time on every daytime pass (the night-side crossing is about twelve hours

later); for Landsat 8 and 9 the US Geological Survey gives 10:12 in the morning. Images taken weeks apart then share a similar local time, which makes them easier to compare, although the sun's height still changes with season and latitude. The price is that the satellite always sees a place at about the same hour, which matters for anything that changes during the day, such as heat, cloud or traffic (chapter 8 returns to this for thermal sensing).

Latency on two clocks

Latency is the time from an event to a product the buyer's software accepts. For satellite data it runs on two clocks, and they answer different questions. The **request clock** starts when the buyer asks for something that has not been collected yet and stops at an accepted product: order, feasibility check, tasking, waiting for a pass, collection, possible cloud and retries, downlink, processing, delivery, acceptance. The **collection clock** starts when the sensor collects and stops at the accepted product: downlink, processing, catalog, delivery. A systematic open mission that images everything on a schedule has no tasking clock. A buyer who needs a scene already taken does not wait for a new observation, but still waits for search, order, any staging or product generation, transfer and acceptance, and should state the oldest scene that is acceptable; a buyer who needs a new view waits for the next scheduled acquisition that turns out usable, then for production and delivery. A tasked commercial order has both clocks and the tasking step as well. For one open example on the collection clock, the US Geological Survey states that Landsat 9 surface reflectance and surface temperature products are produced "within 3 days of acquisition"; that is the agency's availability, before the buyer's own download, ingestion and acceptance.

Each stage has its own distribution, not a single number, and a failed or cloudy attempt sends the request back to wait for the next opportunity. Chapter 12 builds the latency budget on both clocks; here it is enough to write both into the requirement, each with a deadline and the probability of meeting it. "Near real time", said alone, states neither.

The trades that physics imposes

Three trades shape every sensor, and a supplier's specification is a choice among them.

Swath against resolution. A detector line has a fixed number of elements. Spread them over a wider swath and each covers more ground; narrow the swath and each covers less. Landsat 8's imager, for example, takes 30 meter multispectral and 15 meter panchromatic pixels along a 185 kilometer swath, by the US Geological Survey's figures. Halving the ground sample distance multiplies the number of pixels for the same area by four, so with the same bands and bits per sample a sharper camera covers less ground per pass or produces four times the data. A different detector, more detectors or another scan design moves the trade; it does not remove it.

Altitude against resolution. For the same telescope and detector, the ground sample distance grows in proportion to the distance to the ground. A lower orbit gives finer pixels with the same optics and costs a narrower view, shorter passes and, at low altitude, more drag. Appendix B gives the relation between detector pitch, focal length and range.

Data volume against downlink. Every pixel collected must reach the ground, unless it is compressed, selected or processed on board, which is the subject of the seventh book of this series, *Computing in Orbit*. Finer pixels, more bands and more bits per sample all raise the volume; the downlink rate and the minutes of contact with ground stations set how much of it can come down each day. Some missions collect less than they could because the downlink, not the camera, is the limit. Chapter 12 works this through with a real downlink.

Geostationary sensing makes the opposite choice on time. From about 35,786 kilometers above the equator (the altitude at which an orbit takes one sidereal day, a calculated value given in Appendix B) a satellite sees almost a whole hemisphere continuously, and the current generation of GOES imagers scans the full disk every 10 minutes, according to NOAA. For optics of a size that can be flown, the same distance makes the pixels coarse, and places at high latitudes are seen at a grazing angle or not at all. A geostationary imager answers "what is the cloud doing now over this region"; it can help with regional questions about fields, but its pixels are usually too coarse for what is inside one.

Product levels before suppliers

A buyer rarely wants the bits that came off the satellite. Between those bits and an answer lie several processing steps, and agencies name the results by **level**. The names are similar across programs and the content is not, as three agencies' own descriptions show. NOAA's operations office describes how the ground system for the GOES-R series "processes the Level 0 data and creates Level 1b products", in which the imager's measurements "are converted to units of radiance and calibrated, navigated, and remapped to a fixed grid". EUMETSAT describes its Level 1 imager data as "the calibrated radiances sensed by the instrument, geolocated on a reference grid". The US Geological Survey's Landsat Collection 2 holds Level-1 data for every Landsat sensor since 1972, and Level-2 surface reflectance and surface temperature products, generated from the Level-1 inputs, for Landsat 4 to 9.

FIGURE 7.3

Level 1 is the sensor's calibrated measurement; Level 2 is where a model turns it into a geophysical quantity

Level (generic)	What the buyer gets	Public example	What to ask
0: raw	Instrument data as downlinked, reassembled	NOAA GOES-R: ground system processes Level 0 data	Rarely bought; needed only to reprocess
1: calibrated, located	The sensor's measurement, calibrated or with calibration coefficients, located on a map grid or kept in the sensor's geometry (a radar's single look complex product)	NOAA GOES-R Level 1b; EUMETSAT Level 1: calibrated radiances geolocated on a reference grid; Landsat Collection 2 Level-1, all sensors since 1972	Geolocation accuracy; calibration version
2: geophysical	A geophysical quantity, at the ground or in the atmosphere, from a model	Landsat Collection 2 Level-2 surface reflectance and surface temperature, Landsat 4 to 9	Which atmospheric model; quality masks; uncertainty
Gridded and derived	Composites, indices, cloud masks, classified maps; the level assigned varies by program	Program specific	The model, its validation and its version
Analysis-ready	Processed to a stated minimum so scenes from different dates combine	A supplier's or program's own specification	Which specification, and who checked it

A generic ladder of product levels with how three public programs word the same steps; each supplier's own definition still governs.

Source: NOAA OSPO, GOES Rebroadcast page; EUMETSAT, MTG imager pre-operational data release (2024-09-23); USGS, Landsat Collection 2 (all read 2026-11-23). Author's table.

In each scheme, Level 1 is still the sensor's measurement, calibrated (or delivered with its calibration coefficients) and located. Level 2 is where a model has turned it into a geophysical quantity, at the ground (reflectance, surface temperature) or in the atmosphere (cloud top height, a temperature profile), and where a retrieval model adds its assumptions

to those already made in calibration and geometric correction. Gridded composites and derived products, such as a vegetation index, a cloud mask or a classified map, carry further models, and programs place them at different levels. Suppliers also sell **analysis-ready data**: products processed to a stated minimum, with the corrections and quality masks a user would otherwise apply, so that scenes from different dates can be used together. The label is a starting point. It does not answer the buyer's question, and a supplier's own "Level 2" or "analysis ready" label has to be read against its specification, not assumed to match another supplier's.

What the four questions cannot say

Observable, resolution, revisit and latency screen out sensors that cannot answer the question at all. Four more properties decide whether the ones that remain will.

- **Cloud.** An optical revisit is an opportunity, not a delivery. Chapter 8 asks for the cloud-free collection rate over the buyer's area and season.
- **Geolocation.** How far a pixel may be from where the product says it is, at which percentile, over which terrain, and with which elevation model.
- **Calibration.** Whether this scene can be compared with last year's scene and with another satellite's. A change that is smaller than the calibration difference between two sensors cannot be told apart from it without a correction and an uncertainty analysis.
- **Continuity.** Whether the mission will still exist when the buyer needs the tenth year of the record. The US Geological Survey presents the next mission in the Landsat series as Landsat 10, expected to launch in 2031, on its page as read on 23 November 2026; that is the agency's stated plan on that date, not a launch.

THE SYSTEM'S FAILURE

Landsat 6 failed to reach orbit in 1993, according to the US Geological Survey's list of Landsat missions. The record did not break, because Landsat 5, launched in 1984, was still working; the same list credits it with 28 years and 10 months of operation. Landsat 7 followed in April 1999.

What failed was a launch, and what carried the program across the gap was an older satellite that kept working. The point for a buyer: a long data record is a chain of individual satellites, and its continuity at any moment can rest on one of them. A buyer who depends on a time series should know which satellites carry it today and what the operator has stated about the next one.

SECURITY NOTE

This note covers the sensing chapters of this part; chapters 8 to 11 add only what differs. **Who can interfere or command.** The operator commands and tasks the satellite through its own control segment; a commercial customer can request collections but does not command. Open programs let anyone download their products under their terms. A payload downlink that is not encrypted can be received by anyone with a suitable antenna in its footprint; whether a given mission encrypts is stated per mission, and is not published for many. Optical sensors can be dazzled and radars jammed, a category of threat this book names and does not detail. **How it is seen.** By the product: a missing collection, a saturated or striped image, a quality flag, a delivery that does not arrive. Whether a product came from the stated source is a question of provenance and signatures, treated in chapter 12. **How it is recovered.** Another satellite of the same mission, another sensor type that measures a related quantity, or the archive for a date already collected.

Monday rule: write the observable, the area, the resolution in its four senses, the revisit and the latency on both clocks before you look at any catalog.

CHAPTER EIGHT

Optical, Thermal and Hyperspectral Sensing



On 31 May 2003 one part of Landsat 7's imager failed for good, and the satellite went on imaging for more than twenty years with stripes of missing data in every scene; the failure box at the end of this chapter gives the US Geological Survey's account. A buyer of a Landsat 7 archive scene from 2010 buys that history with it. This chapter is about what a camera or a spectrometer in orbit can measure, and what stops it; the decision it changes is to read a sensor's history and its conditions before its headline resolution.

A camera in orbit

An imaging satellite carries a telescope that forms an image of the ground on a detector. Most land imagers today use a **pushbroom** design: a long line of detector elements across the direction of flight, read out again and again as the satellite moves forward, so that the image is built up line by line like a page through a scanner. Older instruments, such as Landsat 7's, swept a mirror from side to side instead, which is why a failed part in the sweep left gaps.

The ground sample distance follows from three numbers: the spacing of the detector elements (the pitch), the focal length of the telescope, and the distance to the ground. Looking straight down at flat ground, the pixel on the ground is about the pitch multiplied by the altitude and divided by the focal length; looking off to the side, it grows, and not by the same amount along and across the view. Appendix B gives the formula with a check value. A finer pixel can come from a smaller pitch, a longer telescope or a lower orbit.

The ground sample distance says nothing about whether the optics can actually separate two points that close. That limit comes from the aperture, the diameter of the telescope, and from the wavelength. Light passing through a circular aperture spreads into a small disk; the smallest angle the telescope can separate is about 1.22 times the wavelength divided by the aperture. As an illustration of the arithmetic only, and not a description of any real instrument: at a wavelength of 0.5 micrometers, from 500 kilometers, separating points 30 centimeters apart needs an aperture of about 1.0 meter (1.22 times 0.5 micrometers times

500 kilometers, divided by 0.3 meters). This is the ideal limit; aberrations, detector response, motion and jitter make a real telescope less sharp, not sharper. That is why fine resolution from orbit means a large telescope, a low orbit or both, and why a supplier's ground sample distance should be read beside its aperture and altitude. A pixel much finer than the optics can resolve adds data with little added detail, though some oversampling helps processing and registration.

Panchromatic, multispectral, hyperspectral

A **panchromatic** band collects light over a wide range of wavelengths, so it gathers more light per pixel and can use a finer pixel for the same signal. A **multispectral** sensor splits the light into a handful of bands chosen for particular surfaces: vegetation reflects strongly in the near infrared, water absorbs it, and soils and minerals have their own shapes in the shortwave infrared. A **hyperspectral** sensor, or imaging spectrometer, records a continuous spectrum in many narrow bands for each pixel, so that materials can be told apart by the shape of their spectra and not only by their brightness in a few bands.

The public record shows the progression. Landsat 1, launched as ERTS in 1972, carried a multispectral scanner with four bands at 80 meters, according to the US Geological Survey. Landsat 9 records nine reflective bands, eight at 30 meters and a panchromatic band at 15 meters, and two thermal bands at 100 meters. France's SPOT series, to which CNES gives a resolution of 10 meters for SPOT-1 to 4 and 2.5 meters for SPOT-5 (the page read does not describe the processing behind the SPOT-5 figure), from an 830 kilometer orbit, showed what a finer civil camera could sell. Italy's PRISMA, in orbit since 22 March 2019 at 615 kilometers, carries a hyperspectral instrument covering the visible, near infrared and shortwave infrared at 30 meters and a panchromatic camera at 5 meters, and its data are requested through the agency's portal, according to the Italian Space Agency. Germany's EnMAP is a second public hyperspectral mission; its agency pages could not be read for this chapter, so no figures for it are printed here.

More bands are not free. Splitting the light into narrow bands leaves less light in each, so each band's **signal to noise ratio** falls unless the pixel grows, the exposure lengthens or the telescope widens. This is why hyperspectral instruments usually have coarser pixels and narrower swaths than multispectral cameras on similar platforms. Before any band can be compared with a laboratory spectrum, the atmosphere's contribution has to be removed (**atmospheric correction**), and the result carries the uncertainty of the atmospheric model. A buyer who needs to detect a gas, a mineral or a crop disease should ask for the detection limit as the supplier states it, with the conditions under which it was established, not for the number of bands.

Thermal: measuring heat

A thermal infrared sensor measures radiation that the surface emits, not sunlight it reflects. It therefore works at night as well as by day, if the operator collects then. Working at night is not seeing through cloud: thermal infrared does not reach the surface through opaque cloud, so thermal products need cloud masks too. The measured radiance is turned into a temperature through a model of the surface's emissivity and of the atmosphere; the result is a land or sea surface temperature with an uncertainty, not a reading from a thermometer. Landsat 9's two thermal bands have 100 meter pixels, more than three times coarser than its 30 meter reflective bands.

Two cautions follow from the physics. First, a surface's **emissivity**, how efficiently it radiates compared with an ideal radiator, varies with the material: water, vegetation, bare soil, metal roofs and asphalt differ, and an error in the assumed emissivity becomes an error in the temperature. A product's temperature is only as good as its emissivity model over the buyer's surfaces. Second, a 100 meter thermal pixel mixes everything inside it. The mixing happens in radiance, not in temperature, and the conversion from radiance to temperature is not linear, so a small hot object, such as a fire front or a cooling outlet, can raise the pixel enough to be detected while its own temperature stays poorly known. Methods that estimate the temperature of a part of a pixel exist, but they rest on extra assumptions. A buyer who needs the temperature of something smaller than the pixel should state the object's size, the detection probability and the temperature uncertainty required, and expect a finer thermal sensor to be the more direct answer.

The time of the pass matters more for heat than for reflectance. A sun-synchronous satellite sees each place at about the same local time on every pass; for Landsat 8 and 9, the US Geological Survey gives an equatorial crossing at 10:12 in the morning. A surface temperature taken in mid-morning is not the afternoon maximum, and a crop's water stress, a city's heat or a river's warming each have their own daily cycle. A buyer of thermal data for such a question should ask at what local time the collections are made, and whether that time answers the question. Sensors in low orbits that are not sun-synchronous see the same place at different hours on different days, which helps for daily cycles and complicates comparison; geostationary imagers see it all day, at coarse resolution.

Cloud, haze, night and sun angle

Reflected-light sensors need daylight and a clear line of sight. Cloud hides the ground; thin cloud and haze change its brightness without hiding it, which is worse for a measurement than an obvious gap, because the pixel looks valid. Cloud shadow darkens clear ground near

a cloud. A low sun in winter or at high latitude lengthens shadows and lowers the signal. Open programs deliver a cloud mask and quality flags with their products; a commercial order should require them, because the usable share of a scene is often less than the whole.

The consequence for a buyer is simple to state. An optical revisit is an opportunity, not a delivery. A satellite that passes every few days over a region with a cloudy season can go weeks without a clear view of a given field. One number that decides whether optical data can answer a question is the **cloud-free collection rate** over the buyer's area and season: the share of opportunities that produced a usable view, from the supplier's own archive, with how long the gaps between usable views ran in the season that matters. A supplier that has collected over the area for years can count it; a supplier that estimates it from a model or a global average should say so, and the buyer should weigh it as an estimate.

Geometry: where the pixel really is

A raw image is in the sensor's geometry: each line is where the satellite was looking at that instant. To place it on a map the processor needs the satellite's position and pointing, and an **elevation model** of the ground. Correcting for terrain and viewing angle so that every pixel sits where it belongs on a map is **orthorectification**. Its accuracy depends on the satellite's pointing knowledge, on ground control points and on the elevation model, and it degrades in steep terrain and at large off-nadir angles, where tall buildings and slopes lean in the image.

A geolocation accuracy is therefore a statement with conditions: a distance, at a percentile, over a kind of terrain, at a range of off-nadir angles, with or without ground control, using a named elevation model. A single number without them cannot be tested at acceptance. When images from two dates are compared, a small misregistration between them shows up as false change along every edge.

Calibration: comparing today with last year

A single image can be looked at. A series of images can be measured only if their calibrations are consistent and traceable, with the uncertainty of any adjustment between them stated. **Radiometric calibration** turns the detector's counts into radiance in physical units. It is set before launch and then maintained in orbit, because detectors and optics age: the operator views known references (on-board lamps or diffusers, the Sun, the Moon, or stable desert and ice sites on the ground) and adjusts the conversion. Each adjustment becomes a new calibration version, and an archive may be reprocessed when a better one is found.

For a buyer, calibration decides three things. Whether a change between two dates is real or a drift of the sensor. Whether two satellites of the same family can be used as one, as the eight day offset of Landsat 8 and 9 invites. And whether data from two different suppliers can be mixed: two cameras with the same band names do not have the same band edges, and

the same surface gives slightly different values in each. A change smaller than the calibration difference between two sensors cannot be told apart from that difference without a correction and an uncertainty analysis. The questions to ask are which calibration version a product carries, what absolute uncertainty the operator states for it, and whether the operator publishes how its sensor compares with a public reference mission.

Small commercial satellites raise the question more sharply than large public ones, because a fleet of many small cameras is many sensors, each with its own response, launched at different times. A supplier selling a daily record from such a fleet is also selling its method of making those sensors agree. The method may be good; the buyer should still ask to see it described, with the statistics of how well the sensors agree.

Reading an optical specification

An optical supplier's specification can be read line by line against the requirement of chapter 7. The table below lists the lines that decide whether a product will answer a question, and what each line must say to be testable. A line the supplier will not fill is itself a finding.

Lines to ask for in an optical, thermal or hyperspectral offer

Line	What a testable answer states
Ground sample distance	At nadir and at the largest off-nadir angle offered; the product's resampled pixel, if different
Optics	Detector pitch, focal length and altitude (to check the pixel), and aperture with the measured image sharpness (to check how fine a detail the optics can deliver)
Bands	Each band's spectral response, or at least its edges in nanometers or micrometers, not only its name; co-registration between bands
Signal to noise	Per band, at a stated scene brightness and sun angle; saturation level; for thermal bands, the noise as a temperature at a stated scene temperature
Radiometric accuracy	Absolute uncertainty and calibration version; comparison with a public reference mission
Geolocation	A distance at a percentile, with terrain, off-nadir range, ground control and elevation model named
Time of collection	Local time of day of the collections over the area, and whether night collections are offered (thermal)
Cloud-free collection rate	Over the buyer's area and season, from the supplier's own archive
Product level	Which corrections are applied, with which models, and which quality masks are delivered
Instrument history	Known defects and outages over the period bought, and where they fall

None of these lines names a supplier, and none needs one. A requirement written this way can be sent to an open program's documentation and to several commercial suppliers, and the answers compared row by row, which chapter 14 does.

The classes a buyer meets

Optical data reaches buyers in a few classes, set out in Figure 8.1. Each row has dated examples from the operators' or agencies' own statements; the counts and resolutions are theirs, not tested here.

- **Free medium resolution mapping.** Landsat, with Collection 2 surface reflectance and surface temperature products from Landsat 4, 5, 7, 8 and 9 (reflective bands at 30 meters; the buyer checks coverage and valid pixels over the area), and the European Sentinel-2 mission. The Copernicus pages for Sentinel-2 and the NASA pages for the harmonized Landsat and Sentinel-2 product could not be read when this chapter was checked, so their figures are not printed here.
- **Daily commercial scanning.** Fleets of small satellites that image most land every day at a few meters. Planet describes a processed product that raises its PlanetScope data to "2 m class" visual resolution; that is an enhancement by processing, and a buyer should ask what the sensor itself sampled.
- **Tasked high resolution.** Satellites that point at a customer's area on request. Satellogic describes its Merlin design, first launched on 1 October 2026, as designed for 1 meter class daily remapping with alerts within 30 minutes; a design is not yet a daily service. Vantor, the name Maxar Intelligence took in October 2025, had launched six WorldView Legion satellites by then, by its own account; their resolution was not on the page read. BlackSky reported that a fifth third-generation satellite "reached first light and revenue operations within 24 hours", in its results of 5 November 2026; the release does not say from which moment the 24 hours run.
- **The 30 centimeter class, as operators state it.** Planet described its first second-generation Pelican, launched in July 2026, as expected to reach "up to 30 cm class imagery". That is an operator claim, dated; the release does not say whether "30 cm class" is the sampled or the delivered pixel, and neither is what can be identified.
- **Public programs of other states.** Brazil and China's CBERS partnership launched CBERS-04A in 2019, and Brazil's space research institute states that it distributes satellite images free of charge. India's remote sensing center offers imagery from its LISS-IV, LISS-III and AWiFS sensors at 5, 25 and 50 meters through its portal, by its own description. The agency pages for Japan's, South Korea's and China's optical missions, and India's mission pages, were sought for this chapter and could not be read; their figures are not printed.

FIGURE 8.1

Optical classes differ in pixel, spectrum and access more than in name

Class	Example	Pixel or class, as stated	Spectral range	Access	State or company	Stated
Free medium resolution	Landsat 8 and 9	30 m reflective; 15 m pan; 100 m thermal	Visible to thermal infrared, 11 bands	Free download (Collection 2)	US	2026-11
Free medium resolution	CBERS-04A	not read	not read	Free images, says the operator	Brazil, China	2026-11
Public national archive	LISS-IV, LISS-III, AWiFS (India)	5, 25, 50 m as offered	not read	Agency portal	India	2026-11
Public hyper-spectral	PRISMA	30 m; 5 m pan	Visible, near and shortwave infrared	Request through agency portal	Italy	2026-11
Daily commercial scanning	PlanetScope	2 m class after pro-cessing	not read	Subscription	Planet	2026-06
Tasked, daily remap	Satellogic Merlin	1 m class (design)	not read	Commercial	Satel-logic	2026-11
30 cm class	Planet Pelican Gen-2	up to 30 cm class (expected)	not read	Commercial	Planet	2026-06
Tasked very high resolution	Vantor WorldView Legion	not read	not read	Commercial	Vantor	2025-10
Historical civil	SPOT-1 to 5	10 m (SPOT-1 to 4); 2.5 m (SPOT-5), as CNES gives them; processing not read	not read	Archive	France	2026-11

Optical, thermal and hyperspectral classes with one or two dated examples each, in the operators' or agencies' own words; blank cells were not published in the sources read.

Source: USGS Landsat 8, 9 and Collection 2 pages; INPE (gov.br/inpe); NRSC home page; ASI PRISMA page; Planet results for the first and second quarters of fiscal 2027; Satellogic third quarter 2026 results; Vantor, 2025-10-02; CNES SPOT page (read 2026-11-22 to 2026-11-23). Operator claims, not tested. Author's table.

National rules on what may be imaged, at what resolution, and who may receive it differ by country and belong to the fourth book of this series, *Who Owns the Sky*. Licenses and prices are chapter 13.

THE SYSTEM'S FAILURE

The instrument part that failed on Landsat 7 on 31 May 2003 was the Scan Line Corrector, which compensated for the satellite's forward motion during each sweep of the scan mirror. The US Geological Survey states that efforts to recover it were not successful and the failure was permanent. Imaging continued: after the duplicated areas of each scene were removed, gaps remained, and 78 percent of a scene's pixels remain. The satellite acquired science data until 19 January 2024 and the mission was decommissioned on 4 June 2025, after 26 years in orbit.

What failed was one mechanism in one instrument; what the program did was to keep the satellite collecting and to document the gaps, so that the data stayed usable for purposes that could tolerate them. For a buyer the point is about the archive: a scene carries the condition of its instrument on the day it was taken. A buyer of historical data should ask for the instrument's status history over the period bought, and check whether a known defect falls on the area of interest.

SECURITY NOTE

As in chapter 7, which covers command, interception, interference and recovery for all of Part II's sensors. **Who can interfere or command.** One point is specific to optical products: an image can be altered after delivery, by anyone with access to the file. **How it is seen.** Detecting an altered image is a forensic question outside this book; what a buyer can check is provenance, the record of where a file came from (chapter 12). **How it is recovered.** By going back to the supplier's archive for the original, or to another supplier's collection of the same place and time where one exists.

Monday rule: ask for the cloud-free collection rate over your area and season, not the revisit.

CHAPTER NINE

Radar Sensing



On 4 November 2025 Sentinel-1D was launched, the fourth satellite of a European radar series that works at 5.405 GHz from 693 km (Copernicus). A radar like it images at night and, at its band, through most cloud. Many organizations that could use such data do not, and the reason is rarely the satellite: a radar image is not a photograph, and someone has to be able to read it. This chapter is about what a radar measures, what its products are, and what a buyer has to have in place before the first order.

A sensor that brings its own light

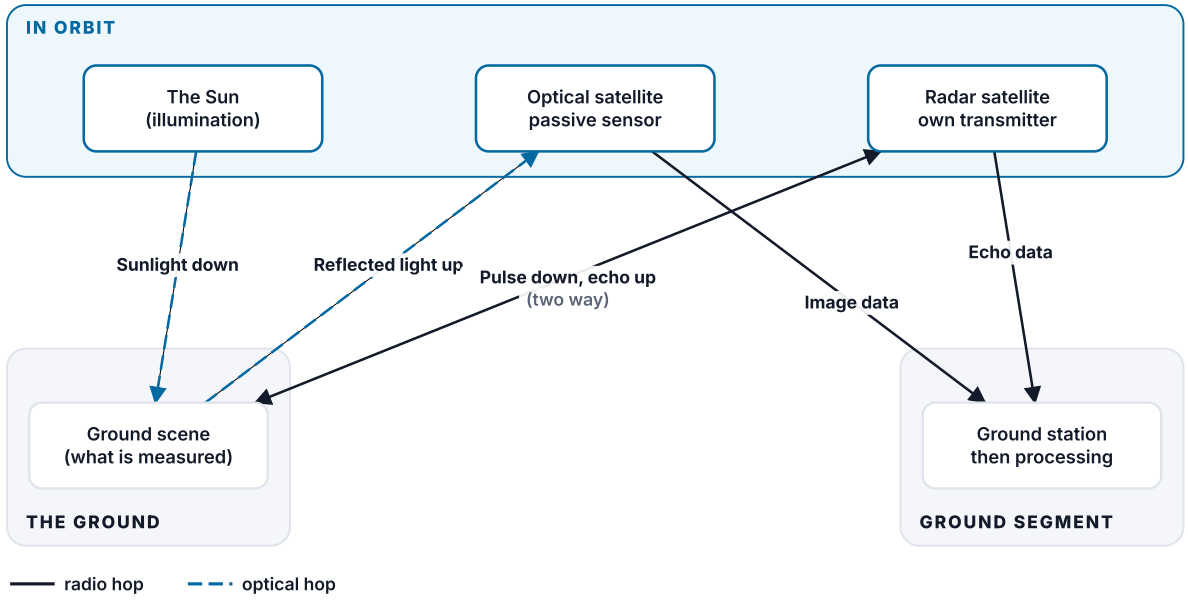
A camera in orbit records sunlight that the ground reflects. A radar sends its own pulses of microwaves toward the ground and records the echo. That one difference sets most of what follows. The radar does not need the Sun, so it works at night. Microwaves pass through most clouds; the United States Geological Survey puts it as "radar waves penetrate most weather clouds and are equally effective in darkness" (USGS). Heavy rain, and the shorter wavelengths, are where that statement needs care, so a buyer asks for the band before accepting "all weather".

The price is paid in three places. **Power:** the satellite carries its own transmitter, and the echo it waits for has traveled down and back. For a radar that does not synthesize an aperture, the textbook radar equation makes the received signal fall with the fourth power of the range; for the signal to noise of a synthetic aperture image, after the processing that builds the aperture, the same source's derivation gives the third power (Guerra and others, *Acta Astronautica*, 2016, peer reviewed, Appendix A). The echo itself still weakens as an ordinary radar's does; the processing gains back part of it. That equation is a measurement model, not a message-delivery budget, so this book does not put it on a Link Ledger page (chapter 1). In practice the echo is very weak, so a radar satellite spends much of its power on transmitting, which a camera never does. **Data volume:** unless the image is formed on board, the raw echoes are stored and sent down before any image exists (Chapter 12). **Reading:** the picture that comes out records how strongly each patch of ground sent the pulse back, which depends on roughness, moisture, structure and the angle of view, not on

color. A radar is therefore not a like-for-like replacement for an optical measurement. It answers some questions that a camera cannot, and it does not answer some that a camera can.

FIGURE 9.1

A radar lights the ground itself; a camera waits for the Sun



The radar's pulse goes down and its echo comes back to the same satellite, so it works at night; the camera records sunlight reflected from the ground, so it needs daylight and a clear view; both then store the data and send it to a ground station.

Author's diagram based on Guerra and others, Acta Astronautica (2016, peer reviewed), Appendix A, and USGS, InSAR page (both in Appendix E).

How a synthetic aperture gets its resolution

A radar looks to the side, not straight down. The direction across the ground track is called **range**, and the direction along the track is called **azimuth**. The two are resolved by different means.

In range, two points are told apart by the time their echoes take to return. A short pulse would do it, but a short pulse carries little energy, so the radar sends a longer pulse whose frequency sweeps across a bandwidth, a chirp, and compresses it on reception. The range resolution then depends on the bandwidth: about the speed of light divided by twice the bandwidth. A bandwidth of 15 MHz gives about 10 m, the example the survey cited above uses. That resolution is measured along the line of sight, the **slant range**. On the ground it is coarser, by a factor that depends on the **incidence angle**, the angle between the radar's line of sight and the vertical at the ground. Pixel spacing is a separate choice: a processor can

resample an image to any spacing, finer or coarser than its resolution. A buyer therefore asks for both the resolution, in slant and ground range, and the pixel spacing of the product offered.

In azimuth, a real antenna resolves two points only if its beam is narrow, and the beam width is the wavelength divided by the antenna length. At microwave wavelengths, fine azimuth resolution from orbit would need a very long antenna, kilometers for meter-scale detail; the length depends on the wavelength, the range and the resolution wanted. The synthetic aperture is the way around it. While the satellite moves, a point on the ground stays inside the beam for a while and returns many echoes; the processor combines them, using the Doppler shift of each echo, as if they had come from one antenna as long as the distance flown while the point was in view (Guerra and others, Appendix A). Because a farther point stays in view longer, the synthetic antenna grows with range, and the azimuth resolution of a stripmap image does not degrade with range the way a real antenna's would. The exact relation, and the conditions under which it holds, are in Appendix B.

Two other effects follow from looking sideways, and both can appear in radar images of hills and buildings, depending on the slopes and the viewing geometry. Where a slope faces the radar steeply, its top can return its echo before its foot, so the image folds the slope over: **layover**. Behind a steep slope the ground receives no pulse at all: **shadow**. A conference paper describing a dual band design names both as artifacts of side-looking geometry (UrtheCast, ISPRS Archives, 2015). Neither is noise. Both are properties of the geometry, and a terrain model can predict where they occur.

Bands, modes and polarization

The band sets what the radar sees. The letter bands are conventions: L band runs from 1 to 2 GHz, C band from 4 to 8 GHz and X band from 8 to 12 GHz, as ESA lists them (ESA, Satellite frequency bands). In wavelength that is about 15 to 30 cm for L, 3.75 to 7.5 cm for C and 2.5 to 3.75 cm for X (calculated: the speed of light over the frequency). Sentinel-1's 5.405 GHz is a wavelength of 5.5 cm (calculated). As a rule of thumb, a longer wave passes further into a canopy before it returns. The UrtheCast design paper uses exactly that to estimate forest height: its X band radar was to locate "the tops of the trees" and its L band radar "the bottom of the tree". That was a design aim: turning the two echoes into a forest height needs a validated model, and a longer wave does not reach the ground under every canopy. The same property makes the bands complementary, not ranked.

A **mode** is how the radar spends its time and beam. In stripmap the beam stays fixed and sweeps a continuous strip. In wide swath modes, often called ScanSAR, the beam steps between several sub-swaths and covers a wider area at coarser resolution. In spotlight modes the beam is steered to stay on one place for longer, which buys finer azimuth

resolution over a small area. Each operator names its modes in its own way, so the buyer compares the resolution, swath, incidence angle range and polarization of each mode, not its name.

Polarization is the orientation of the wave's electric field, horizontal or vertical. A radar can transmit one and receive one (HH or VV, like-polarized; HV or VH, cross-polarized). Like-polarized echoes come strongly from surfaces and from structures that return the pulse directly; cross-polarized echoes come mostly from volumes that scatter it in many directions, such as vegetation. A system that records all four combinations coherently, with their relative phase, is **fully polarimetric**, which ASI describes for the wide field mode of its second generation COSMO-SkyMed satellites ("quadruple polarization mode"). More polarizations cost data volume and usually swath.

FIGURE 9.2

Band, mode and polarization each change what one radar image holds

Choice	Options	What it changes	Source
Band	L band 1 to 2 GHz (about 15 to 30 cm); C band 4 to 8 GHz (3.75 to 7.5 cm); X band 8 to 12 GHz (2.5 to 3.75 cm)	How far the wave passes into a canopy or dry soil before it returns; a longer wave passes further. Sentinel-1 uses 5.405 GHz (5.5 cm)	ESA band list; wavelengths calculated; Copernicus
Band, in a proposed design	X and L together on one design	X band aimed at the tops of trees, L band at the ground beneath, for forest height (a design aim; a height needs a validated model)	UrtheCast, ISPRS 2015
Mode	Stripmap; wide swath (ScanSAR); spotlight	Resolution against swath and time on target: a wider swath is coarser, a spotlight is finer over a small area	Operator mode tables; compare by numbers, not names
Polarization	HH or VV (like); HV or VH (cross); all four (fully polarimetric)	Like-polarized: mostly surface returns. Cross-polarized: mostly volumes such as vegetation. The reading depends on angle, wavelength and target; it is not a classifier. More polarizations cost data and usually swath	ASI (quad polarization on COSMO-SkyMed Second Generation)
Product level	Single look complex; detected, ground range; geocoded and calibrated backscatter	Whether phase is kept (needed for interferometry) and whether a pixel is a calibrated measurement	ICEYE product specification 6.0.8

A buyer specifies all three, because two products with the same pixel size can hold different information.

Source: ESA, Satellite frequency bands; Copernicus SentiWiki, S1 Mission; UrtheCast, ISPRS Archives XL-7/W3 (2015); ASI, COSMO-SkyMed; ICEYE product specification 6.0.8 (2026-09-24). Wavelengths calculated in this book.

What a radar product is

The first product a radar processor makes is a complex image: each pixel holds an amplitude and a phase. Operators call it a **single look complex** product, and it is the input for interferometry. Most users do not start there. They take a **detected** product, in which the phase is dropped, several looks are averaged to reduce speckle, and the image is projected to ground range or to a map. ICEYE's product specification, for example, lists a quick look, a ground range detected product (GRD), a single look complex (SLC) and further products, and gives the end of availability of two legacy formats as 31 December 2026 (ICEYE, product specification version 6.0.8, dated 24 September 2026). The names are similar across operators; the processing behind them is not, and Chapter 12 gives the checks for accepting any of them.

The number a scientist wants from a detected pixel is the **backscatter coefficient**: the echo strength normalized for a reference area, given as a linear coefficient or in decibels. Getting it requires radiometric calibration, which corrects for the antenna pattern and the range and delivers a named quantity; the quantities (beta nought, sigma nought, gamma nought) differ in the reference area they normalize to, so a buyer asks which one is supplied, and whether in linear units or decibels. Correcting the brightness for slopes over hills, often called terrain flattening, is a further step that not every product includes. A geocoded, calibrated pixel with its steps stated is a measurement. An uncalibrated one is a picture.

Two properties of radar images surprise people who know photographs. The first is **speckle**: because many small scatterers inside one pixel add their echoes with random phases, a uniform field looks grainy. Averaging looks or neighboring pixels reduces speckle at the cost of resolution. The second is that **brightness is not a material label**. A bright pixel can be a metal roof, a wall facing the radar, a rough wet field or a corner formed by a building and the street. Identification needs context, other dates, other bands or an optical image.

Interferometry: motion along the line of sight

The phase in a complex image is a fraction of a wavelength, and it encodes the distance from the radar to the ground. Compare the phase of two images of the same place taken from nearly the same position on different dates, and the difference holds the change of that distance, mixed with contributions from the terrain's height, small orbit differences, the atmosphere and noise. Remove or estimate those, and what is left is motion. That is **radar interferometry** (InSAR). The USGS describes it as "a technique for mapping ground deformation" in which "any movement of the ground surface toward or away from the satellite can be measured", the change appearing "as a phase difference", over a large area "with centimeter-scale accuracy" (USGS Volcano Hazards Program).

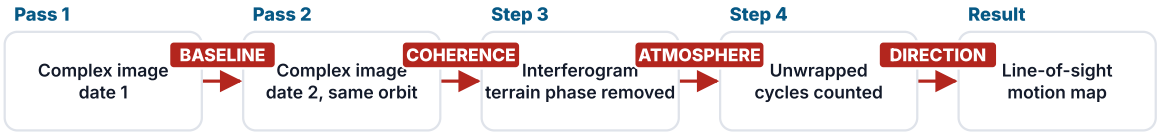
The scale is set by the wavelength. Because the pulse travels down and back, one full cycle of phase corresponds to a change of half a wavelength along the line of sight: 2.8 cm at Sentinel-1's frequency (calculated). The phase repeats every cycle, so the processor has to count the cycles across the image, a step called **phase unwrapping**. The motion it yields is relative, so the product also names a reference point assumed stable, and that assumption is part of its uncertainty. Where coherence is low, unwrapping can miscount and create false motion, so the buyer asks for the method and its quality layer.

Four conditions decide whether a pair of images gives a usable map, and a buyer of a deformation product asks for each:

- **Coherence.** The scatterers in each pixel must stay similar between the two dates. Vegetation growth, plowing, snow and water tend to reduce it; bare rock and buildings tend to keep it, though the outcome depends on the wavelength and the time between passes. The TanDEM-X team at the German Aerospace Center notes that the change of coherence itself reveals changes in soil and vegetation (Krieger, Zink and Moreira, IAC 2012).
- **Baselines.** The temporal baseline is the time between the passes; the perpendicular baseline is the separation of the two acquisition positions measured across the radar's line of sight. A long one of either kind reduces coherence, and the perpendicular baseline also sets how strongly terrain height shows in the phase.
- **The atmosphere.** Water vapor delays the pulse differently on the two dates, and the ionosphere adds a delay that grows at lower frequencies such as L band (it falls with the square of the frequency, chapter 2); either looks like motion unless it is corrected or averaged out over many dates, so the buyer asks which corrections were applied.
- **The direction.** The result is motion along the radar's line of sight, which is slanted. It is not vertical motion. Vertical and east-west motion are separated only by combining views from different directions, for example ascending and descending passes, under stated assumptions.

FIGURE 9.3

Two passes become one map of motion along the line of sight, if four conditions hold



Red chips mark the four conditions; the result is relative to a reference point assumed stable.

The four conditions of the text appear where they bite: the baselines between the passes, coherence in the interferogram, the atmosphere before unwrapping, and the line-of-sight direction of the result, which is not vertical motion.

Author's diagram based on USGS, InSAR page, and Krieger, Zink and Moreira, TanDEM-X (IAC 2012).

A deformation map delivered without its coherence, its reference point, its dates and its line-of-sight direction cannot be checked, and Chapter 12's acceptance table asks for all four.

The suppliers a buyer meets

Public radar missions are compared in Figure 9.4 as products, with the same columns for each: who operates it, its band, its dates, its repeat cycle or revisit as the operator states it, and how a user obtains the data. A repeat cycle (the orbit returns over the same ground track) and a revisit (some satellite can see the place again) are different quantities, and the table keeps the operator's own word. The table also shows what could not be read. The agency pages for NISAR, the ALOS series and the RADARSAT Constellation Mission could not be read when this book was checked on 23 November 2026, so their rows say so instead of repeating figures from secondary sources. Sentinel-1's figures were read on the Copernicus mission page on 22 November 2026; its 2026 status was not read.

FIGURE 9.4

Public radar missions, compared as products, as read in November 2026

Mission	Operator	Band	Satellites and dates	Repeat or revisit, as stated	Access	Read
Sentinel-1	Copernicus (EU, ESA)	C, 5.405 GHz	1A 3 Apr 2014; 1B 25 Apr 2016, no data since 23 Dec 2021; 1C 5 Dec 2024; 1D 4 Nov 2025; 693 km	Not read	Copernicus terms (Chapter 13)	2026-11-22
COSMO-SkyMed	ASI with the Italian Ministry of Defense	X	First 7 Jun 2007; first generation complete 5 Nov 2010; CSG-1 18 Dec 2019; CSG-3 3 Jan 2026; count in operation not dated on the page read, so not printed	Revisit: "a few hours" (ASI wording)	Institutional portal; commercial through e-GEOS	2026-11-23
SAOCOM	CONAE, in collaboration with ASI	Not on the page read	1A 7 Oct 2018; 1B 30 Aug 2020	Repeat: 16 days each; 8 for the pair	Not on the page read	2026-11-23
NISAR	NASA and ISRO	Not read	Not read	Not read	Not read	Not readable 2026-11-23
ALOS-2, ALOS-4	JAXA	Not read	Not read	Not read	Not read	Not readable 2026-11-23
RADARSAT Constellation	Canadian Space Agency	Not read	Not read	Not read	Not read	Not readable 2026-11-23

The same columns for each mission; a row whose agency page could not be opened says so rather than repeating secondary figures.

Source: Copernicus SentiWiki, S1 Mission (read 2026-11-22); ASI, COSMO-SkyMed; CONAE, SAOCOM (both read 2026-11-23). NISAR, JAXA and CSA pages could not be read on 2026-11-23 (Appendix D lists them as sought, not read).

Two of the public programs show how access differs. Italy's COSMO-SkyMed is, in ASI's words, "a program of the Italian Space Agency and the Ministry of Defense": institutional users request data through ASI's portal, and commercial users through e-GEOS (ASI). Argentina's SAOCOM, developed by CONAE in collaboration with ASI, flies two satellites launched on 7 October 2018 and 30 August 2020, each on a 16-day repeat, which CONAE gives as 8 days for the pair (CONAE). Neither page read states a free download policy, so none is claimed here.

Germany's TerraSAR-X and TanDEM-X, whose archive is sold commercially (Chapter 13 prices one product), were not sought as mission pages for this edition. The commercial radar operators read for this book sell mostly by tasking (Chapter 12). The operators state their fleets in their own terms, and those terms differ. ICEYE gives 76 satellites launched in total as of 7 July 2026, and says its Gen4 satellites image "at up to 16 cm"; it does not give the number still operating, and "16 cm" is an operator claim about one mode, not a statement about what can be identified in an image (ICEYE, 2026-07-07). ICEYE also says that seven

European governments have procured sovereign systems, satellites delivered with their own ground segments. Capella Space has been part of IonQ since 15 July 2025 (Capella Space). Umbra launched its satellites 13 and 14 on 20 October 2026 (Via Satellite, trade press). Satellite counts for the others were not published in the sources read; Appendix D carries only dated counts.

For a buyer the useful comparison is not the fleet but the product: the band, the mode and its resolution and swath, the polarizations, the archive over the area, the repeat that the program commits to over that area, and the license. A larger fleet raises the chance of a collection inside a window; it does not change what a single image contains.

THE SYSTEM'S FAILURE

Sentinel-1B, December 2021. Sentinel-1B was launched on 25 April 2016 to fly with Sentinel-1A. The Copernicus mission page records that it has returned no radar data since 23 December 2021; Sentinel-1C followed on 5 December 2024 and Sentinel-1D on 4 November 2025 (Copernicus, read 22 November 2026). The cause of the anomaly and the formal end of the mission are on ESA pages that could not be opened for this book, so they are not described here.

What the record supports is narrow. For about three years the program flew one satellite where it had been designed for two, so places that had been imaged by both were imaged by one. Users of interferometry, who need regular pairs from the same orbit, lost continuity, not resolution: the loss did not make the surviving satellite's images coarser, and there were fewer of them. The size of the change over any one area depends on the acquisition plan, which was not read. The lesson is the one the chapter's Monday rule turns into a habit: the interval between acquisitions over a place is a property of the fleet and its acquisition plan on a date, while each satellite's own repeat cycle is a separate number.

SECURITY NOTE

Who can interfere or command. As for every sensing satellite (Chapter 7): the operator tasks and commands; an open program lets anyone download its archive. Some commercial radar is sold as sovereign systems with the buyer's own ground segment (ICEYE), which moves command and data into the buyer's hands and the buyer's risk. A radar announces itself: its pulses can be detected by receivers within reach of its beam. How hard that is depends on the design, and no operator document read for this book describes it. Ground transmitters that share the band appear in images as interference; the rules on the band are covered in depth later in this series. **How it is seen.** Interference appears as bright stripes or patterns unrelated to the ground; a missing collection appears as a gap in the archive or a failed tasking report. **How it is recovered.** Another satellite or another band over the same area, the archive for the period before the gap, and an optical image where cloud allows.

Monday rule: before buying radar data, ask who in your organization can read it, which product level they need, and what repeat the supplier commits to over your area on which dates.

CHAPTER TEN

Weather and Climate Data: Imagers, Sounders and the Products Built on Them



At 15:00 UTC on 7 April 2025, GOES-19 became GOES-East, replacing GOES-16, according to NOAA's satellite operations office. NOAA's small-dish broadcast of warnings and images now came from a different satellite; a receiving station in its footprint, with a suitable dish and receiver, needed no one's permission and paid no one to keep taking it. Weather satellites have flown since 1960, and they send much of their data to anyone in view; they are also a case where a buyer can easily buy the wrong thing. The decision this chapter changes is the first one: whether you need observations, derived products or forecasts, before you choose a satellite or a supplier.

The meteorological fleet

TIROS-1, launched on 1 April 1960, sent television pictures of clouds for 78 days, and NOAA counts more than 19,000 usable pictures from it. SMS-1, the prototype of NOAA's geostationary weather series, followed in 1974 (earlier experimental satellites had imaged weather from geostationary orbit), and GOES-1 on 16 October 1975, according to NOAA. Europe's Meteosat-1 was launched on 23 November 1977 and scanned the full disc every 30 minutes in three channels, as ESA's history of the program records. The shape of the system was set in those years and has held: satellites in **geostationary orbit** watch the same hemisphere all the time, and satellites in **polar orbits** pass over every part of the globe, including the high latitudes that geostationary satellites see poorly or not at all.

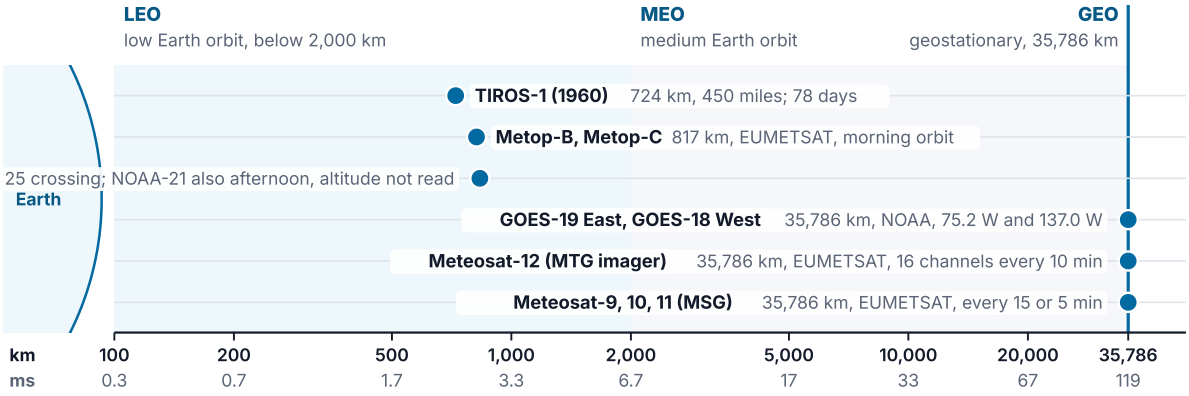
The operators' own status pages, read in November 2026, give the fleet as of the dates they state. NOAA operates GOES-19 as GOES-East at 75.2 degrees west and GOES-18 as GOES-West at 137.0 degrees west; GOES-18 replaced GOES-17 on 4 January 2023. GOES-16 and GOES-17 are in on-orbit storage, and NOAA names GOES-16 as the backup should either operational satellite need replacing. The current GOES generation images the full disk every 10 minutes, according to NOAA.

EUMETSAT, the European organization for meteorological satellites, operates Meteosat-9, 10 and 11 of its second generation. One provides full disc imagery every 15 minutes, a second images Europe every 5 minutes, and the third sits over the Indian Ocean, a service EUMETSAT provides "on a best-effort basis". Its third generation began with Meteosat-12, launched on 13 December 2022, whose imager "produces images of Europe and Africa in 16 channels every 10 minutes"; EUMETSAT began disseminating its data as pre-operational on 23 September 2024; its later status was not read for this book. The sounding satellite of the same generation, Meteosat-13, was launched on 1 July 2025.

In polar orbit, EUMETSAT operates Metop-B and Metop-C in a morning orbit at about 817 kilometers, and launched the first of a second generation, Metop-SGA1, on 13 August 2025; it was in commissioning when read. NOAA covers the afternoon: its operations office lists NOAA-21 as the primary afternoon satellite, NOAA-20 as secondary and Suomi NPP as tertiary, crossing the equator at 13:25 local time. The morning and afternoon split is written into an agreement between EUMETSAT and NOAA, which EUMETSAT says also covers exchanging instruments and sharing ground stations.

FIGURE 10.1

Weather satellites work in two layers: geostationary for minutes, polar for the whole globe



km: altitude above the surface (log scale). ms: light time straight up, one way (altitude divided by the speed of light).

The weather satellites of NOAA and EUMETSAT named in this chapter, from TIROS-1 to today's, with their roles as each operator stated them on the dates read (Meteosat-12's later status was not read); other states' fleets are not drawn because their pages could not be read.

Source: NOAA NESDIS (TIROS-1, read 2026-11-22); NOAA OSPO GOES and JPSS status pages; EUMETSAT Metop series, MSG and MTG pages (read 2026-11-23). NOAA-20's 833 km is from its status summary; NOAA-21's altitude was not on the page. Geostationary altitude about 35,786 km is calculated (Appendix B).

Other states fly weather satellites that a buyer in their regions will meet, among them Japan's Himawari series, China's Fengyun series, India's geostationary satellites and South Korea's GEO-KOMPSAT-2A (whose pages were not sought for this edition). The World Meteorological Organization keeps a register of all of them, but its pages, and the Japanese, Chinese and Indian operators' pages, could not be read when this chapter was checked, so their figures are not printed here. One fact from a readable source shows how the system is joined up: NOAA's small-dish broadcast, described below, carries imagery from Himawari as well as from GOES.

Imagers and sounders

A weather satellite carries two kinds of main instrument. An **imager** takes pictures in a set of channels, visible and infrared, at the finest spatial detail the orbit allows: clouds, fog, snow, smoke, fire, sea surface temperature. A **sounder** measures many narrow channels across the absorption bands of carbon dioxide, water vapor or oxygen. Each channel is most sensitive to a different, broad and overlapping layer of the atmosphere, so together they can be turned into vertical profiles of temperature and humidity, with a vertical detail limited by that overlap, by noise and by cloud. That turning is a **retrieval**: a model that finds the profile most consistent with the measured radiances and with a first guess.

Infrared sounders give fine vertical detail where the sky is clear. Microwave sounders work at longer wavelengths, which pass through most non-precipitating cloud, at the cost of coarser pixels. The polar satellites carry both: NOAA's status pages list an infrared sounder (CrIS) and a microwave sounder (ATMS) on NOAA-20 and NOAA-21, and EUMETSAT says its Metop satellites provide temperature and humidity profiles for numerical weather prediction. From geostationary orbit, EUMETSAT's Infrared Sounder on its third generation gives a 30 minute repeat cycle over Europe, which the agency says will fill gaps between the 12-hourly balloon soundings.

Newer geostationary instruments add quantities that are neither pictures nor profiles. EUMETSAT's Lightning Imager reports the time, position and intensity of detected optical pulses converted into flashes, and accumulates them over 30 seconds, with a timeliness target of 120 seconds and a goal of 60. The agency notes a limit of its own method: with optical pulse detection, cloud-to-ground and cloud-to-cloud lightning cannot be told apart. A buyer who needs strikes to ground needs another source.

What a weather buyer actually buys

The products built on these instruments come in four kinds, set out in Figure 10.2, and they are bought for different reasons. An **observation** is a calibrated radiance, located on a grid; it is what the satellite saw. A **retrieved product** is a geophysical quantity derived from

observations by a model: a cloud top height, a temperature profile, a fire, a lightning flash. An **analysis** combines observations of many kinds, from satellites, balloons, aircraft and ground stations, in a numerical model, to give the best estimate of the present state of the atmosphere. A **forecast** runs the model forward.

FIGURE 10.2

A weather buyer can buy four different things, and the terms differ for each

What is bought	What it is	Example from the sources read	Terms, as stated
Observation	Calibrated radiances, located on a grid (Level 1)	GOES-R Level 1b on the GOES Rebroadcast; MTG imager Level 1 from EUMETSAT	GRB: a broadcast, no registration required (NOAA); EUMETSAT: licenses under its data policy
Retrieved product	A geophysical quantity from a model (Level 2): cloud top height, temperature and humidity profiles, lightning flashes	GOES-19 cloud top height (NOAA outage notice, 2026-11-21); MTG lightning flashes accumulated over 30 s	Per provider; under the WMO policy, terms depend on whether the dataset is designated core or recommended
Analysis	Observations of many kinds combined in a model to give the best estimate of the present state	Numerical weather prediction centers	Per provider; not in the sources read
Forecast	Model output for future times	National services; WMO members	Per provider and per dataset designation under the WMO policy

Observation, retrieval, analysis and forecast: what each is, who provides it, and the terms stated in the sources read.

Source: NOAA OSPO, GOES Rebroadcast and GOES status pages; EUMETSAT, MTG imaging services and data policy pages; WMO, Unified Data Policy page (all read 2026-11-23). Author's table.

Many weather users outside the national services want an analysis or a forecast, not satellite data at all, for example a construction firm deciding whether to pour concrete, a utility planning for load, an airline routing around storms. They are buying a model's output, which

depends on satellites among many inputs. A buyer who wants observations, by contrast, is usually building a product of their own: a nowcast, a fire alert, a solar energy estimate. The first question is which of the four the decision needs, and at what age. For an analysis or a forecast the requirement adds its own lines: valid time, lead time and update interval, skill over the buyer's region with its uncertainty, by lead time and against a named reference forecast, on a period the supplier did not pick after the fact, how revisions are announced, and a second delivery path.

Terms differ by dataset and by provider. The World Meteorological Organization's Unified Data Policy, adopted as Resolution 1 of its Extraordinary Congress in 2021, divides data into two categories. **Core data** "must be exchanged, free and unrestricted, with no conditions on use"; **recommended data** "should be exchanged; conditions on use may apply". The policy binds the organization's member states, and its own summary says it "does not impose obligations on private companies, universities or other organizations". EUMETSAT implements its own data policy through a set of licenses; NOAA states that there is no fee or license requirement to receive its small-dish broadcast. A commercial forecast or a private sensing service carries its own contract. The source of a product, not the satellite under it, decides what a buyer may do with it.

Direct broadcast

A weather satellite does something an imaging satellite of chapter 8 rarely does: it sends its data to anyone in view, continuously, by design. NOAA's GOES-R series carries two such services, compared in Figure 10.3.

The **GOES Rebroadcast** (GRB) relays full resolution, calibrated Level 1b data from each instrument and Level 2 lightning data. NOAA's ground station at Wallops processes the raw data and uplinks the products to the satellite, which rebroadcasts them at 1686.600 MHz: 31 Mbit/s in total, 15.5 Mbit/s of data on each of two circular polarizations. A receive station needs a G/T of 15.2 dB/K for worst-case locations, and NOAA gives a nominal 4.5 meter dish. NOAA's sizing allows an operating margin of 2.5 dB and cautions that this "may be insufficient in parts of North America where strong interference from cellular and mobile internet service providers exists". The broadcast requires no registration; NESDIS had counted 96 GRB receive stations at 68 sites as of December 2020.

FIGURE 10.3

Two NOAA direct broadcasts: the full data stream needs a large dish, the small dish gets a selection

Item	GOES Rebroadcast (GRB)	HRIT/EMWIN
Content	Full resolution Level 1b data from every instrument; lightning Level 2	Warnings, charts, selected GOES and Himawari images, relayed data collection messages
Center frequency	1686.600 MHz	1694.1 MHz
Rate	31 Mbit/s in total: 15.5 Mbit/s on each of two circular polarizations	400 kbit/s
Modulation	QPSK, rate 9/10 coding, the default since 2017 (8PSK rate 2/3 defined)	BPSK, 927 ksymbol/s
Receive station	Nominal 4.5 m dish, 120 K system noise; G/T of 15.2 dB/K for worst-case locations	At least 1.0 m at 10 degrees elevation or more
Access	A broadcast, no registration required	No fee or license from NOAA; open format

The two direct broadcast services of the GOES-R series as NOAA's operations office describes them; EUMETSAT's and other operators' services were not read.

Source: NOAA OSPO, GOES Rebroadcast (GRB) page and HRIT/EMWIN page (read 2026-11-23). Operator claims.

The **HRIT/EMWIN** broadcast serves the small dish. It combines two older services into one stream of 400 kbit/s at 1694.1 MHz, carrying weather warnings, charts, a selection of GOES and Himawari images and relayed messages from environmental data collection platforms. NOAA gives the minimum antenna as 1.0 meter at 10 degrees elevation or more (a dish alone does not make a station: amplifier, receiver, decoder and the local noise and interference all count), and states that there is no fee or license requirement to receive it. The frequency itself records a decision outside meteorology: NOAA explains that the GOES-R design moved the center frequency "to minimize the impact on commercial licensees due to the auctioned shared spectrum above 1695 MHz in 2015". The neighbor of a weather broadcast is now a commercial licensee, a matter for the fourth book of this series, *Who Owns the Sky*.

The HRIT/EMWIN service is a one way data broadcast that anyone in view may receive, and its Link Ledger fits it the way chapter 1 describes for a broadcast. Its page 1 follows; the source of every number on it is listed for this chapter in Appendix E. It has no page 2: the frequency, rate, modulation and minimum dish are published, but the satellite's transmitted power and the required signal quality for its coding were not in the pages read, and a budget without them would be invented. NOAA's page points to its GOES-R series technical documents, where a receiver builder would look for those values; they were not read for this book. The ledger is a requirement for a later bench step (a dish of 1.0 m or more, a low noise amplifier and a software radio for 1694.1 MHz), not a claim that the broadcast has been received: no reception of it by the author exists.

LINK LEDGER · LL-2016-03 · SERVICE LEDGER

2016 (series first launch); checked 2026-11-23

System: GOES-R series HRIT/EMWIN direct broadcast to a small dish (GOES-19 East, GOES-18 West)

In service | Class: service only

1 Requirement	Let any receiver in the footprint take warnings, charts, GOES and Himawari images and relayed data collection messages, with no registration, fee or license from NOAA, on a dish of 1.0 m at 10 degrees elevation or more (1.2 m at 5 degrees).
2 Ends and path	NOAA's broadcast stream, formed at Suitland, at one end; at the other, any receiver: dish, low noise amplifier, software radio and computer, bought or built by the user. **Path:** Transparent relay: uplinked from Wallops (backup site: Fairmont) and rebroadcast by dedicated transponders on the operational satellites. One way to the user.
3 Orbit and time	Geostationary: GOES-19 at 75.2 degrees west (GOES-East since 7 April 2025), GOES-18 at 137.0 degrees west (GOES-West since 4 January 2023). **Time:** About a quarter second, uplink to receiver (calculated); the schedule sets refresh, not age (mesoscale image every 15 minutes).
4 Band and permission	**Satellite to user.** 1694.1 MHz, 1.205 MHz wide, BPSK, linear vertical; NOAA; frequency authorization not in the source read **Ground to satellite.** From Wallops or Fairmont; frequency not in the source read
5 Capacity	**Up.** None from the user; no user transmitter exists in this service. **Down.** 400 kbit/s at 927 ksymbol/s, shared among products by virtual channel and priority. One more receiver takes nothing from another; the 400 kbit/s stream sets how often each product repeats.
6 Who owns each end	**Space segment.** NOAA (GOES-R series, GOES-19 and GOES-18) **Ground segment.** NOAA NESDIS: stream formed at Suitland, uplinked from Wallops or Fairmont **Customer relationship.** None; equipment from commercial or community sources **The exit.** No contract; continuity is NOAA's decision, not stated as a term
7 Trust	Only NOAA forms and uplinks the stream and commands the satellites. The format is open; the sources read describe no authentication.
8 How it fails, and how we would see it	A satellite or ground anomaly stops or degrades products; a change of operational satellite changes the source; strong signals in nearby spectrum can interfere (NOAA's warning for its wider rebroadcast). **How we would see it:** At the receiver, as loss of lock or rising frame errors; at NOAA, as outage notices on its status pages.
9 Cost shape	No charge at the point of use. The user pays for dish, amplifier, radio and computer; NOAA's appropriations pay for the system. Amounts not in the sources read.
10 Evidence	1694.1 MHz, 1.205 MHz; 400 kbit/s, 927 ksymbol/s; BPSK; both dish sizes; no NOAA fee or license (operator claim) NOAA OSPO, HRIT/EMWIN, 2026-11-23 GOES-19 East, GOES-18 West (operator claim) NOAA OSPO, GOES status, 2026-11-23 About 0.24 s propagation (calculated) Appendix B, 2026-11-23

Service only, no hop budget: NOAA's pages read give frequency, rate, modulation, polarization and the minimum dish, not the satellite's EIRP or the required Eb/N0, so no budget is printed.

Polar satellites have direct broadcasts too, received by stations as the satellite passes overhead, and Europe disseminates its data also through commercial telecommunication satellites. The NOAA and EUMETSAT pages describing those services could not be read when this chapter was checked, so their frequencies and rates are not printed here.

Continuity: the spare in orbit

Operational weather services keep more satellites in orbit than they need on a given day, and their own documents say so. NOAA lists GOES-16 as the backup for GOES-East and GOES-West and keeps GOES-17 in storage as well. NOAA flies three afternoon polar satellites, with ranks of primary, secondary and tertiary. EUMETSAT still operates three satellites of its second geostationary generation while the third generation comes into service, and two first-generation Metop satellites while the second generation is commissioned. Whether a reserve exists is a fact to check per provider, from the provider's own pages, not to assume from these two.

For a buyer, continuity is a requirement like any other. A product built on one instrument's channels needs that instrument, or a successor with the same channels, for as long as the product is sold. The successor is rarely identical: EUMETSAT's third generation imager has 16 channels where its predecessor had 12, and the products change with it. A buyer of a weather data product should ask which satellites and instruments it rests on today, which replace them, and how the provider will tell users about the change.

A climate record asks more of continuity than a forecast does. A series that spans decades is built from several instruments, so the buyer of a climate product asks how each instrument was calibrated against the one before it, whether the whole series was reprocessed with one method and in which version, how it was checked against independent records, and with what uncertainty a trend can be stated. These are the same questions as for the optical time series of chapter 8, asked over a longer span.

THE SYSTEM'S FAILURE

EUMETSAT's newest imager reached users late. When the agency began disseminating pre-operational data from Meteosat-12's imager on 23 September 2024, its Director-General said that the instrument "experienced a serious anomaly during the commissioning phase of MTG-I1, which has delayed the release of the data longer than we had anticipated". The satellite had been launched in December 2022. The release did not describe the anomaly further, and neither does this book.

NOAA's own record shows a different path to the same kind of outcome. Its status page lists GOES-17's imager as operational with a limitation and records that GOES-18 replaced GOES-17 as GOES-West on 4 January 2023, less than five years after GOES-17's launch on 1 March 2018. The nature of the limitation was not in the pages read. In both cases what failed was an instrument, and what the operator did was to say so in public and to rely on other satellites while it lasted. Two narrow points follow from the operators' own records: a new instrument's start date is a plan until its data are released, and an operator's status page is where a buyer learns that an instrument is limited.

SECURITY NOTE

As in chapter 7, with three additions. **Who can interfere or command.** Only the operator commands the satellites and forms the broadcast streams. Anyone with a transmitter near a receive site can interfere with its reception, and NOAA itself warns that strong terrestrial signals in nearby spectrum can exceed the margin of its sizing. **How it is seen.** As loss of lock or rising frame errors at the receiver; an operator's outage notice covers its own faults, not interference local to one site. The sources read do not describe any authentication of the broadcast, so a receiver relying on them has no documented way to prove the origin of what it decodes. **How it is recovered.** Weather data are exchanged between states under the World Meteorological Organization's arrangements, so a product lost on one path can often be taken from another, over the internet or another satellite, where the buyer has arranged that path in advance; and the operators' spare satellites can take over the broadcast itself, after a move and a transition that are not instantaneous.

Monday rule: decide whether you need observations, products, analyses or forecasts before you choose a satellite.

CHAPTER ELEVEN

Other Sensors a Buyer Meets: Listening, Microwave, Altimetry and Gases



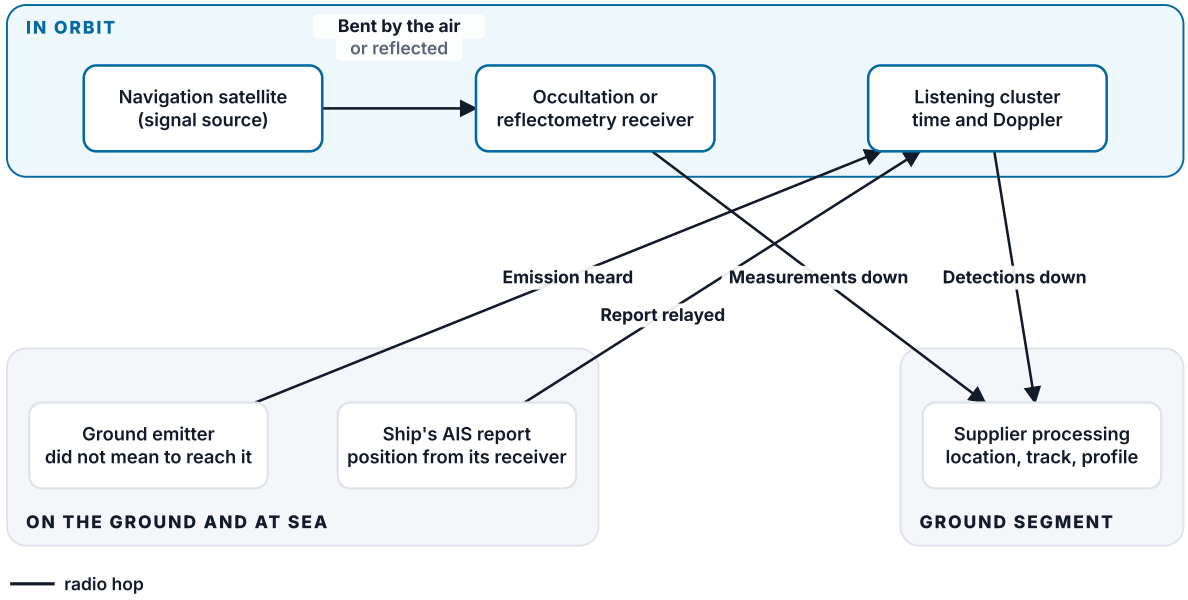
On 25 June 2019 six small satellites of the COSMIC-2 mission were launched for the United States and Taiwan. They carry no camera and no radar. They listen to navigation satellites near the horizon and measure how much the atmosphere bends their signals, more than 4,000 times a day (UCAR). Cameras and radars are the sensors most buyers know. This chapter is about the others a buyer meets: satellites that listen to radio emissions, that measure the Earth's own microwave glow, its height, or the gases above it. For each the question is the same: what is the observable, and how does the system reach a number?

Three listening chains, kept apart

Three different services are all described as satellites that "listen", and a buyer should not mix them up. Each has a different source of signal, a different product and a different weakness. Figure 11.1 sets them side by side.

FIGURE 11.1

Three ways a satellite listens, and what each product depends on



An emitter locator estimates where a transmitter was; a broadcast receiver relays what a ship says about itself; radio occultation and reflectometry use navigation signals to measure the atmosphere or the surface.

Author's diagram based on UCAR (radio occultation), ITU-R M.1371-6 (AIS), SES patent US 9,086,471 and Clements and others, arXiv 2503.17791, preprint, not peer reviewed (emitter location).

Locating emitters that did not mean to reach a satellite. A radio transmitter on the ground, a ship's radar, a handheld radio or a jammer, sends part of its energy upward. Whether a receiver in low orbit hears it depends on the antenna's pattern and pointing, the power, the frequency and the receiver; some emissions reach orbit strongly enough, others do not. Several receivers flying close together can compare the times and the Doppler shifts at which the same emission arrives, and so estimate where it came from; the technique, time and frequency difference of arrival, is described in operators' patents, for example one filed by SES for locating sources of interference (US 9,086,471). A single satellite can also do it from the change of Doppler over one pass: a team from the University of Texas at Austin and Spire Global reports locating a test transmitter that broadcast spoofed navigation signals from a known site, using one receiver in low orbit (Clements and others, arXiv 2503.17791, preprint, not peer reviewed). What such a service sells is an estimated location and a description of the signal, not the content of the transmission. The listening satellites have an ordinary tasking link and payload downlink, but the path from an emitter that never meant to reach them is not a communication service, so this book prints no Link Ledger for it

(chapter 1). HawkEye 360, which trades on the New York Stock Exchange, reported third quarter 2026 revenue of $59.3 million and launched its clusters 15 and 16 in October 2026, the first it built to collect and send down mission data at the same time (HawkEye 360, operator release).

The estimate has an uncertainty, and its shape matters. A location derived from a few passes of a few receivers is usually stretched along one direction. A buyer asks which signals are monitored and how likely an emitter of stated power and duration is to be detected, with false alarms; then for the stated error ellipse at a stated confidence for each detection, the time of the emission and how many satellites heard it. None of those were published in the sources read for this book, so none is quoted.

Receiving broadcasts that were meant for everyone. Ships report their identity, position, course and speed by radio under the Automatic Identification System (AIS), whose technical characteristics are set by ITU-R Recommendation M.1371 (version 6, approved February 2026; ITU). The broadcasts are meant for nearby ships and shore stations, but a receiver in orbit can collect them over open ocean, where no shore station hears. Here the satellite does not estimate the position: the ship reports it, from its own navigation receiver. The supplier market changes owners. Spire, which built a satellite AIS business, sold its maritime business to Kpler on 25 April 2025 (Spire Global, release of that date), so a buyer of ship tracks in 2026 may be buying from a different company than in 2024.

Sounding the atmosphere with someone else's signal. Radio occultation measures the atmosphere itself. A receiver in low orbit tracks a navigation satellite as it sets or rises behind the Earth's limb. On the way, in UCAR's description, "molecules and electrons bend their paths and slow their progress", and the receiver measures "their bending and signal delay" (UCAR, GNSS radio occultation). From the bending, the processor derives the refractivity of the air, and from that, with further assumptions or other data where the air is moist, profiles of temperature and humidity; the two navigation frequencies bend by slightly different angles, which lets the processing remove most of the ionosphere's effect (Spire Global, US Patent 10,379,260). COSMIC-2's six satellites, launched on 25 June 2019 by a partnership led by NOAA and the US Air Force with Taiwan's National Space Organization and UCAR, track "more than 4,000 high-quality profiles per day" (UCAR). Commercial operators sell occultation profiles too; Spire's satellites carry the payload (Spire Global releases, 2026). Weather centers assimilate these profiles into forecasts (Chapter 10).

All three measure radio signals; they differ in what the product depends on. The first infers where a transmitter was from arrival times and frequencies; the second relays what a ship said about itself; the third turns the signals into a property of the atmosphere or the surface. That difference decides how each can be wrong, which is the subject of this chapter's failure box.

Reflections of navigation signals

Navigation signals also reach a satellite after bouncing off the surface. A receiver compares the reflected signal, taken by an antenna looking down, with the direct one, taken by an antenna looking up, and the shape and strength of the reflection carry information about the surface: rough seas spread it, calm water and wet soil make it strong. This is GNSS reflectometry. Its attraction is cost: the transmitters already exist, so the satellite carries only a receiver. Its products include ocean surface winds, soil moisture and the extent of flooding. NASA's CYGNSS mission is the reference case for ocean winds in storms; its pages could not be read for this book on 23 November 2026, so its dates and figures are not given here. A buyer of a reflectometry product asks the questions of Chapter 7: what is the observable, at what resolution and revisit, and how was it validated against independent measurements.

The Earth's own microwave glow, and the wind on the sea

Everything warm emits microwaves. A **passive microwave radiometer** measures that emission, as a brightness temperature, at chosen frequencies. At low microwave frequencies the emission depends strongly on the water in the top layer of soil; at other frequencies it responds to sea ice, rain and water vapor. A radiometer needs a large antenna for modest resolution, because the wavelength is long. NASA's SMAP mission, launched on 31 January 2015, carried "a radar, a radiometer and the largest rotating mesh antenna ever deployed in space" (NASA JPL, SMAP). Its radar stopped working in July 2015, which the mission site reports only through news headlines, so no further detail is given here. ESA's soil moisture mission, SMOS, could not be read on the date checked.

A **scatterometer** is a radar that does not form an image. It measures how strongly the sea returns its pulses from several directions; small wind-driven waves set that return, so the measurement gives the wind speed and direction at the surface over the open ocean. EUMETSAT, the European weather satellite agency, publishes a page on its scatterometer, ASCAT; it could not be read on 23 November 2026, so no figures are given.

In both cases the product is a geophysical quantity retrieved by a model from the raw measurement. The buyer asks for the retrieval's version and its validation, and treats a change of version as a change of product.

Height: altimetry by radar and by laser

An **altimeter** measures the time a pulse takes to reach the surface below and return. With the satellite's orbit known precisely (often from its own navigation receiver), and the time corrected for the atmosphere and for the shape of the returned echo, the time becomes a surface height: of the sea, of an ice sheet, of a lake. Radar altimeters see through cloud; laser altimeters resolve finer spots but need a clear path. The SWOT mission, launched on 16

December 2022 and developed by NASA and CNES with contributions from the Canadian and United Kingdom space agencies, extends the measurement from a line to a swath with an interferometric radar, as its mission pages call it; its stated aim is "the first global survey of Earth's surface water" and to "observe the fine details of the ocean's surface topography" (NASA JPL, SWOT). The reference series of radar altimeters (Sentinel-6 in 2026) and the laser altimeter ICESat-2 were sought and could not be read (Appendix D). For a buyer, altimetry is mostly bought as a product from a public program: sea level series, lake and river heights, ice elevation change. The questions are the reference surface (which ellipsoid or geoid, as in Chapter 2), height or anomaly against a mean, the corrections applied (atmosphere, tides, sea state, echo shape) and their version, the along-track spacing and the repeat, and how the series is kept consistent when one satellite replaces another.

Gases: what is in the air above a place

Spectrometers that look down at sunlight reflected through the atmosphere can measure gases by the wavelengths those gases absorb. The public reference is TROPOMI, launched in October 2017 aboard the Copernicus Sentinel-5 Precursor. Its team states that it "monitors trace gases and aerosols relevant for air quality and climate", measuring across ultraviolet, visible, near infrared and shortwave infrared bands, at "3.5 x 5.5 km for most data products, and 7 x 5.5 km for shortwave infrared data products" (TROPOMI team, tropomi.eu). That resolution suits regional maps and large plumes. At that pixel size it does not image individual facilities.

Finer resolution is where commercial and philanthropic missions have moved. Planet, for example, agreed with Carbon Mapper and NASA's Jet Propulsion Laboratory to design a shortwave-infrared-only version of its Tanager satellite with a wider swath for gas detection (Planet, first quarter fiscal 2027 release). Several other greenhouse gas services exist; their status pages were not readable on the date checked, so none is listed as in service here. Each such service reports a gas column, an enhancement, a plume, a source or an emission rate (which also needs the wind), with an uncertainty that depends on wind, surface brightness, cloud and the retrieval model; a non-detection is not proof that nothing was emitted. The buyer's question is not "can it see methane" but "what is the detection limit, in the quantity supplied (as an emission rate only for a source-rate product), under which wind and surface conditions, and how often over my sites?"

One matrix for all of them

Figure 11.2 puts the sensors of this chapter in the columns that Chapter 7 uses for cameras and radars: the observable, the typical product, how its uncertainty is stated, how a user gets it, and example missions with their status as read. Where a primary page was not readable, the cell says so.

FIGURE 11.2

The other sensors in one buyer's matrix, as read in November 2026

Sensor	Observable	Typical product	Uncertainty stated as	Access	Examples, as read
Emitter locator	Arrival time and frequency of an emission (location is inferred)	Location and signal description per detection	Error ellipse at a confidence (ask; not published in sources read)	Commercial subscription or tasking	HawkEye 360: clusters 15 and 16 launched Oct 2026
AIS receiver	A ship's own report, decoded	Ship tracks	Accuracy and age of the ship's own fix, relayed; not measured by the supplier	Commercial data feeds	Spire sold its maritime business to Kpler, 25 Apr 2025
Radio occultation	Bending of navigation signals	Temperature and humidity profiles	Retrieval error per profile	Public and commercial	COSMIC-2: six satellites, 25 Jun 2019, over 4,000 profiles a day
Reflectometry	Reflected navigation signals	Ocean wind, soil moisture, flood extent	Error statistics against independent data	Mostly public programs	CYGNSS: not readable 2026-11-23
Microwave radiometer	Microwave emission (brightness temperature)	Soil moisture, sea ice, rain	Retrieval error, coarse footprint	Public programs	SMAP: launched 31 Jan 2015; SMOS not readable
Scatterometer	Radar return from the sea surface	Ocean wind speed and direction	Retrieval error	Public programs	ASCAT: not readable 2026-11-23

Sensor	Observable	Typical product	Uncertainty stated as	Access	Examples, as read
Altimeter	Time of flight to the surface; across a swath, interfero-metric phase too	Sea, lake, ice heights	Height error against a stated refer-ence surface	Public programs	SWOT: launched 16 Dec 2022
Gas spec-trometer	Absorption of reflected sunlight	Gas columns, plumes, emission rates	Uncertainty of the column or rate; detec-tion limit by wind and surface, sep-arately	Public; commer-cial emerging	TROPOMI: Oct 2017, 3.5 × 5.5 km for most products

Most products are retrievals or estimates, and AIS tracks are relayed reports, so the version, the stated uncertainty and an independent check belong in the order.

Source: HawkEye 360 Q3 2026 release; Spire Global release of 2025-04-25; UCAR, COSMIC-2; NASA JPL, SMAP and SWOT; TROPOMI team, tropomi.eu. Not readable on 2026-11-23: CYGNSS (University of Michigan), SMOS (ESA), ASCAT (EUMETSAT).

Two habits carry across the whole matrix. First, most of these products are retrievals or estimates: a model turns a raw measurement into the quantity the buyer wants, so the model's version is part of the product. An AIS track is the exception: it is a relayed report, and the supplier's processing (decoding, filtering, building tracks) is what to ask about. Second, each has a natural partner that can check it: a radar or optical image for an emitter location or a ship track, a surface station or a weather balloon for an occultation profile, a tide gauge for an altimeter.

THE SYSTEM'S FAILURE

False positions in honest reports. An AIS report carries the position that the ship's own navigation receiver computed. If that receiver is spoofed, the ship can broadcast a plausible wrong position in good faith; if it is jammed, the report may carry no position, a stale one or a wrong one, depending on the equipment. A satellite that decodes the report relays what was sent; the share of reports received was not stated in the sources read. A 2025 paper by authors from the University of Texas at Austin, Spire Global and Virginia Tech notes that "anomalous positioning information broadcast by ships in Automatic Identification System (AIS) messages, and airplanes in Automatic Dependent Surveillance-Broadcast (ADS-B) messages, indicate recent widespread jamming and spoofing", and that the ships and aircraft affected "are likely unintended targets" near conflict zones (Clements and others, arXiv 2503.17791, preprint, not peer reviewed). Reports can also be falsified on purpose; operators have patented methods for detecting false reports and vessels that stop reporting, for example by comparing reception at two satellite receivers (Spire Global, US Patent 11,156,723).

The failure is in the cooperative chain, not in the satellite: a report the satellite decodes carries what the ship sent. Kept to what the sources show, the conclusion is that a track built from someone else's transmissions is a report, not a measurement. It is evidence of what was transmitted; it becomes an independently checked position only when it is cross-checked: with a radar or optical image of the same place and time, or with an independent location of the transmitter.

SECURITY NOTE

Who can interfere or command. The operators task and command their own satellites, as in Chapter 7. Beyond that, anyone who transmits can shape what a listening service records: a deliberately false AIS report, a transmitter moved to mislead an emitter locator, a jammer that corrupts the navigation fix a ship reports. Authentication of AIS reports was not described in the sources read, and a buyer should not assume it. The downlinks of listening satellites are exposed like any other (Chapter 12). **How it is seen.** A reported position that disagrees with an image or with physics (a ship moving faster than it can, a track over land); an emitter location whose error ellipse is large or that only one pass supports. **How it is recovered.** Cross-checking with another sensor type, another supplier or the archive, and treating unconfirmed locations as leads.

Monday rule: treat a location derived from someone else's transmission as a lead to check: for an emitter location ask for its error ellipse and the time it was heard, and for a relayed report its age and validity.

CHAPTER TWELVE

From Photon to Product: Tasking, Downlink, Processing, Delivery, Acceptance



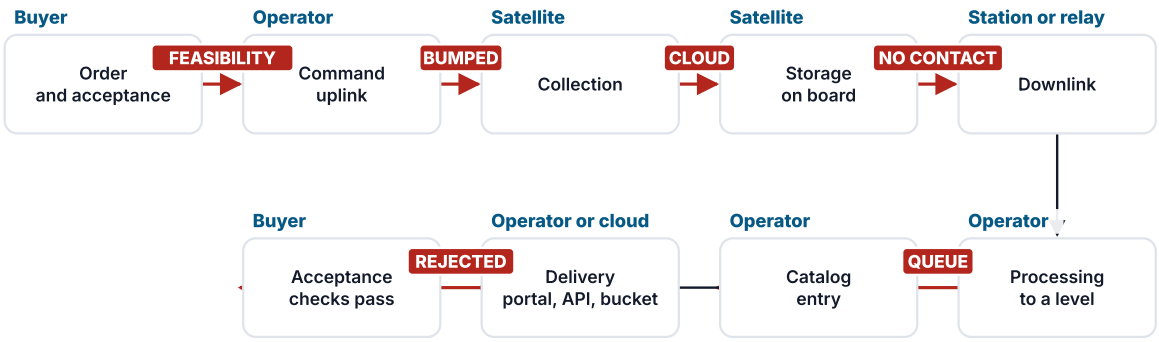
On 15 February 2022 the US Geological Survey made Landsat 9's Collection 2 products available in the commercial cloud, and today it states that a Landsat 9 scene reaches users as a Level-1 product 4 to 6 hours after the satellite records it (USGS). For a buyer that number matters more than any figure about the satellite, and it is only one of several clocks. This chapter follows the data from request to accepted file, asking at each step where the time goes and who owns it.

The chain

A product from an imaging satellite in low orbit passes through the same stages when it is collected, whoever operates them: an order and its acceptance, a command uplink, the collection itself, storage on board, a downlink, processing, a catalog entry, delivery and, last, the buyer's own acceptance. An open program that images on a fixed plan has no buyer's order: its commands come from the operator's own plan, and collection, storage and downlink run as for any satellite. A commercial tasking order runs every stage on the buyer's request. An archive purchase buys a product that already passed through them; its own clock runs from search to acceptance. A direct broadcast weather product reaches the user without a catalog or delivery portal, because the user's own station receives and processes it; the geostationary rebroadcast of Chapter 10 is assembled and queued on the ground first. Figure 12.1 shows the chain with the party that usually owns each stage.

FIGURE 12.1

From photon to accepted product: nine stages, several owners



Red chips mark where a collection can be delayed or lost; the line under each stage names its usual owner.

An open program on a fixed plan has no buyer's order and commands from its own plan; a tasking order runs every stage on request, and each stage can lose time or the collection itself.

Author's diagram based on the operator documents of Capella Space, Umbra and ICEYE, and USGS Landsat pages (Appendix E).

Each stage has its own failure modes and delays, and its own owner: the buyer, the supplier, a rented ground network or a cloud provider. A service level on one stage does not cover the others. A buyer who asks "how long does it take?" gets an answer for whichever stage the supplier measures.

Tasking: what an accepted order actually promises

A **tasking order** asks an operator to collect a new image of a place within a time window. Before accepting it, the operator checks feasibility: whether a satellite will pass within the window at a usable geometry, and what competes for that pass. The published scheduler rules show what the buyer is buying.

- **Scheduling cycles.** Capella states that its scheduler "runs every 15 minutes" over "a rolling one-week-out scheduling window" (Capella Space support, June 2025). Umbra's scheduler places submitted tasks "in batches every 10 minutes", and Umbra says it is "generally safe to submit Tasks up to three hours before the desired collection time" (Umbra documentation, September 2025).
- **Priority tiers.** Capella's "Urgent tasks are considered for scheduling first"; its Standard tier "provides assured data collection upon acceptance"; its Flexible tier "does not come with No Bumping assurance", which means another order can displace it (Capella Space

support). ICEYE states no such assurance; its background tasks "may be displaced" (read 2026-11-24).

- **Cancellation.** Both radar operators read for this book charge on a sliding scale. Capella: no charge more than 72 hours before the first collection, 25 percent between 12 and 72 hours, the full value under 12 hours. ICEYE, for constellation tasking orders: free more than 72 hours before the window starts, 10 percent from 72 to 48 hours, 20 percent from 48 to 24 hours and the full value under 24 hours (ICEYE product specification 6.0.8, 24 September 2026).

None of these documents says what happens when an accepted collection fails: when a higher priority order bumps it, when the satellite has a fault, or, for an optical order, when cloud covers the scene. Whether a missed window counts as a supplier failure, a retry or a refund is a contract term, and the buyer has to ask for it in writing. For an optical order, cloud is a common reason a scheduled collection does not produce a usable image, and an operator's cloud threshold, the fraction of cloud above which it retries, belongs in the order too.

Some published times are not about a customer's order at all. BlackSky reported that its fifth third-generation satellite "reached first light and revenue operations within 24 hours" (BlackSky, Form 8-K exhibit, 5 November 2026), without saying from which moment. That statement is about how fast a new satellite was commissioned. It says nothing about how long a customer waits for an image.

Downlink: contact minutes, stations and relays

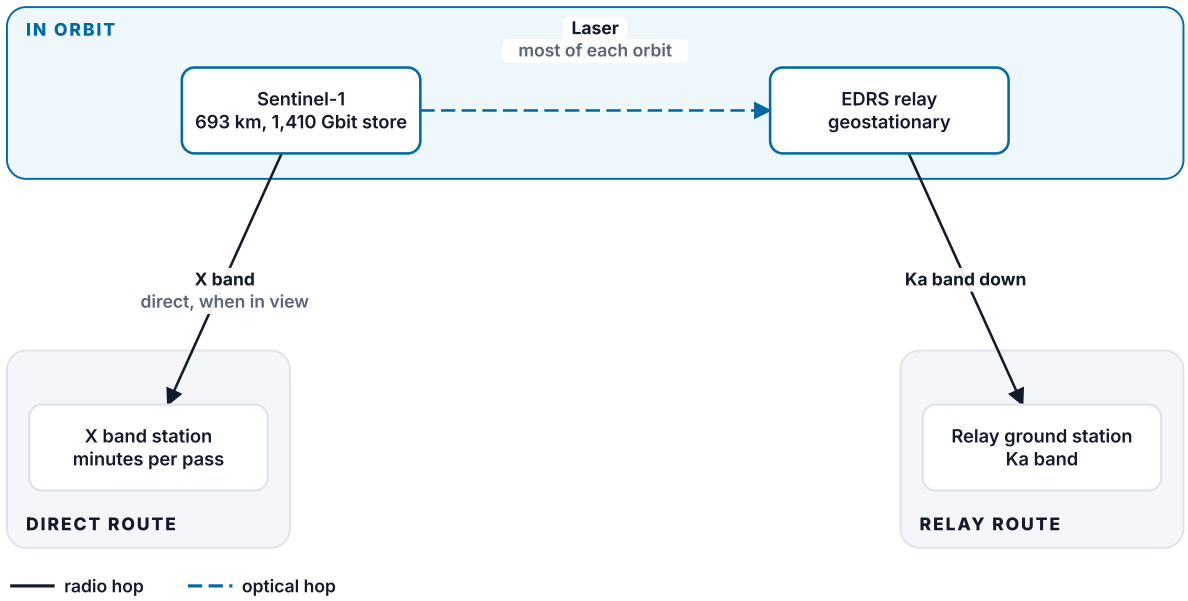
A satellite in low orbit can send data only when a ground station is in view, or a relay satellite is. At 705 km, Landsat 9's altitude, an overhead pass above 5 degrees of elevation lasts at most about 11.7 minutes in a model that ignores the Earth's rotation, and most passes are shorter (calculated, Appendix B). The satellite circles the Earth about 14.5 times a day (calculated from its 99-minute orbit). A station near a pole sees a polar-orbiting satellite on many of those orbits; a station near the equator sees it on few. That is why the Landsat Ground Network's five core stations include Svalbard in Norway and Gilmore Creek in Alaska, beside Sioux Falls, Alice Springs and Neustrelitz (USGS).

The volume to move sets the pressure. The Copernicus documentation gives Sentinel-1 1,410 Gbit of storage on board and 520 Mbit/s, as two channels of 260 Mbit/s, for payload data, and names both an X band downlink and an optical route through the European Data Relay System (Copernicus); the pages read do not settle which rate belongs to which route. As an illustration only: if the full 520 Mbit/s were available on one route, a full recorder would need about 45 minutes of contact to empty, while an overhead pass at Sentinel-1's 693 km lasts at most about 11.5 minutes above 5 degrees and so moves at most about 360 Gbit

(calculated). A full recorder needs four such passes or more. A program that collects continuously therefore needs many passes a day, many stations, a relay, or all three. Figure 12.2 shows the two routes.

FIGURE 12.2

Two ways down: a station in view, or a relay that is almost always in view



Sentinel-1 has an X band downlink to stations and, as documented for 2016 (status today not checked), an optical route through a relay in geostationary orbit; the relay trades about a quarter second of light time for far more minutes of contact.

Source: Copernicus SentiWiki, S1 Mission (read 2026-11-22); relay route as in the first book of this series (LL-2016-01).

The relay route is told in full in the first book of this series, *The Bit's Path*, which owns its service ledger; this book prints its page 1 for the buyer's question. A relay in geostationary orbit is in view of a low satellite for much of each orbit, so data can come down without waiting for a station; the price is the distance, about 270 ms of light time for the longest laser hop and a station directly below the relay, more for a station elsewhere, which is still small against hours of product time. Being in view is not the whole story: the relay's terminal must also be scheduled and must acquire the laser link.

Two ledger pages follow: the relay's page 1, then Landsat 9's own downlink, written as a service ledger for the same reason as the relay (the radio figures of the downlink were not read in a primary page on the book's date). Its field 1 is written from the buyer's side: the requirement is the product time, not a data rate.

LINK LEDGER · LL-2016-01 · SERVICE LEDGER

2016 (historical) System: Sentinel-1 to the EDRS-A relay by laser, then Ka band to the ground (historical)

Status on the book's date: not checked | Class: service only

1 Requirement	Bring radar imagery from a low orbit satellite down to the ground segment without waiting for a pass over a ground station.
2 Ends and path	Sentinel-1 (radar satellite, 693 km); the EDRS-A relay payload in geostationary orbit; a Ka band ground station. **Path:** Two hops through a relay: laser from low orbit up to geostationary orbit, then Ka band radio down to the ground.
3 Orbit and time	Sentinel-1 at 693 km; the relay at 35,786 km; the laser hop up to 45,000 km long. **Time:** About 270 ms one way for a 45,000 km laser hop plus the relay's path to a station directly below it (150.1 ms plus 119.4 ms, calculated, propagation only); a station off that point adds more.
4 Band and permission	**Sentinel-1 to EDRS-A.** Optical (laser): no radio frequency assignment; wavelength not read in a primary source **EDRS-A to the ground.** Ka band; frequencies and license not read
5 Capacity	**Up.** Laser terminal: 1.8 Gbit/s over up to 45,000 km with BPSK, the nominal capability as one study reports it second-hand (Vieira and others). **Down.** Ka band to the ground: rate not read in a primary source. The Copernicus documentation gives 520 Mbit/s for Sentinel-1 payload data and names both the X band route and the laser route; which rate belongs to which route was not settled. On-board storage: 1,410 Gbit.
6 Who owns each end	**Space segment.** Sentinel-1: the Copernicus program; EDRS: a European Space Agency program with an industrial operator **Ground segment.** Not read **Customer relationship.** Copernicus **The exit.** Not assessed: a public program; data access terms not read
7 Trust	Not published in the sources read. The laser beam is narrow, which limits interception from the side; it is not encryption.
8 How it fails, and how we would see it	The laser hop is above the weather; the Ka band hop to the ground is not. Acquisition must succeed before every session. **How we would see it:** Not published in the sources read.
9 Cost shape	Not published.
10 Evidence	1.8 Gbit/s up to 45,000 km operator claim Vieira and others, arXiv 2212.02030 (preprint), reporting it second-hand, 2026-11-23 Terminals on Alphasat (2013), Sentinel-1A (2014) published history Elser and others, arXiv 1510.04507 (preprint), 2026-11-23 693 km; 1,410 Gbit on board; 520 Mbit/s operator claim Copernicus SentiWiki, 2026-11-22 About 270 ms one way, longest laser hop plus nadir Ka calculated Distance over light speed; relay at 35,786 km, 2026-11-23

Service only, no hop budget: the laser terminal's transmit power, apertures and receiver sensitivity, and the Ka band hop's figures, were not read in a primary source or a peer-reviewed paper on the book's date.

Historical: status as of 2016, when EDRS-A entered service; its status on the book's date was not checked.

LINK LEDGER · LL-2021-01 · SERVICE LEDGER

2021 (launch); read 2026-11-23 System: Landsat 9 payload data in X band to the Landsat Ground Network

In service | Class: service only

1 Requirement	Bring Landsat 9's image data down fast enough for the stated product times: Level-1 in 4 to 6 hours after acquisition, Level-2 in about 3 days (USGS).
2 Ends and path	Landsat 9 at 705 km; the five core stations of the Landsat Ground Network; processing at the USGS EROS Center. **Path:** Direct to ground: raw image data received by X band at a station in view, then by ground network to processing.
3 Orbit and time	705 km, sun-synchronous, one orbit every 99 minutes, 16-day repeat, offset 8 days from Landsat 8. **Time:** Light time 2.4 to 8.6 ms; an overhead pass above 5 degrees lasts at most about 11.7 minutes (both calculated; Earth's rotation ignored). Light time is negligible against the 4 to 6 hours; which stage dominates was not published.
4 Band and permission	**Landsat 9 to ground stations.** X band; frequencies and licenses not read in a primary page
5 Capacity	**Up.** Command uplink not part of this ledger (not read). **Down.** Downlink rate not read in a primary page on the book's date. About 750 scenes a day (USGS wording; other official pages: "more than 700", "740"). About 14.5 orbits a day (calculated).
6 Who owns each end	**Space segment.** Landsat program of NASA and the US Geological Survey **Ground segment.** USGS EROS, Geoscience Australia, NOAA, German Aerospace Center, Kongsberg Satellite Services (five core stations) **Customer relationship.** USGS: download and commercial cloud access **The exit.** Downloaded copies stay with the user; use terms not read (Chapter 13)
7 Trust	Encryption or authentication of the downlink: not stated in the sources read.
8 How it fails, and how we would see it	A missed contact or a station outage delays data to the next station in view; how often was not published. **How we would see it:** Products later than the stated 4 to 6 hours; station logs were not found in the pages read.
9 Cost shape	No charge to download; public funding carries the system. The user pays storage, egress and processing (Chapter 13).
10 Evidence	705 km; 99 min; 16 days; 750 scenes a day; in service (operator claim) USGS, Landsat 9 page, 2026-11-23 Five core stations; X band (operator claim) USGS, Landsat Ground Network, 2026-11-23 Level-1 4 to 6 h; Level-2 about 3 days (operator claim) USGS, Collection 2 Level-2 page, 2026-11-23 2.4 to 8.6 ms; 11.7 min; 14.5 orbits (calculated) Appendix B, from 705 km and 99 min, 2026-11-23

Service only, no hop budget: the X band power, antenna gain, data rate, coding and the stations' G/T were not read in a primary page on the book's date.

Renting antenna time and relay capacity, and processing on board, change this stage; both are covered in depth later in this series. One operator detail shows the direction: HawkEye 360 describes its clusters 15 and 16, launched in October 2026, as the first it built to collect and send down mission data at the same time (HawkEye 360).

Processing: levels, tiers and versions

Raw downlinked data is not an image a buyer can use. Processing turns it into **levels**, and two public programs show how much the names alone leave out. The USGS organizes Landsat data into Collection 2, which "contains Level-1 data from Landsats 1-9, and Level-2 and Level-3 science products from Landsats 4-9" (USGS). Inside Level-1 it sorts scenes into tiers. "Tier 1" holds scenes "with the highest available data quality", which must register to each other within "12-meter radial root mean square error"; scenes that fail go to Tier 2. Landsat 8 scenes first appear in a Real-Time tier and are reprocessed into Tier 1 or Tier 2 later (USGS, Collection 2 Level-1). Level-2 adds surface reflectance and surface temperature, which correct for the atmosphere.

The same agency's pages give different times for what reads as the same step, and do not say whether they count from the same event. For the Landsat 8 move from Real-Time to Tier 1 or Tier 2, one USGS page says "after 3 to 10 days", another "approximately 4-11 days", a third "approximately 14-16 days". For Level-2, one says "within 24 hours" and another "typically available within 24-72 hours" (USGS, three pages read on 23 November 2026). For a buyer this is practical: a latency printed on a web page is an operator claim with a date, and an order should quote the one the supplier will be held to.

On top of the levels sit **analysis-ready data**: products processed to a minimum set of requirements so that users can compare them across dates without redoing the corrections. The USGS describes the Committee on Earth Observation Satellites (CEOS) scheme as recognizing data "processed to a minimum set of requirements" and offers its own Landsat analysis-ready data over the conterminous United States, Alaska and Hawaii (USGS). The CEOS pages themselves could not be read on the date checked. Analysis-ready data saves work; it does not answer the buyer's question, which still needs the analysis.

The European program's level names could not be read for this book. Schemes are compared by what each level does (calibrated, projected to a map, corrected for the atmosphere), not by its number.

Delivery: the interface is part of the product

A product reaches a buyer by download from a portal, through an application programming interface (API), pushed into the buyer's own cloud storage, or inside a platform where the analysis runs next to the data. Capella states that "all delivery of SAR imagery products is via

the Capella online platform consisting of the Capella Console web application and the Capella API" (Capella Space support, May 2025); Umbra delivers to its own platform by default and can send data to a customer's storage through a delivery configuration (Umbra documentation). USGS delivers Landsat Collection 2 as Cloud Optimized GeoTIFF files with SpatioTemporal Asset Catalog (STAC) metadata (USGS). STAC is an open specification for describing geospatial files so that software can search them; the Open Geospatial Consortium publishes web interface standards for the same purpose. Both are named here so that a buyer can ask for them; their own pages could not be read on the date checked.

Formats and interfaces end. ICEYE's product specification lists two legacy formats with "final availability on December 31, 2026" (ICEYE, specification 6.0.8). A pipeline that reads them has a date by which it must change. The same holds for an API version, a portal, a bucket layout or a platform, and the failure box below shows it at the scale of a whole service.

Latency on two clocks

"How fast" has two honest answers, and a buyer needs both. The **request clock** runs from the moment the buyer asks to the moment the buyer's software accepts a file. The **collection clock** runs from the moment the sensor records the scene to the same acceptance. An archive purchase has a short request clock (search, order, preparation, transfer and checks) and a collection that may be years old; the age of the acquisition is a separate number from the delivery time. A tasking order has both, and the gap between them, waiting for a feasible pass and for a clear sky, is often the largest part.

Each stage has a distribution, not a number. A satellite may need several attempts; a station may miss a pass; a processing queue may be long on a busy day. Stage percentiles cannot simply be added: the 90th percentile of the whole chain is not the sum of the stages' 90th percentiles. A supplier's end-to-end figure is only meaningful with the probability attached: "within 6 hours for 90 percent of accepted orders over the last quarter", for example, measured by whom; and it binds the supplier only if the order makes it a term.

Figure 12.3 works the two clocks for an open mission and for a commercial radar order, the latency case of this book. Every figure in it from an operator is an operator claim with its date, a stage no source covers says "not published", and the rows that set out the clocks are the author's. The optical side of the case could not be sourced: the tasking documents of the optical operators sought for this book were not readable on 23 November 2026, so the case is radar only, and Chapter 14 completes it as a requirement.

FIGURE 12.3

Latency on two clocks: an open mission and a commercial radar order, as the operators state them

Stage	Open mission: Landsat 9	Radar order: ICEYE	Radar order: Capella and Umbra
Order to acceptance	No tasking: imaged on a fixed plan; an archive request has its own short clock	Order by email or API; two order types (constellation, single satellite)	Umbra: feasibility and task submission "within a few minutes"
Scheduling	Not applicable	Not published	Capella: every 15 minutes, one-week window; Umbra: batches every 10 minutes, submit up to 3 hours before
Wait for a feasible collection	Set by the 16-day repeat and the acquisition plan; a clear view is a separate wait	Not published	Not published; Capella tiers: Urgent first, Standard assured on acceptance, Flexible may be bumped
Failed or cloudy attempts	Not published in the pages read	Not published (radar: cloud not the limit)	Not published
Collection to delivery	Level-1 in 4 to 6 hours; Level-2 in about 3 days	"1 hour or less after acquisition"; options 1, 3, 8 h; 24 h at background priority. Marketing page counts from downlink	Umbra: "generally" 1 to 4 hours after the window ends. Capella: "93%" in under 3 hours (operator statistic; start, period and sample not stated)
Request to delivery	Archive request: not published	"Usually" within a few hours of the initial request (marketing page)	Not published
Cancellation	Not applicable	Constellation orders: free over 72 h before window; 10 percent at 72 to 48 h, 20 percent at 48 to 24 h, 100 percent under 24 h	Capella: free over 72 h; 25 percent 12 to 72 h; 100 percent under 12 h

Stage	Open mission: Landsat 9	Radar order: ICEYE	Radar order: Capella and Umbra
Acceptance by the buyer	Buyer's checks (Figure 12.4)	Buyer's checks	Buyer's checks

Every cell is an operator claim with its date or says that no source covers it; the stages are not added, because each has its own distribution.

Source: USGS Landsat 9 and Collection 2 pages (read 2026-11-23); ICEYE SAR product specification 6.0.8 (2026-09-24) and ICEYE tasking page (read 2026-11-23); Capella Space support articles (2025-05 to 2025-06) and home page; Umbra documentation (2025-09). Optical operators' tasking pages were not readable on 2026-11-23.

Three things stand out. First, the operators state delivery from different starting points: ICEYE's specification counts "1 hour or less after acquisition time", while its marketing page counts "of the data being downlinked", and Umbra counts from the end of the collection window. Second, the stage a buyer cannot see, the wait for a feasible collection, is the one no source quantifies. Third, the open mission has no tasking clock, because its satellite images on a fixed plan; for a place it covers, the wait for an acquisition is set by the repeat cycle and the acquisition plan, and the wait for a clear acquisition is a separate interval that depends on cloud. A user who requests an existing product still has a short request clock. Which stage dominates differs by case: the archive purchase is quick but old, the relay shortens the downlink, and a contested tasking window can take days. No general claim holds across them.

Acceptance and provenance

A file that arrives is not yet a product the buyer accepts. Acceptance is the buyer's last stage, and the checks belong in the order before the first delivery. Figure 12.4 lists them: units and scaling, the nodata value and quality masks, uncertainty, calibration consistency with earlier deliveries, completeness over the area, the product version and any reprocessing, the coordinate system and the elevation model used for projection, and for interferometry the four items of Chapter 9.

FIGURE 12.4

Acceptance: what to check in every delivery, and how

Check	What to ask for	How to test it
Units and scaling	Physical unit per band; scale factor and offset	Convert a sample; compare with a known target or an earlier delivery
Nodata and masks	Nodata value; cloud, shadow and quality masks with their meaning	Count usable pixels over the ordered area; reject if the usable fraction is below the agreed minimum
Uncertainty	Stated uncertainty per product or per pixel	Compare with independent data on a validation sample
Calibration	Calibration version; consistency with earlier deliveries	Stable targets, at matched sun and view angles, should not move beyond their stated uncertainty
Geolocation	Absolute accuracy, its statistic and conditions; relative registration between scenes is a separate figure (Landsat Tier 1: within 12 m radial RMSE)	Check points from an independent survey of known accuracy, in the same frame
Completeness	Area covered, acquisition time, all ordered bands	Footprint against the ordered area
Version and lineage	Product version, processing baseline, reprocessing policy	Record the version; treat a version change as a new product
Coordinates and terrain	Coordinate system, datum, and the elevation model used	Read the metadata; reproject a sample
Interferometry only	Coherence, reference point, dates, line-of-sight direction	Mask low coherence; check the reference is stable
Origin and integrity	Checksums; signatures where offered	Verify on receipt; a signature shows origin, not truth

Written into the order before the first delivery, these checks turn a file that arrived into a product that was accepted.

Author's checklist; geolocation example from USGS, Landsat Collection 2 Level-1 data page (read 2026-11-23).

Provenance is the record of where a product came from. Metadata asserts when, where and how a scene was collected and processed. Where a supplier signs its deliveries, a valid signature shows that the file came from the holder of the signing key and was not changed since; it does not show that every fact in the metadata is true. The lineage of data products as a discipline is covered by *Every Record Counts*.

THE SYSTEM'S FAILURE

A ground service that was retired, 2024. Microsoft announced on 3 October 2024 the retirement of Azure Orbital Ground Station, its service for downlinking data from customers' satellites into its cloud. Access for public spacecraft ended on 28 October 2024 and for private spacecraft on 18 December 2024, and the notice named no direct replacement, pointing customers to partner networks (Microsoft retirement notice, as archived; Microsoft Learn redirect, observed 22 November 2026). The product address now leads to Microsoft's Planetary Computer, a data platform.

The source shows a service ending on stated dates: 25 days after the notice for public spacecraft and 76 days after it for private spacecraft (calculated from the notice's dates). It does not show what each customer did. The conclusion stays at that level: the stages between a satellite and a file are services, each with an owner and a lifetime, and an order should name what happens when one of them ends.

SECURITY NOTE

Who can interfere or command. Who may task, and who may see an order, matters: a tasking request reveals an interest in a place and a time. Delivery endpoints and API keys are ordinary targets for attack and need ordinary protection. Failure domains span the radio links, the spacecraft, the ground stations, processing and delivery, and are assessed case by case, not assumed independent. **How it is seen.** Missing or late deliveries against the stated clock; files whose metadata or checksums do not match; a signature that fails where a supplier signs. **How it is recovered.** A second delivery route, a local archive of accepted products, and a second supplier for collections that cannot wait.

Monday rule: measure latency from your request to a file your software accepts, and write that number and its probability into the order.

CHAPTER THIRTEEN

Open Programs and Commercial Suppliers: Licenses, Prices, Platforms and Rules



In May 2026 Capella Space issued version 2.1 of the license agreement that governs its radar data. Section 19 says that when the agreement terminates, the customer "shall delete or destroy all Products, Derivatives and Documentation" and certify the deletion in writing within 30 days (Capella License Agreement, version 2.1, May 2026). The same agreement says that products are "licensed and not sold" (section 11). A team that builds a monitoring service on those images has bought the right to use them for a term, under conditions, and not the images themselves. This chapter reads the terms before the specification: what an open program and a commercial supplier let a buyer do, what an answer costs in total, and who can switch the supply off.

Open programs: free, full and open, and what that leaves out

Two public programs set the floor that every commercial offer is compared against. The US Geological Survey states that "in 2008, the Landsat products stored in the USGS EROS archive became available for download at no cost to users"; a user registers for a free account to search and order (USGS, Landsat Data Access). That page speaks of cost; the terms of use for Landsat data were not read for this book, and payment and permission are separate questions. The archive holds Level-1 data from Landsat 1 to 9, and Chapter 12 gives the product levels and delivery times.

The European program states its terms in a legal notice from the European Commission. It says that EU law gives users "a free, full and open access to Copernicus Sentinel Data and Service Information without any express or implied warranty, including as regards quality and suitability for any purpose." The lawful uses it names are reproduction, distribution, communication to the public, and "adaptation, modification and combination with other data and information." The notice cites Regulation (EU) No 377/2014 and Commission Delegated Regulation (EU) No 1159/2013 as the law behind it; the regulations, and any later ones that replaced them, could not be read for this book on 24 November 2026, so the

notice's own words are used here as the terms it states, not as the current legal framework in full (European Commission, Legal notice on the use of Copernicus Sentinel Data and Service Information).

"Open" is not "without conditions." Where a user communicates the data to the public or distributes it, the same notice requires a credit line, "Copernicus Sentinel data [Year]", or "Contains modified Copernicus Sentinel data [Year]" for adapted data. It allows "specific limitations of access and use in the rare cases of security concerns, protection of third party rights or risk of service disruption." And a user "renounces to any claims for damages against the European Union and the providers." Weather data have their own open regime under the World Meteorological Organization, covered in Chapter 10.

Three things the access pages and legal notice read here do not promise: a delivery time (Chapter 12 shows the agency's own pages giving different latencies for the same step), fitness for a purpose (the Copernicus notice disclaims it in so many words), and continuity beyond the missions that are funded. Landsat's successor is presented by the USGS as Landsat 10, expected to launch in 2031 (Chapter 7). A plan that depends on an open program depends on funding decisions made by others.

A commercial license, read clause by clause

A commercial supplier sells pixels, a subscription, or a platform where the analysis runs next to the data, and each comes with a license. Of the suppliers whose pages were read for this book, Capella published its full license, so it serves here as a worked reading, not as a judgment of Capella against others. Its legal page lists the licenses on offer: a single-organization end user license, two United States Government licenses that the page says are issued by the National Reconnaissance Office, a Public Release license, and an open data collection under Creative Commons Attribution 4.0 (Capella, Legal and Compliance Information, read 23 November 2026). The license decides who may see the data.

The consolidated agreement, version 2.1, May 2026, is the standard license read here; the government and public release licenses are separate documents, and the open data collection carries its Creative Commons license instead. The grant is "non-exclusive, non-transferable, non-sublicensable, limited, and terminable": others may license the same data, the customer may not pass the license on, and it can be ended. Under it the customer may:

- use, reproduce and store the data "during the Term solely for Customer's Internal Use", where internal use means "solely for the Customer's internal business or organizational purposes";
- process the data and create derivatives, again during the Term and for internal use only;

- "use Data to train Models that Customer uses to provide services or deliverables to Third Parties";
- use a platform named in the order during its subscription term, which is one year unless the order says otherwise.

The restrictions follow. Without another grant, the customer may not "distribute, sublicense, transfer, assign, rent, sell, lease, loan, make publicly available, publish" the products or their derivatives, and may not "scrape or download Data in bulk" beyond what the documentation and the order allow. Sharing with affiliates is an option with its own fee. Fees are "non-cancelable" and "non-refundable", and taxes are extra (sections 1, 2, 4, 8 and 9).

What a buyer learns from one reading: a map published on a website, a figure in a report to a regulator and a product sold to a client are three different rights, and the internal-use tier grants none of them. A model trained on the data may serve third parties under this agreement; the images and their derivatives may not be handed over. The agreement defines a derivative broadly, including "any addition or extraction of data, information, or other content to or from the Product", and a model as one that does not contain the data "in its original, raw, extractable form or enable reconstruction of the Data". Where a model's output ends and a derivative begins is not settled by those words, so a buyer who plans to deliver model outputs to clients asks the supplier in writing. The warranty is narrow: the products, "as delivered, will substantially comply in all material respects with the applicable Documentation", and a claim must be made within 30 days of the first delivery, with repair, replacement or a refund as the remedy, and the warranty is void if a defect results from "accident, abuse, misuse, misapplication, or modification" by anyone other than Capella (section 16). A defect found later may fall outside that remedy, so the acceptance checks of Chapter 12 belong inside the window.

A platform adds a layer to the same question. The agreement read lets the customer use a platform only "during the Subscription Term" and forbids creating derivatives of the platform itself; what happens to the scripts, layers and settings a buyer builds inside it, who owns them and whether they can be exported, is not settled by the clauses quoted, and belongs in the order. Platforms that fuse several suppliers' data add a further layer: content from third parties, the same agreement says, comes under the third party's own terms and "may be withdrawn at any time" (section 5). A buyer of a platform therefore reads two or more licenses, not one.

Price shapes, and what a price leaves out

Commercial imagery is priced in a few shapes: per square kilometer with a minimum area, per scene, by subscription to an area or a platform, and by reserved capacity on a fleet. None of the operators whose pages were read for this book published a price list. A reseller that

does is Apollo Mapping, whose list states that its satellite and radar prices were "modified last on July 8, 2025" and asks buyers to verify them with its sales team (Apollo Mapping price list, read 24 November 2026; reseller prices, operator claim). Read as shapes, not as a quote:

- **Per area, with a minimum.** 30 cm natural color (the list's product name) from the WorldView fleet: $22.50 per square kilometer from the archive with a 25 square kilometer minimum; standard tasking $32.50 with a 50 square kilometer minimum; rush tasking $100 with the same minimum. The smallest order is therefore $562.50 from the archive, $1,625 tasked and $5,000 rushed (calculated). The same list adds a $30 per square kilometer "high demand" uplift for tasking one satellite family in listed countries.
- **Wider and cheaper.** PlanetScope 3 m multispectral from the archive: $2.25 per square kilometer with a 250 square kilometer minimum.
- **Per scene.** TerraSAR-X Staring SpotLight radar, "up to 25 cm" as the list puts it (a radar's resolution differs by direction, and the list gives one figure), on a scene of about 4 by 3.7 km: $3,062.50 for an archive scene older than one month, $6,125 for a newer archive scene or a tasked one.

Three things follow. The minimum area, not the price per square kilometer, sets the cost of a small site. Freshness is priced: the same radar scene costs twice as much in its first month. And a list price names a product and a resolution but not the license tier, the processing level beyond the one stated, delivery, taxes or the analysis. Every price printed in a plan needs its date, its source and what it leaves out, as above, or it should not be printed at all.

Reserved capacity is sold to governments, and the public record shows it only as dated contract news: Germany awarded Planet a dedicated-capacity tender worth up to 25 million euros over five years in August 2026 (Planet results release, quarter ended 31 July 2026); ICEYE states that seven European governments have procured sovereign systems (ICEYE, 7 July 2026); Satellogic reported about $37 million for three satellites sold in orbit (Satellogic results release, third quarter 2026). These are announcements by the companies, not service terms a reader can buy.

The total cost of an answer

A buyer pays for an answer, not for pixels. The data line is one of several, and not necessarily the largest. The other lines are the platform subscription, if the analysis runs on the supplier's platform; moving data out of a cloud, where the provider charges for it; storage of the archive the buyer must keep to compare dates; processing to the level the question needs; and the time of the analysts who turn a product into a decision, including the training to read radar (Chapter 9). Open data removes the data line; the others remain. Figure 13.1 sets the four kinds of supply side by side on the same rows.

FIGURE 13.1

Four kinds of supply on the same rows, as the terms read state them

Row	Open program (Landsat, Copernicus)	Commercial archive	Commercial tasking	Platform subscription
What is supplied	Collections on the program's own plan, at its levels	A scene already collected, at a stated age	A new collection in a window, if feasible	Data and tools in the supplier's environment
License, as read	Landsat: no cost since 2008 (use terms not read). Copernicus: free, full and open; credit line when shared; no warranty	Supplier license; in the one read, internal use during the term, tiers for public release and government	As archive; the order fixes tier and term	Use during the subscription term only (one year by default in the agreement read)
Price shape (dated example)	No charge for the data	Per km2 with a minimum, or per scene; a newer radar scene priced at twice an older one (reseller list, 2025-07-08)	Per km2 with a larger minimum; standard, priority and rush tiers	Subscription; not published in the terms read
Latency	Agency figures per step (Chapter 12); no commitment	Search, order, preparation and transfer; collection age is separate	Both clocks (Chapter 12); feasibility not guaranteed	As the data feeding it
Continuity	Funded missions; successor plans dated by the agency	The archive's coverage of your area	The supplier's fleet and owner	The supplier, its platform and its formats
Who can stop it	The program, for security, third party rights or service risk	Supplier; a government restricting collection or sales	As archive; plus a higher priority order	As archive; plus the end of the subscription

Row	Open program (Landsat, Copernicus)	Commercial archive	Commercial tasking	Platform subscription
What you keep at exit	Copernicus: reuse as the notice allows; Landsat: use terms not read	In the agreement read: rights end with the term; on termination, delete and certify within 30 days	As archive	Ask: ownership and export of what you build inside is not settled by the clauses read
Costs beyond the data	Storage, processing, analyst time	Same, plus license tier and taxes	Same, plus retries and cancellation fees	Same, plus egress where charged

Each cell is what the terms read say, or this book's reading of them where a clause is silent; the commercial license cells come from one supplier's published license (Capella, version 2.1, May 2026), and other suppliers' terms must be read separately.

Source: USGS Landsat Data Access (read 2026-11-23); European Commission, Legal notice on the use of Copernicus Sentinel Data and Service Information (read 2026-11-24); Capella License Agreement v2.1 (May 2026) and legal page (read 2026-11-23 and 24); Apollo Mapping price list, modified 2025-07-08 (read 2026-11-24); Chapter 12 for latency and cancellation.

The comparison is only meaningful against a requirement. An open program at 30 m may answer a question about fields and forests at no data cost, and it cannot show the detail of a single house, whatever the price. Chapter 14 starts from the requirement and only then compares supplies.

The market in late 2026: dated company statements

Suppliers change owner, name and policy, and a buyer's contract outlives some of those changes. The record shows several in the period this book covers, each from the company's own statement: Maxar Intelligence became Vantor (Vantor, blog post dated 2 October 2025); IonQ completed its acquisition of Capella Space on 15 July 2025 (Capella); Spire completed the sale of its maritime business to Kpler (Spire release dated 25 April 2025); and ICEYE's product specification retires two legacy formats with "final availability on December 31, 2026" (Chapter 12). These are the companies' own statements of events, not a trend, and this book draws no market-wide cause from them.

Fleet sizes change with every launch and retirement, and the operator statements read for this book often give satellites launched rather than satellites in service. Appendix D prints a count only with its date and who counted, and it lists the counts this book sought and could

not source. A buyer asks a supplier the question that matters instead: how many satellites can collect over my area in my window, as of which date.

Who can switch it off, and what you keep

Three kinds of party can stop a supply, and the terms read say so. The program or supplier: the Copernicus notice allows limitations for "security concerns, protection of third party rights or risk of service disruption." A government: Capella "may also immediately suspend or terminate this Agreement and associated license rights ... upon written notice if a government authority limits or restricts Capella from collecting and/or distributing such Products" (section 19), and its force majeure clause includes the "failure of a satellite, ground station, or communications network" and "a change in law or regulation (including export control regulations)" (section 24.4). The reseller's list names countries for which some satellites' imagery may not be sold and adds that "conflict zones ... can be added to this list at no notice." Under United States law, a person subject to US jurisdiction or control needs a license from the Secretary of Commerce to operate a private remote sensing space system (51 U.S.C. 60121 and 60122); national licensing and its conditions are covered in depth later in this series.

What a buyer keeps at the end differs as much. Copernicus data downloaded under the notice above stays usable, with the credit line; Landsat's use terms were not read for this book. Under the commercial agreement read here, the rights run "during the Term"; on termination the products and derivatives are deleted and the deletion certified. What the agreement requires when a term simply runs out is not spelled out in the clauses quoted beyond the end of the rights, and a buyer asks. The exit question belongs in the order before the first delivery: what may be kept, in which form, after the contract ends, and what a second supplier would need to continue the series. How such terms are drafted is a matter for contract counsel, outside this book.

> **OUR VIEW, AS OF NOVEMBER 2026**
>
> Of all the rows in Figure 13.1, the exit row separates open and commercial supply most sharply, and it is the row a buyer reads last. A monitoring program that compares this year with last year needs last year's data. If the license deletes it at the end of a term, the program needs either a perpetual archive right, written into the order, or an open source that covers the same question at a coarser level as its long record.

THE SYSTEM'S FAILURE

Landsat data, priced by policy, 1984 to 2008. The Land Remote-Sensing Commercialization Act of 1984 (Public Law 98-365, 17 July 1984) directed the Secretary of Commerce, through a competitive process and subject to appropriations, to contract with a United States private party "for the marketing of unenhanced data collected by the Landsat system", and required that the contract "provide that the contractor set the prices of unenhanced data", selling "to all potential buyers on a nondiscriminatory basis" (section 202).

Eight years later Congress recorded what it found. The Land Remote Sensing Policy Act of 1992 (Public Law 102-555, 28 October 1992) states that "the cost of Landsat data has impeded the use of such data for scientific purposes", that "full commercialization of the Landsat program cannot be achieved within the foreseeable future", and that "funding and organizational uncertainties over the past several years have placed its future in doubt." It directed that program management pass from Commerce to the Department of Defense and NASA, and required a Landsat 7 data policy that makes unenhanced data available "to all users at the cost of fulfilling user requests" (findings of Public Law 102-555, section 2, as printed with 51 U.S.C. 60101 in the 2023 edition of the Code; section 60113). In 2008 the USGS made its Landsat archive available for download at no cost (USGS).

The sources show a policy that failed by its own measure and was replaced; they give no price or usage figure, and none is printed here. What follows stays at their level: the license and price of Landsat data changed by decision, not by a change in what the satellites could do, and such terms can change again.

SECURITY NOTE

Who can interfere or command. The license is the authorization: it names who may use the data, and a platform login is its key (the agreement read makes the customer responsible for its credentials). The grant is non-exclusive, so other customers may be able to buy the same image of your site, subject to the supplier's own access rules; Umbra describes its archive catalog as "tens of thousands of SAR images", with new images added daily and searchable through a STAC interface by account holders (Umbra documentation, August 2026). A government can restrict a supplier's collection or sales, as the clauses above provide. **How it is seen.** A notice from the supplier, a refused order, or a delivery that stops. **How it is recovered.** A second supplier in another jurisdiction, written into the plan before it is needed, and the open programs as a floor wherever they meet the requirement.

Monday rule: read the license before the specification; it decides what you may build.

CHAPTER FOURTEEN

Writing the Requirement and Reading the Offer



On 29 January 2025 India launched its navigation satellite NVS-02. ISRO later reported that it remained in its transfer orbit because "the orbit raising operations from the elliptical to circular orbit could not be carried out" (ISRO, NVS-02 Spacecraft On-Orbit Observations; Chapter 3). A buyer who had read "launched" as "usable" would have planned on a satellite that, in the notice read, had not joined the service. This chapter turns the rest of the book into two sheets a buyer fills before talking to any supplier, works them for four cases, and shows how to read an offer against them, including what a supplier leaves blank.

The positioning and timing sheet, worked twice

Appendix A holds the blank sheet, twenty lines long. Two uses that share a receiver type need two sheets, because the lines that matter differ. The tables below show selected lines only, not complete sheets. The values in the requirement column are the buyer's choices for the example, not facts about any product; the column on the right names where the book sources what a provider commits to.

Case 1: a delivery fleet tracker. Vans report their position to a dispatch system every few seconds, in cities and on highways.

Line	Requirement written for the example	What stands behind it
1 Use and decision	Show each van on a map and estimate arrival times; a wrong position delays a dispatch decision, it does not endanger anyone	The buyer
2 Horizontal accuracy	10 m at 95 percent in suburban streets over a month; 30 m at 95 percent in dense city centers	The GPS standard specifies 8 m horizontal position accuracy at 95 percent as a global average, under its stated receiver assumptions and with no local obstructions (Chapter 2); it promises nothing for these streets, so the receiver and antenna must be tested there
6 Integrity	Not needed: the use is not safety related, and gross errors are screened by the route check in line 15 (a plausible wrong fix near the route is not caught, and the use tolerates that)	The buyer, stated with its reason
11 Update rate and age	One fix every 5 s; a fix older than 30 s is shown as stale	Receiver data sheet; network contract
12 Frame and time	WGS 84 as the map library uses it; UTC to the second	The map supplier's documentation
14 When absent	Last position with its age; dead reckoning from the vehicle's speed for at most 2 minutes	Device design
15 When wrong	A position more than 200 m off the planned route, or a jump faster than the van can drive, is flagged and not used for arrival times	Dispatch software
17 Threats	Jamming near some depots; detection of loss is required, detection of spoofing is not	Chapter 6

Line	Requirement written for the example	What stands behind it
20 Test	Drive the three worst routes with the chosen device and a reference receiver whose own error is known; a week of drives is a first check, and the monthly figure needs a sample sized for the confidence wanted, with fixes that are missing counted as failures	The buyer's test, before the order

The sheet does not prescribe integrity or a correction service, and it leaves the choice of frequencies to the route test: a device that passes line 20 is acceptable however many it uses. Lines the buyer waives are written "not needed", with the reason, so that the choice is visible to whoever revisits it.

Case 2: a timing site for a time-division radio cell. A base station that transmits and receives on the same frequency at different times needs its time aligned with its neighbors'.

Line	Requirement written for the example	What stands behind it
4 Time, phase, frequency	Time error at the radio within 1.5 microseconds of the common reference, the class the recommendation lists for time-division radio including NR TDD	ITU-T G.8271 (03/2020), Table 1, as cited in Chapter 5
5 Reported uncertainty	The receiver reports its estimated time error and its tracking state to the network management system	Receiver data sheet
12 Time scale	UTC; the receiver applies the broadcast offset from GPS time	The GPS commitment on the offset data, 30 ns at 95 percent (Chapter 5)
14 When absent	Hold the cell in specification for 8 hours on the local oscillator, then stop transmitting	Oscillator data sheet and the buyer's policy
15 When wrong	Compare against a second time source over the network, with its own uncertainty stated and its independence from satellite navigation shown; alarm on disagreement beyond a set threshold. A disagreement shows that one source is wrong, not which one, so the alarm leads to holdover	Chapter 5 and Chapter 6
16 Holdover	8 hours within the budget left after the other contributors, from 10 to 40 degrees Celsius, after 48 hours locked	Oscillator data sheet, under those conditions only
17 Threats	Jamming and spoofing near the site. Loss of signal, detected interference and a failed consistency check lead to holdover; spoofing that escapes detection is caught only by the comparison of line 15. Comparisons bound the error only if the receiver also limits how fast its output may step or drift between them; that limit, the second source's uncertainty, the threshold, the interval and the response time go into the budget of line 4, and holdover starts only from a clock state that agreed with the second source	Chapter 6
18 Promises relied on	Provider commitment for the signal; equipment warranty for receiver and oscillator; no service contract for the signal	The four kinds of promise of Chapter 1

Line	Requirement written for the example	What stands behind it
20 Test	Measure time error at the radio against a reference of known uncertainty, at installation and after a forced 8 hour holdover; in a test bed, inject a time step and a false signal and check that the alarm fires within the set time and leads to holdover; with the error budget from antenna to radio written down	The buyer's test

The two sheets share a receiver type and almost nothing else. The tracker needs meters and a route check; the cell needs microseconds, a holdover with conditions, and a decision about what to do when time is wrong. A single sheet "for GNSS" would have hidden both.

The data sheet, worked twice: monitoring and a tasked order

Case 3: seasonal monitoring of an agricultural district. An agency wants to know, field by field, whether crops have emerged by a date each spring. The observable comes first, then everything else.

Line	Requirement written for the example	What stands behind it
1 Observable	Surface reflectance in red and near infrared, from which a vegetation index is computed per field	Chapter 7
2 Uncertainty needed	The emergence call per field agrees with field visits in at least an agreed share of fields, set before the season, with missed and false emergence calls counted separately	The agency; checked under line 16
4 Spatial resolution	At least nine whole pixels inside the smallest field of interest	Nine 30 m pixels cover 0.81 hectare (calculated); field shape, the pixel grid and geolocation error mean a field must be larger than that to hold nine whole pixels
7 Revisit	One clear acquisition per field in each two-week window of the season	Landsat 8 and 9 offset by 8 days (Chapter 7); cloud decides the rest
8 Latency	Collection clock: a clear acquisition processed within 7 days; no tasking	USGS states Level-2 for Landsat 9 in about 3 days (Chapter 12); that is processing time, not a promise of a clear view
9 Cloud	Fields with cloud or shadow masked; a window with no clear view is reported as missing, not filled	The product's quality masks (Chapter 12)
13 Product	Level-2 surface reflectance, Collection 2, version recorded per scene	USGS Collection 2
15 License	Publication of derived maps required	Landsat at no cost, its use terms not read for this book (confirm before publishing); Copernicus with its credit line (Chapter 13)

Line	Requirement written for the example	What stands behind it
16 Validation	Field visits to a sample of fields each season, matched in time to the scenes, with the sample size and confidence set before the season	The agency
17 Exit	The open archive is the long record; any commercial top-up must allow keeping derived maps	Chapter 13

The sheet points to an open program first. A commercial optical supplier becomes relevant for line 7 in a cloudy season, where more opportunities raise the chance of a clear view but cannot guarantee one, or for fields too small for line 4; radar would change the observable of line 1 and need its own validation. Lines 15 and 17 then decide whether such data can join the record.

Case 4: a tasked radar collection after an event, latency case L1 completed. Chapter 12 built the case from three radar operators' published terms (Figure 12.3). Here it becomes a requirement. A port operator wants an image of its quays within a day of a storm, at night or under cloud, to see which berths are blocked.

Line	Requirement written for the example	What the published terms say (Chapter 12)
1 Observable	Radar backscatter at a resolution that separates a ship from a berth	Chapter 9
2 Performance needed	Blocked berths and clear berths each called correctly against the harbor master's own record, matched in time, for a test set of past scenes kept apart from any tuning, at an agreed rate for each	The port; not a supplier figure
6 Radar	X band, spotlight mode, one polarization; incidence within a stated range for comparison with earlier scenes, and a look direction that keeps the berths out of radar shadow and layover	Operator product specifications
8 Request clock	From order to the buyer's acceptance within 24 hours for at least 90 percent of orders over a year, with refused orders, failed collections and late files counted as misses	No operator read publishes a request-to-delivery figure with a probability; ICEYE's marketing page says "usually within few hours"
8 Collection clock (supplier's part)	From the end of collection to the supplier's delivery within 3 hours; the buyer's own checks are timed separately	ICEYE: "1 hour or less after acquisition", options 1, 3, 8 hours; Umbra: "generally" 1 to 4 hours after the window ends; Capella: "93%" under 3 hours (operator statistic; start, period and sample not stated)
8 Scheduling	Order accepted or refused within 1 hour	Capella schedules every 15 minutes; Umbra in batches every 10 minutes, tasks up to 3 hours before collection
8 Priority	Not displaceable once accepted	Capella: Standard "assured data collection upon acceptance"; Flexible may be bumped. ICEYE: no such assurance stated; background tasks may be displaced

Line	Requirement written for the example	What the published terms say (Chapter 12)
8 Failed attempt	The supplier states what happens if the accepted collection fails, and whether the retry is at its cost	Not published in the terms read
14 Tasking window and cancellation	Free cancellation if the storm misses the port	Capella: free over 72 hours before the first collection, 25 percent at 12 to 72 hours, full under 12 hours. ICEYE (constellation orders): free over 72 hours before the window, 10 percent at 72 to 48 hours, 20 percent at 48 to 24 hours, full under 24 hours. An order whose first collection (Capella) or window start (ICEYE) is within a day pays 25 or 100 percent at Capella and the full value at ICEYE
15 License	Share with the harbor authority and insurers	The internal-use tier of Chapter 13 does not allow it; a wider tier is priced separately

Three findings come out of filling the sheet. First, the clocks the operators publish start at different moments (acquisition in ICEYE's specification, downlink on its marketing page, the end of the collection window for Umbra), so the requirement names its own start and asks each supplier to restate its figure from that start. Second, the stage that decides the request clock, the wait for a feasible collection, is not quantified by any supplier read, so the requirement asks for it with a probability rather than assuming it. Third, the cancellation bands run on the time left before the first collection or the window start: an order whose collection is due within a day is charged in part or in full if canceled, under the terms read, so for an urgent order the decision to order is largely a decision to pay. And a date is not a promise unless the contract makes it one: the license agreement read in Chapter 13 says that "any delivery date set forth in a Customer Agreement is an estimate only" (section 13). A deadline the buyer depends on is written into the order as a binding term that states it takes precedence over the estimate-only clause, with what happens when it is missed.

Attempts matter more than the speed of any one stage. As an illustration only, with an assumed chance of 0.6 that any one accepted attempt yields a usable image (an assumption, not a published figure), one attempt meets the deadline 60 percent of the time, two attempts 84 percent and three 93.6 percent, if the attempts fail independently, if every attempt can still be collected, delivered and accepted before the deadline, and if "success" means an image the buyer accepts (calculated). Whether a supplier has two or three feasible attempts inside 24 hours over the port is the question that sets the deadline probability, and only the supplier can answer it.

The optical side of the case could not be sourced: no optical operator's tasking terms were readable on the dates checked. As a requirement it adds two lines the radar case does not need: the cloud threshold above which the supplier retries, and whether a cloudy collection counts as delivered. A reseller's list shows the shape of the answer for one 50 cm optical product: standard tasking at $14 per square kilometer with "20% or less clouds", and priority tasking on a specific day with "up to 100% clouds" at $28, twice the price (Apollo Mapping price list, modified 8 July 2025). At the lower price the image must meet the cloud limit, so the day of collection is not fixed; at twice the price the order names the day and accepts a cloudy image; whether collection on that day is guaranteed, and what happens if it fails, is in the order terms, not in the list. The buyer pays either in waiting or in cloud risk.

Requirement first, then the options

Only with a sheet filled does a comparison of supplies make sense. For each option, open, commercial or a mix, four questions are answered against the same sheet: does it meet the lines, at all; what is the total cost of the answer, with the items of Chapter 13; what is the probability of meeting the deadline, on the buyer's own clock; and what is the risk, meaning who can stop it and what remains at exit. Case 3 ends with an open program and a possible commercial top-up. Case 4 ends with a commercial order, because no open program in this book offers tasking, and with a second supplier named in advance because a single supplier's feasibility is not known until the order is placed.

A mix is often the honest answer, and it brings its own line: products from different suppliers must agree well enough to be compared, which is a matter of calibration, geometry and versions (Chapter 12), not of resolution alone.

Reading the supplier's lines

The first book of this series, *The Bit's Path*, asks a supplier for its figures line by line and treats a declined line as a finding. The same discipline applies here, with three purchases a buyer of this book meets. Figure 14.1 lists the lines to ask for and what a usable answer contains.

FIGURE 14.1

The supplier's lines for three purchases: a usable answer names its conditions, and a blank is a question still open

Purchase	Line to ask for	A usable answer states	If declined or blank: unresolved
Receiver	Position and time accuracy	Value, percentile, conditions (sky view, antenna, signals), test method	Test on your own routes or site before ordering
Receiver	Holdover and loss behavior	Hours within an error bound, temperature range, time locked before; output on loss	Force a holdover in your acceptance test
Receiver	Interference and spoofing detection	What is detected and reported, and how it reaches your system	Do not rely on detection; plan a second source (Chapter 6)
Correction service	Accuracy and convergence	Tier, percentile, convergence time, coverage area, frame and epoch	No basis for line 2 of the sheet; trial in your area
Correction service	Delivery and status	Transport (satellite or network), age limit, outage notices, service level if any	Ask how outages are announced before relying on it
Imagery or platform	Latency on both clocks	Start and end of each clock, figure with a probability, period it was measured over	Use your own measured clock from a trial order
Imagery or platform	Failed and cloudy collections	Retry policy, cloud threshold, whether a failed window is charged	Ask in writing; budget for retries until answered
Imagery or platform	License and exit	Tier (internal, public release, affiliates), term, what is kept after the term	Do not plan sharing or retention until answered in writing

Purchase	Line to ask for	A usable answer states	If declined or blank: unresolved
Imagery or platform	Product definition	Level, version, calibration, geolocation accuracy with its statistic, masks	Run your own checks inside the warranty window

Ask for every line in writing; a line the supplier declines or leaves blank is tested by the buyer or written into the contract.

Author's table based on Chapters 4 to 6 and 12 to 13 of this book; the supplier terms named there (Capella License Agreement v2.1, May 2026; Capella, ICEYE and Umbra tasking terms, read 2026-11-23).

A blank is information. A correction service that states no percentile for its accuracy, an imagery supplier that publishes no figure for failed collections, a receiver whose holdover has no temperature range: each is a line the buyer must test or contract for, because no document read promises it. The four kinds of promise of Chapter 1 sort the answers: a provider's public commitment, a service contract, an equipment warranty, and a managed service each cover different lines, and a line covered by none of them is the buyer's own risk.

Announced, launched, in service, usable: dating the answer

An offer mixes statuses, and the order must keep them apart. The record of this book shows each step separately:

- **Designed or announced.** Satellogic describes its Merlin satellites as designed for daily remapping at 1 m class with alerts within 30 minutes; the first was launched on 1 October 2026 (Satellogic results release). A design aim is not a service.
- **Launched, not usable.** NVS-02, launched on 29 January 2025, remained in its transfer orbit (ISRO).
- **Broadcast, not yet committed.** The GPS standard of 2020 describes the L2C and L5 civil signals as pre-operational, used at the user's own risk (Chapter 3).
- **Authorized for service, dated.** ESA reported a Galileo satellite authorized for service on 23 July 2026 (Chapter 3 and Appendix D).

For a buyer, one further step counts: in service for my country, my use and my device, on a date. A supplier's statement is written into the order with its date, and Appendix D shows how such statements age.

Acceptance testing, before signing and at delivery

Testing comes twice. Before signing, a small order or an evaluation runs the buyer's own checks on the supplier's real output: the fleet tracker's three routes, the timing site's forced holdover, a sample of fields, an archive scene of the port. The agreement read in Chapter 13 sets the evaluation period at 30 days when the order states none, and warns that evaluation products come "as-is".

At delivery, the checks of Figure 12.4 run on every product, inside the warranty window: in the agreement read, a claim must be made within 30 days "following the initial delivery"; for an order delivered in parts or a subscription, ask in writing when that clock starts. A defect found after that window may fall outside the warranty remedy. The test line of each sheet (line 20 for positioning, line 16 for data) names the test, who runs it and the pass criterion, so that acceptance is a procedure, not an impression.

> **THE SYSTEM'S FAILURE**
>
> This is a method chapter, and it has no failure case of its own. The failures it is built to catch are those told in the earlier chapters: a navigation outage that a receiver did not flag, a satellite launched but not usable, an instrument that degraded, a ground service retired on stated dates, a policy that changed the price of the same pixels. Each sheet line traces back to one of them.

> **SECURITY NOTE**
>
> The two sheets carry the five questions as fields: line 19 of the positioning and timing sheet and line 18 of the data sheet ask who is authorized to use and to command, who can intercept, who can interfere, how the output is authenticated and how service is recovered. **Who can interfere or command.** Answered per case, as in Chapters 6 and 12. **How it is seen.** Lines 5 and 15 of the positioning sheet and line 16 of the data sheet. **How it is recovered.** The fallback and exit lines, written before the order.

Monday rule: fill one sheet for something you already use; the empty fields are your questions.

Epilogue: What Moves Next



Many of this book's numbers are physics and geometry: a nanosecond is 30 centimeters of light travel, a 705 km orbit takes about 99 minutes, and the optics limit what a pixel can show. Others are moving now. This epilogue names them, keeps what is announced apart from what is in service, and makes no forecast outside the box marked as the author's view.

The numbers that are moving

Authentication of open navigation signals. Galileo's open signal has carried an authenticated navigation message since July 2025, in the European Commission's words; the Commission has announced a signal authentication service "from 2027" (chapter 6). What a buyer should watch is not the announcement but three later facts: the published terms of the service, receivers that implement it, and what it proves about the ranging signal as opposed to the data. Until then, the distinction of chapter 6 stands: message authentication shows where the data came from, not where the signal came from.

Positioning and time from low orbit. A signal from low orbit loses less to distance, all else equal, and its geometry changes fast, which is why several operators and the European Union describe low orbit services as a complement to the medium orbit systems. The European Union's plan is announced (chapter 6); a private service was offered by subscription in 2020, as a peer-reviewed paper describes, and its status on this book's date was not checked (chapter 5); others are announced by their operators. Each enters a register only with its country, its status and the date of the source that speaks for it.

Radar revisit. Commercial radar fleets are growing, and with them the number of looks a buyer can order at one place. Chapter 9 dates each fleet with its operator's own count. The number that matters to a buyer is not the fleet size but the probability that a tasked collection is delivered by a deadline, which no fleet count states.

Latency through relays and processing on board. Optical relays shorten the wait between collection and downlink, and processing on board can send a result instead of a scene. Chapter 12 puts both on the two clocks of the latency budget; the computing side is

the subject of the seventh book of this series, *Computing in Orbit*, and rented ground stations and relays of the fifth, *Rent Before You Build*.

RECONSTRUCTION · 2026 · THE ADJUSTER'S PHONE, NO TOWER IN REACH

In the 2026 scene of this series, the insurer's adjuster stands where no cell tower reaches. The phone can still show a position, and it matters which of three it is. A fix computed from the satellites alone needs no network at all; if the orbit data the phone holds are too old to use, it must first collect them from the sky, which takes longer than the assisted start it is used to (chapter 2). A position the phone kept from its last fix, or one it estimated from networks it heard earlier, is a position from the past, however precise it looks. In this reconstruction the phone has had no network for hours, so a fresh position can only be the first kind, after a start that may be slower, or an estimate the phone carries forward from its last fix with its own motion sensors, which ages like any estimate. Whether a given phone shows which kind it is showing, and how old it is, is a property of its software, not a rule; the scene says nothing about any particular device.

OUR VIEW, AS OF NOVEMBER 2026

We expect the next few years to make authentication and low orbit signals ordinary features of receivers, and we expect the hard problems to stay where this book put them: in the requirement a buyer writes, in the second source that does not share the first one's failure, and in the test of what the system does when the position or the time is wrong. A feature that is announced can be relied on only when it is in service, in the buyer's country, in the buyer's receiver, on a stated date.

The first book of this series, *The Bit's Path*, carries the radio link under all of this; the fourth book, *Who Owns the Sky*, the rules that decide who may transmit, sense and sell. This book has tried to show what the link alone does not settle: what is measured, how well, how fast, who stands behind the promise, and what happens when the signal is denied or falsified.

APPENDIX A

The Forms: Link Ledger, Positioning and Timing Sheet, Data Sheet, Latency Template, Index of Ledgers

This appendix holds the blank forms the book uses: the series' two-page Link Ledger with a guide to reading it for a broadcast, the positioning and timing requirement sheet, the data requirement sheet, and the latency template with its two clocks. It ends with the index of the worked examples. Chapter 14 fills the two sheets and completes the latency case. Copy the pages and write a date on every copy: most of what they hold changes.

Reading the Link Ledger for a broadcast

The Link Ledger was drawn for a link that carries a message from one end to another. A navigation broadcast, a correction broadcast and a weather satellite's direct broadcast carry the same bits to every receiver in view and never hear back. The fields still apply; four of them read differently, and one thing the form cannot show at all.

- **1 Requirement.** Write "let any receiver in the service area compute position and time to a stated quality", or "let any station in view receive this data stream", not "deliver this message". The quality is the positioning and timing sheet below.
- **5 Capacity.** One more receiver uses no airtime. What still matters is the message rate, how old the data can be when it is used, and, for corrections sent over a network, the capacity per user.
- **6 Who owns each end.** The operator owns the transmitting end; the user owns or controls the receiver; a correction or data provider is a third party with a contract.
- **9 Cost shape.** No charge at the point of use for an open signal. The receiver, the corrections, the integration work and the public budget carry the cost. Zero access charge is not zero cost.
- **What page 2 cannot show.** A hop budget says whether the signal arrives with enough quality to be tracked. Positioning quality also depends on the geometry of the satellites in view and on the receiver's measurement model (chapter 2). Neither appears on page 2.

For Earth observation the radio hop is one stage of a product chain. Page 2 covers the payload downlink; the time from a request to a usable file belongs on the latency template, and the measurement itself (the radar equation, optical radiometry) belongs to the sensor's own model, not to the form.

The positioning and timing requirement sheet

Fill one sheet per use: a fleet tracker and a timing site need different sheets even if they share a receiver. Every accuracy value carries its percentile and its conditions. Write "not needed" with a reason rather than leave a line blank.

#	Field	What to write	Entry
1	Use and decision	What the position or time is used for, and what goes wrong if it is wrong	
2	Horizontal accuracy	Value, percentile (for example 95 percent), conditions, over what period	
3	Vertical accuracy	Value, percentile, conditions; or "not needed"	
4	Time, phase, frequency	Each separately, at the endpoint that uses it, with its tolerance	
5	Reported uncertainty	Must the receiver report its own uncertainty; how that report is checked	
6	Integrity	Integrity risk, alert limit, time to alert; or "not needed" with the reason	
7	Availability and continuity	Availability: share of time the output meets lines 2 to 6, over which period, where. Continuity: the chance of keeping it without interruption through an operation of stated length	
8	Time to first fix	Cold, warm, hot and assisted start, each with its conditions	
9	Environment	Open sky, urban, under foliage, indoor; antenna placement	
10	Dynamics	Speed and acceleration of the receiver	
11	Update rate and age	Fixes per second; the oldest fix the application may use	

#	Field	What to write	Entry
12	Where the answer is expressed	Reference frame and epoch; height system and geoid model; time scale (UTC or a system time)	
13	Systems, signals, corrections	Constellations and frequencies used; correction service, its transport and contract	
14	When the output is absent	What the system does on loss; the longest tolerable outage	
15	When the output is wrong	How a wrong output is detected, and whether the system alarms, withholds or stops	
16	Holdover	Hours, with the error bound and the operating conditions (temperature, oscillator)	
17	Threats assumed	Jamming, spoofing, a provider fault; what must be detected, not how an attack is made	
18	Promises relied on	Provider commitment, service contract, equipment warranty, managed service: which stands behind each line	
19	Security	Who is authorized to use and to command; who can intercept; who can interfere; how it is authenticated; how service is recovered	
20	Test	For each line: the test, where, by whom, the sample and its confidence, and the pass criterion	

The data requirement sheet

Fill one sheet per question the data must answer. Lines 1 and 2 come first: a sheet that starts at resolution has skipped the question.

#	Field	What to write	Entry
1	Observable or decision	The physical quantity (reflectance, temperature, backscatter, height, displacement, gas column) or the decision the data supports	
2	Uncertainty needed	Of the observable, with its unit and confidence; detection or classification performance where relevant	
3	Area	Boundary, size in square kilometers, terrain	
4	Spatial resolution	Sampled and delivered pixel spacing, and the effective resolution, each with its definition (for radar, range and azimuth resolution); what must be resolved	
5	Spectral and radiometric	Bands or wavelength ranges; signal to noise; bit depth only as quantization	
6	Radar	Band, mode, polarization, incidence range; or "not radar"	
7	Revisit	Successful collections needed per period, not the orbit's repeat cycle	
8	Latency	On both clocks (template below), with the deadline and the probability of meeting it	
9	Cloud and light	Cloud tolerance, season, sun angle, night	
10	Acquisition geometry	Off nadir or incidence limits; stereo; same geometry between passes	
11	Geolocation	Accuracy with its statistic (a percentile, or RMSE) and the elevation model used	
12	Usable area and masks	Minimum usable fraction of the area; cloud, shadow and nodata masks required	
13	Product	Level and version (the supplier's own definition, quoted); coordinate system; format	
14	Archive or tasking	Earliest acceptable date for archive data; tasking window if new collection	

#	Field	What to write	Entry
15	License	Who may use it, for what, for how long; derived products; publication	
16	Validation	Reference data and its uncertainty, matched in time and kept apart from any tuning; sample size, confidence and method that will decide acceptance; for a classification, misses and false alarms per class	
17	Exit	What is kept when the contract ends; a second source	
18	Security	Who may task and see the order; who can intercept the delivery; who can interfere; how provenance is shown; how delivery is recovered	

The latency template: two clocks

Clock A runs from the request to a product the buyer accepts. Clock B runs from the moment of collection to the same accepted product. An archive order has only clock A, and its rows for uplink, collection and downlink do not apply (record the scene's age instead); a monitoring service is usually judged on clock B; a tasking order needs both. One row per stage.

Stage	Owner	Stated time: median and tail	Source, class, date	Clock	How it fails
Request and its acceptance				A	
Wait for the next command uplink				A	
Wait for a feasible collection opportunity (pass, geometry, competing orders)				A	
Collection attempts (each with its success probability, cloud included)				A	
Storage until the next downlink or relay				A, B	
Downlink				A, B	
Processing to the product level ordered				A, B	
Catalog and delivery				A, B	
The buyer's acceptance check				A, B	
End to end, and probability of meeting the deadline	Combine the stages as joint distributions, with their dependencies and retry rules, by simulation or from the supplier's own end-to-end figure. Never add stage percentiles. State each clock's start and end event and the time scale of the timestamps.				

Three rules keep the template honest. A stage the supplier does not publish is written "not published", not guessed. A failed or cloudy attempt adds at least another wait for a feasible opportunity and another collection, so the number of attempts matters more than the speed of any one stage. And adding the 90th percentile of every stage does not give the 90th

percentile of the total: stage percentiles alone do not determine the end-to-end percentile, and their sum can overstate or understate it, depending on how the delays are distributed and how they move together. It also says nothing about the chance of meeting a deadline.

Index of the worked examples

Every Link Ledger printed in this book, with its class and what this book prints of it. Two belong to the first book of this series, *The Bit's Path*, which prints them in full; this book prints their page 1 only. LL-1964-01 is the one page ledger of the second book, *From Telstar to the Phone in Your Pocket*, printed here as that book prints it. Latency case L1, a commercial tasking order, has no ledger id: it is a time budget, built in chapter 12 and completed in chapter 14.

The worked Link Ledgers in this book

Id	Date	System	Class	Status	Budget	Requirement	PDF page
LL-1964-01	1964	Transit (Navy Navigation Satellite System): a position fix at sea	service only	Retired	service only	Positions for ballistic missile submarines several times a day, 0.1 nautical mile per fix, from passive receivers. Later: a usable pass on average within 4 hours anywhere on Earth.	18
LL-2000-02	2000-05-02	GPS L1 C/A, satellite to any receiver (civil signal after Selective Availability)	full	In service	page 2 not printed in this book	Deliver time and the satellite's orbit to any number of receivers wherever a satellite is in view, with no uplink and no subscription; the receiver usually needs four satellites to solve for position and its own clock.	22
LL-2003-01	2003-07 (into service)	WAAS: GPS augmentation broadcast on L1 from geostationary satellites (FAA)	service only	In service	service only	Let any equipped receiver correct its GPS fix and be told within a stated time when it is unsafe; for aviation, guidance to 200 feet with certified avionics and an approved procedure.	45

Id	Date	System	Class	Status	Budget	Requirement	PDF page
LL-2016-01	2016 (historical)	Sentinel-1 to the EDRS-A relay by laser, then Ka band to the ground (historical)	service only	Not checked	service only	Bring radar imagery from a low orbit satellite down to the ground segment without waiting for a pass over a ground station.	128
LL-2016-02	2016-12-15	Galileo Open Service on E1 (since 15 December 2016), with message authentication (OSNMA) since July 2025	service only	In service	service only	Let any receiver compute position and time from Galileo's open signal, and let an equipped receiver check that the navigation data it uses came from Galileo unmodified.	72
LL-2016-03	2016 (series first launch); checked 2026-11-23	GOES-R series HRIT/EMWIN direct broadcast to a small dish (GOES-19 East, GOES-18 West)	service only	In service	service only	Let any receiver in the footprint take warnings, charts, GOES and Himawari images and relayed data collection messages, with no registration, fee or license from NOAA, on a dish of 1.0 m at 10 degrees elevation or more (1.2 m at 5 degrees).	113
LL-2021-01	2021 (launch); read 2026-11-23	Landsat 9 payload data in X band to the Landsat Ground Network	service only	In service	service only	Bring Landsat 9's image data down fast enough for the stated product times: Level-1 in 4 to 6 hours after acquisition, Level-2 in about 3 days (USGS).	129

The blank pages follow: page 1 with its field guide, then page 2 for a radio hop.

LINK LEDGER · BLANK · SERVICE LEDGER

Link id (LL-year-nn) Date System

Status: Planned | In service | Suspended | Retired | Failed | Not checked

Class: full | service only | budget only

1 Requirement What must be delivered: size, deadline, coverage, availability.	
2 Ends and path Who talks to whom; the path as it really is (transparent, regenerative, crosslinked, store and forward).	
3 Orbit and time Altitude, pass or continuous; delay one way and round trip; scheduling and queueing; Doppler.	
4 Band and permission Frequencies per hop; who holds the license, under which rule, in which country.	
5 Capacity Up and down separately; peak against sustained; contention.	
6 Who owns each end Space segment, ground segment, customer relationship, the exit.	
7 Trust Who can command it; whose keys; how it is updated and recovered; jamming and spoofing.	
8 How it fails, and how we would see it Silent failure named; the evidence that shows it.	
9 Cost shape Per minute, per megabyte, per month or per terminal; per kilogram for launch; a price only with its date and what it leaves out.	
10 Evidence Each number with its evidence class, source and date; an assumption is marked so.	

The six questions

1. What must be delivered, and by when?
2. How is the work divided between user, space and ground?
3. Does each hop close, with what margin, under which assumptions?
4. Who owns each end, and who gave permission?
5. How does it fail, who can interfere, and what would show us?
6. What can I use or rent before I build?

The evidence classes

measured From an instrument or a log; who and when.

calculated From stated inputs by a formula the text gives.

simulated From a named model and its settings.

operator claim Stated by the operator; not independently checked.

standard From a named standard or rule, clause or table.

assumption To verify: no primary source read; name what settles it.

published history Published history: an agency history or labeled scholarship.

LINK LEDGER · BLANK · HOP BUDGET

Hop name: _____ (one block per radio hop; a variant of it is a case: Case A, Case B)

From ____ to ____ · frequency · distance · reference plane · information rate · symbol rate · stated error rate

Part	Line	Value, in its own unit	dB, signed	Evidence	Source and date
TRANSMIT POWER AND ANTENNA GAIN	Transmitter output (dBW)				
	Feeder loss				
	Transmit antenna gain (dBi)				
LOSSES	Free space path loss				
	Atmosphere and rain				
	Polarization and pointing				
RECEIVE SENSITIVITY	Receive G/T: antenna gain less system noise temperature (dB/K)				
	Boltzmann's constant: add 228.6 dB (it is -228.6 dBW/K/Hz)				
BANDWIDTH	Information rate (bit/s): for Eb/N0, subtract 10 log10 of it				
	Symbol rate (baud): for Es/N0, subtract 10 log10 of it instead				
INTERFERENCE	Interference, as the step from C/N0 to C/(N0+I0)				
CODING	Modulation, code and implementation loss				
REQUIRED SIGNAL QUALITY	Required Eb/N0, Es/N0 or C/N0 (choose one; the same quantity as above) for the stated error rate				
RESULT	**Achieved Eb/N0, Es/N0 or C/N0: the sum of every line above the required one**			calculated	
	Required: the Eb/N0, Es/N0 or C/N0 for the stated error rate			source:	
	Margin: achieved less required			design minimum: ___ dB	

Verdict (circle one): CLOSES · DOES NOT CLOSE, with a margin of _____ dB

Operating point (rate, direction, elevation, weather, availability):

Source of the required value (a standard or a published curve):

If it does not close, the line that fails, and by how many dB:

Transparent circuit: the combined line. Combine C/N0 (or C/(N0+I0)) of each hop, before the rate and the implementation loss. Uplink C/N0: _____ dBHz. Downlink C/N0: _____ dBHz. Combined (the inverse ratios add): _____ dBHz. Less the rate and the implementation loss, once: _____ dB. Required: _____ dB. Margin: _____ dB. Two passing hops are not a passing circuit.

How to add it up. Write every line in decibels with its sign: gains positive, losses negative. Beside each number you may write the level after that line (dBW after the transmitter, dBW/K after G/T, dBHz after Boltzmann's constant, dB after the rate). After Boltzmann's constant the level is C/N0 in dBHz. Es/N0 = C/N0 minus 10 log10(symbol rate in baud); Eb/N0 = C/N0 minus 10 log10(information rate in bit/s). Compare like with like: the required value is the same quantity as the achieved one. Write a dB value on one rate line only, and on neither for C/N0. The achieved value is the sum of every line above the required one. The margin is the achieved value less the required value. The hop closes when the margin is at or above the design minimum you wrote down before you started.

APPENDIX B

Formulas and Check Values

The formulas the chapters use, each with its conditions and a check value computed from the inputs shown and rounded once. Illustrative inputs show the arithmetic, not a real instrument or service.

B.1 Constants

Constant	Value	Source
Speed of light, c	299,792,458 m/s (exact)	SI Brochure, 9th edition, 2019
Earth's gravitational parameter, μ	3.986004418e14 m^3/s^2	WGS 84 defining parameters
Earth's equatorial radius	6,378.137 km	WGS 84 defining parameters; used to turn an altitude into an orbit radius
Mean Earth radius	6,371 km	the value used for pass geometry, as in the first book of this series, *The Bit's Path*

B.2 Time and range

A navigation receiver measures time and converts it to distance with the speed of light, so an error in a signal's travel time is an error in its measured range, a pseudorange error: distance = c x time. The receiver's own clock error is different: it is estimated as one more unknown. An error common to every satellite's clock would be absorbed into that estimate, leaving the position nearly unchanged and the time wrong.

Time	Distance at the speed of light
1 nanosecond	0.300 m
1 microsecond	299.8 m
One chip of the GPS L1 C/A code (1/1.023 MHz = 977.5 ns)	293.1 m

The chip rate, 1.023 million chips per second, is from IS-GPS-200N.

B.3 Dilution of precision

The receiver solves four unknowns: three position coordinates and its own clock offset. Write one row per satellite i: the components of the unit vector from the receiver to the satellite, with a minus sign, and a 1 for the clock, G_i = [-e_i, -n_i, -u_i, 1] in east, north and up. Stack the rows into the matrix G and form Q = (G^T G)^-1. Then:

- GDOP = square root of the sum of all four diagonal elements of Q;
- PDOP = square root of the first three; HDOP of the first two; VDOP of the third; TDOP of the fourth.

Conditions. The ratio "position error equals DOP times range error" holds when the range errors of all satellites are independent, have zero mean and the same standard deviation. Correlated errors, such as a shared ionospheric residual, break it (chapter 2). The GPS performance standard uses the same product to express the user's position error: position error = user equivalent range error x PDOP (GPS SPS Performance Standard, 5th edition, April 2020, Appendix B, equation B-14).

Check geometry (calculated)	GDOP	PDOP	HDOP	VDOP	TDOP
One satellite overhead, three at 10 degrees elevation, 120 degrees apart in azimuth	1.96	1.82	1.17	1.40	0.73
Four satellites clustered: elevation and azimuth 60 and 0, 50 and 20, 55 and 40, 65 and 30 degrees	177	126	66	107	124

With a PDOP of 2.0 and a range error of 1.5 m (one standard deviation), the three-dimensional root-mean-square position error is 3.0 m, under the conditions above; that is not a 68 percent radius. The matrix must have full rank: four satellites in a plane with the receiver give no solution.

Time. The same standard gives the user's UTC error as the root-sum-square of the user range error times the time transfer DOP divided by c, and the broadcast UTC offset error (equation B-7); the 30 nanosecond UTC offset accuracy of chapter 5 is that second term; the 30 nanosecond time transfer standard is a separate figure for the signal in space.

B.4 Clocks, holdover and distribution

Time error from a frequency error. A clock whose rate is wrong by a fraction y gains or loses y x t seconds in t seconds. If the rate also drifts by a fraction D per second, the time error after t seconds is x(t) = x0 + y0 t + D t^2 / 2. These are the arithmetic of chapter 5, not the behavior of any product: real oscillators change with temperature and age in ways a constant does not describe.

Illustrative case (calculated)	Time error
Constant frequency error 1e-11, for 24 hours	864 ns
Constant frequency error 1e-9, for 1 hour	3.6 microseconds
Constant frequency error 1e-9, for 24 hours	86.4 microseconds
No initial error, drift 1e-10 per day, for 24 hours	4.32 microseconds

Path asymmetry. Two-way time protocols compute the clock offset as half the sum of the two one-way differences (RFC 5905, section 8, for NTP; the Precision Time Protocol uses the same assumption). If the outbound and return delays differ by A, the computed offset is wrong by A/2. Check: an asymmetry of 2 microseconds gives a 1 microsecond error, and the four timestamps of the exchange cannot reveal it; only an independent reference or a calibration can.

Phase angle and time on a power grid. At a grid frequency f, a time error dt shifts a measured phase angle by 360 x f x dt degrees. A 1 percent total vector error from phase alone is an angle of 2 arcsin(0.005), 0.573 degrees, which is 26.5 microseconds at 60 Hz and 31.8 microseconds at 50 Hz (calculated; the 60 Hz value matches the NASPI report cited in chapter 5).

B.5 Imaging geometry

Ground sample distance. For a camera looking straight down, similar triangles give GSD = p x H / f, with p the detector pitch, H the distance to the ground and f the focal length. Check (illustrative inputs): p = 10 micrometers, H = 500 km, f = 1.0 m gives 5.0 m. Looking

off nadir across the track by an angle q, over flat ground, the sample grows to about GSD / cos^2 q across the track and GSD / cos q along it: 6.7 m and 5.8 m at 30 degrees. This is the flat-ground approximation; Earth curvature adds to it.

Diffraction limit. The smallest angle a circular aperture of diameter D can separate at wavelength λ is about 1.22 λ / D (the Rayleigh criterion, for two point sources and an ideal aperture; a convention, not an absolute limit), so the smallest separable distance on the ground is about 1.22 λ H / D. Check, as in chapter 8 (illustrative inputs): to separate points 0.3 m apart from 500 km at 0.5 micrometers needs D of about 1.0 m.

B.6 Orbits, revisit and passes

Period. A circular orbit of radius a has period T = 2π (a^3/μ)^1/2. Check: 705 km above the equatorial radius gives 98.9 minutes and 14.56 orbits a day; the US Geological Survey gives Landsat 9's period as 99 minutes (chapter 12). In 16 days the calculated period gives 233.0 orbits (calculated); a real repeat cycle also depends on the Earth's rotation and the orbit's precession.

Longest pass over a station. For a circular orbit at altitude h, seen above an elevation mask ε, the Earth central angle from the station to the edge of visibility is β = arccos(R cos ε / (R + h)) - ε, with R the mean radius. An overhead pass lasts at most T x 2β / 360 degrees, ignoring the Earth's rotation, with T computed for the same radius R + h. The mean radius is a chosen spherical approximation. Checks (calculated):

Altitude, mask	Half angle β	Longest pass
705 km, 5 degrees	21.2 degrees	11.7 minutes
705 km, 10 degrees	17.5 degrees	9.6 minutes
500 km, 5 degrees	17.5 degrees	9.2 minutes
693 km, 5 degrees	21.0 degrees	11.5 minutes

Most passes are shorter, because most do not cross overhead. **Data volume per pass** is the rate times the usable time: 300 Mbit/s for 600 seconds is 180 Gbit, or 22.5 gigabytes (illustrative rate, not a real downlink).

Geostationary altitude. An orbit whose period equals one sidereal day, 86,164.1 seconds, has radius a = (μ T^2 / 4π^2)^1/3: 42,164 km, so its altitude above the equatorial radius is 35,786 km (calculated). Chapters 7 and 10 use this value.

Slant range and light time. From a station to a satellite at altitude h seen at elevation ε, the distance is d = ((R + h)^2 - (R cos ε)^2)^1/2 - R sin ε, and the light time is d / c. Checks (calculated): Landsat 9 at 705 km is 2.4 ms away straight overhead and 2,573 km, 8.6 ms, at 5 degrees elevation; a geostationary satellite is 119.4 ms away straight down, so a broadcast relayed through it takes at least 238.7 ms, about a quarter second, from uplink to receiver (chapter 10); a 45,000 km laser hop, the longest of the relay route in chapter 12, takes 150.1 ms. Propagation only: equipment, queues and processing add more.

B.7 Radar resolution

Slant range. With a chirped pulse of bandwidth B, the resolution along the line of sight is about c / (2B) (Guerra and colleagues, Acta Astronautica, 2016, Appendix A, equation 2). Checks: 15 MHz gives 10.0 m, the example in chapter 9; 100 MHz gives 1.5 m.

Ground range. Projected onto flat ground, the slant-range resolution grows to c / (2B sin θ), with θ the incidence angle; the same paper's expression for the minimum resolved area divides by sin θ. Checks at 100 MHz: 4.4 m at 20 degrees, 2.6 m at 35 degrees, 2.1 m at 45 degrees. Steep incidence gives coarse ground range resolution.

Azimuth, real aperture. An antenna of length D along the track resolves about λ R / D (equation 3). Check (illustrative): at 5.405 GHz (λ = 5.55 cm), R = 800 km and D = 12 m, about 3.7 km, far too coarse for most imaging from orbit.

Azimuth, stripmap synthetic aperture. The synthetic aperture is about as long as the antenna's footprint along the track, λ R / D; coherent processing of the two-way phase history over that length gives a resolution of about D / 2, independent of range and wavelength. Check: a 12 m antenna gives about 6 m. Conditions: single-look stripmap processing of the whole time a point is in the beam, ideal motion compensation, flat ground. This last relation is a derivation from the two equations above, shown so it can be checked, not a value read from a source.

Wavelength and interferometric phase. Wavelength is c divided by frequency: 5.405 GHz gives 5.55 cm. On a two-way path, one full cycle of interferometric phase corresponds to half a wavelength of motion along the line of sight, 2.8 cm at 5.405 GHz (calculated; chapter 9).

B.8 Rules and standards sought and not read

Several chapters would have quoted the documents below. Each was sought on the date given and could not be opened; no value from it is printed, except where a chapter quotes a labeled trade press report of it. National rules on remote sensing and on navigation

equipment belong to the fourth book of this series, *Who Owns the Sky*; no regulator's page outside the United States and the European Union was sought for this book.

Document sought	For	Date sought
FCC rules on handset location for emergency calls (47 CFR 20.18); EU Delegated Regulation 2019/320	Chapter 2, assisted starts	2026-11-23
EU business clock rule (Commission Delegated Regulation 2017/574, RTS 25)	Chapter 5, figure 5.2	2026-11-23
BIPM, General Conference on Weights and Measures 2022, resolution on the leap second; IERS Bulletin C	Chapters 2 and 5	2026-11-23
EASA Safety Information Bulletin 2022-02R3 (read only as reported by trade press)	Chapter 6	2026-11-23
US Maritime Administration advisories on navigation interference	Chapter 6	2026-11-23
FAA WAAS Performance Standard; FAA requirements for receiver integrity monitoring	Chapter 4	2026-11-23
Copernicus data regulations: Delegated Regulation 1159/2013, Regulation 377/2014 and Regulation 2021/696 (EUR-Lex)	Chapter 13	2026-11-24
USGS terms of use for Landsat data	Chapter 13	2026-11-24

APPENDIX C

Glossary

The terms the chapters use, in plain words. The number in brackets is the chapter where a term is introduced or worked; R is the Reader's Brief, P the Prologue, and A and B the appendices. Link terms (decibel, hop budget, C/No, Eb/No) are defined in the first book of this series, *The Bit's Path*, and repeated here only where this book uses them.

Term	Meaning
Accuracy	How close a reported position or time is to the truth, stated at a percentile (for example 95 percent) under stated conditions [R, 2, 4]
Acquisition	Finding a satellite's signal by searching over its code timing and Doppler shift until the receiver's copy lines up [2]
Analysis-ready data	Products processed to a stated level, such as surface reflectance with masks, so that a user need not repeat the preprocessing the specification covers; what is included differs by specification and supplier [7, 12]
Augmentation	A service that adds corrections or integrity information to a navigation system's own signals, broadcast from satellites or sent over a network [4]
Backscatter	The radar energy a surface returns toward the sensor; calibrated products express it as a normalized coefficient (sigma nought or gamma nought, which differ in the reference area) that depends on geometry and polarization [9]
Control segment	The ground part of a navigation system that tracks the satellites, computes their clocks and orbits, uploads their messages and commands them [1, 2]
Correction service	A service, usually under contract, that sends data letting a receiver remove more of its errors, by satellite or over the internet [4]

Term	Meaning
Dilution of precision (DOP)	The ratio of the position error's standard deviation to the range error's, under stated assumptions; it grows when the satellites in view are bunched together. PDOP is the three dimensional form, GDOP adds the clock [2, B]
Direct broadcast	A weather or Earth observation satellite's transmission of its data to anyone in view with a suitable antenna [10]
Ephemeris	A satellite's precise orbit, predicted by the control segment and broadcast in its message; it ages until the next upload [2]
Geoid model	A model of the surface of equal gravity potential, close to mean sea level, used to convert ellipsoidal height to orthometric height [2]
Ground sample distance	The spacing of pixels on the ground; not the size of the smallest object that can be identified [7, 8]
Holdover	How long, and within what error bound, a clock keeps acceptable time after it loses its reference [5]
Integrity	The ability to warn in time when a position should not be used, stated as an alert limit, an integrity risk and a time to alert; different from accuracy [R, 4]
Interferometry (InSAR)	Comparing the phase of two radar images of the same place; the phase holds terrain height, motion along the radar's line of sight, atmosphere and noise, and a measurement of motion needs the others removed [9]
Ionosphere	The ionized upper atmosphere; to first order it delays the code and advances the carrier phase by an amount that falls with the square of the frequency, which a second frequency reveals [2]
Jamming	Transmitting noise or another signal so that a receiver cannot hear the satellites [6]

Term	Meaning
Latency	The time to a usable result; this book measures it on two clocks, from request to accepted product and from collection to accepted product [R, 7, 12]
License (data)	The terms under which data may be used, shared and built upon; it decides what a buyer may do with a product [13]
Message authentication	A cryptographic check that a navigation message came from the system; it does not by itself show that the ranging signal is genuine [6]
Observable	The physical quantity a buyer needs measured, such as reflectance, temperature, backscatter, height, a gas column or a displacement [R, 7]
Orthometric height	Height roughly above mean sea level, used on maps and in engineering; computed with a geoid model from the ellipsoidal height a receiver gives [2]
Performance standard	A provider's published commitment about its signal in space and its constellation, with stated conditions; not a contract with the user and not a statement of the user's result [1, 2, 3]
Precise point positioning (PPP)	A correction method that uses precise satellite orbits and clocks to reach high accuracy with one receiver, after a convergence time [4]
Product level	How far data has been processed, from raw counts through calibrated and geolocated data to derived products; the names differ between suppliers [7, 12]
Pseudorange	The range a receiver measures from a signal's travel time, which still contains the receiver's own clock error [2]
Radiometric resolution	How finely a sensor divides the brightness it records; bit depth is quantization, not accuracy [7]

Term	Meaning
Real-time kinematic (RTK)	A correction method using carrier phase from a nearby base station or network; "fixed" means the whole cycles of the carrier have been resolved, "float" that they have not [4]
Reference frame	The coordinate system and its realization in which a position is expressed, with an epoch when the frame moves; GPS uses WGS 84 [2]
Reported uncertainty	What a receiver says about its own error; an estimate, not a guarantee [R, 4]
Revisit	How often a satellite or constellation can observe the same place; different from the repeat cycle of an orbit and from a successful collection [7]
Spatial, spectral and temporal resolution	Three of the four meanings of resolution: the ground detail a sensor resolves (which pixel spacing alone does not set), the width and number of wavelength bands, and how often data are collected [7]
Spoofing	Sending false or replayed navigation signals that a receiver accepts as genuine [6]
Synthetic aperture radar (SAR)	A radar that combines echoes received along its path to form a fine image from a small antenna [9]
System time	The time scale a navigation system keeps, steered toward a realization of UTC and published with its offset [2, 5]
Time to first fix	The time from switching a receiver on to its first position; cold, warm, hot and assisted starts differ in what the receiver already knows [2]
User range error	The error of the range a satellite's signal in space implies, from its clock and orbit data, before any local effect; the quantity a performance standard commits to [2]
UTC	Coordinated Universal Time, the international civil time scale, kept from atomic clocks and adjusted by leap seconds [2, 5]

APPENDIX D

Dated Register: Systems, Fleets, Service Status, and Systems Sought and Not Sourced

Some facts in this book will be out of date soon after it is read: how many satellites a navigation system has, which augmentation service is commissioned, which sensing operator has how many satellites, and who owns whom. The chapters use these facts for their analysis; this register keeps them in one place, each with the date it describes, its source and the date the source was read. It also lists, under the rule of the Reader's Brief, every system the book sought and could not source, so that nothing is dropped in silence. Before relying on any row, read its source again.

How to read a row

- **As of** is the date the fact describes: a launch, a declaration, a status page, the end of a reporting period.
- **Read** is the date the source was read for this book. A status row (in service, commissioned, operational) needs a source that speaks for the date given; an older announcement is never upgraded to a current status.
- **Kind** is one of the seven evidence classes of the Reader's Brief. An operator claim is what an operator or agency says about itself, or about another provider in a summary it publishes (the FAA's worldwide summary of augmentation systems is marked so); a company's statement known only through a trade press report is marked "(trade press)". A measurement names who measured.
- **Ch** is the chapter that uses the fact.
- A count is printed only with its date and who counted. "Latest launch", "in service" and "usable" are different facts and are kept in different rows.

Navigation systems: counts, launches and declared service

Fact	As of	Source	Read	Kind	Ch
GPS: 31 operational satellites (not counting decommissioned spares on orbit)	2023-07-03	GPS.gov, Space Segment	2026-11-23	operator claim	3
GPS: 5 IIR-M, 11 IIF and 0 IIIF satellites on orbit; other cells of the table not readable in the text extraction, so no total is printed	2026-04-13	US Space Force, briefing to the CGSIC (agency presentation), 2026-04-21	2026-11-22	operator claim	3
GPS: launch of GPS III SV10, the last of its block (no later GPS launch was checked)	2026-04-21	Lockheed Martin news release	2026-11-22	operator claim	3
GPS: initial operational capability (civil signal) 1993-12-08; full operational capability 1995-04-27, announced 1995-07-17	1993 to 1995	GPS SPS Performance Standard, 2020 and 2008 editions	2026-11-23	standard	3
GPS: L2C and L5 pre-operational, used at the user's own risk	2020-04 (edition date)	GPS SPS Performance Standard, 5th edition	2026-11-23	standard	3
GLONASS: declared operational 1993; 24 satellites 1995; 7 satellites 2002	1993 to 2002	Russian Information and Analysis Center for PNT, About GLONASS	2026-11-22	operator claim	3
Galileo: initial services from 2016-12-15, with 18 satellites in orbit	2016-12-15	European Commission, IP/16/4366	2026-11-23	operator claim	3

Fact	As of	Source	Read	Kind	Ch
Galileo: satellite 33 authorized for service May 2026, satellite 34 on 2026-07-23; four first generation satellites still to be launched	2026-07-24	ESA, Two new Galileo satellites enter service	2026-11-22	operator claim	3
Galileo: High Accuracy Service entry into service	2023-01-24	European Commission, SPEECH/23/341	2026-11-23	operator claim	3, 4
Galileo: message authentication (OSNMA) protecting users "since July" (day not stated)	2025-09-10 (statement)	European Commission, SPEECH/25/2072	2026-11-23	operator claim	3
Galileo: Public Regulated Service initial services still described as upcoming	2026-01-27	European Commission, SPEECH/26/228	2026-11-23	operator claim	3
BeiDou: BDS-3 constellation of 30 (24 medium orbit, 3 geostationary, 3 inclined geosynchronous) completed June 2020; commissioned 2020-07-31	2020-07-31	State Council Information Office, BeiDou white paper, 2022-11-04	2026-11-23	operator claim	3
NavIC: NVS-02 launched 2025-01-29; not raised to its operational orbit	2025 (ISRO notice)	ISRO, NVS-02 Spacecraft On-Orbit Observations	2026-11-23	operator claim	3
NavIC: IRNSS-1F atomic clock stopped; satellite continues for one way messaging only	2026-03-13	ISRO, IRNSS-1F completes 10-year mission	2026-11-23	operator claim	3

Fact	As of	Source	Read	Kind	Ch
NavIC: NVS-03 launched 2026-10-30; final orbit reached, health normal	2026-11-04	ISRO, Final Orbit manoeuvring of NVS03 spacecraft	2026-11-23	operator claim	3
NavIC: S band frequency 2492.028 MHz in both interface documents; 2498.028 MHz on ISRO's services page	2017-08 and 2023-08 (issue dates)	ISRO SPS ICD 1.1; ISRO L1 ICD 1.0; ISRO Satellite Navigation Services	2026-11-23	standard	3
GPS: Selective Availability ended a few minutes past midnight EDT after the end of 1 May 2000; GPS III to be built without it (announced September 2007)	2000-05-02	GPS.gov, Selective Availability	2026-11-22	operator claim	1, 2
GPS: 24-slot baseline; three slots expanded in June 2011	2011-06	GPS.gov archive, Space Segment	2026-11-22	operator claim	3
GPS: master control station at Schriever, 6 monitor stations and 11 of another agency; GPS IIIF planned up to 22 satellites	2026-04-13	US Space Force, briefing to the CGSIC (agency presentation), 2026-04-21	2026-11-22	operator claim	1, 3
GPS IIIF: the builder under contract for 12 satellites; first IIIF launch date not stated	2026-04-21	Lockheed Martin news release	2026-11-22	operator claim	3
Transit: open to civil users 1967; terminated 1996-12-31	1996-12-31	APL Technical Digest 19(1), 1998	2026-11-23	published history	2

Fact	As of	Source	Read	Kind	Ch
Galileo: the pair that became satellites 33 and 34 launched	2025-12-17	ESA, Two new Galileo satellites enter service	2026-11-22	operator claim	3
Galileo: search and rescue return link announced	2021-04-06	European Commission, MEX/21/1602	2026-11-23	operator claim	3

Augmentation and correction services

Fact	As of	Source	Read	Kind	Ch
WAAS: commissioned July 2003; dual-frequency service in development for 2027	2025-11-27 (fact sheet)	FAA, SBAS worldwide fact sheet	2026-11-23	operator claim	4
WAAS: broadcasts from PRN 131, 133 and 135 evaluated over the quarter	2026-07-01 to 2026-09-30	FAA Technical Center, WAAS Performance Analysis Report 98	2026-11-23	measured (by the FAA Technical Center)	4
WAAS: 4,219 LPV procedures at 2,035 airports; 759 LP procedures at 548 airports	2025-11-27	FAA, WAAS Quick Facts	2026-11-23	operator claim	4
WAAS: 38 reference stations	2021-06-14	FAA, WAAS Program Overview	2026-11-23	operator claim	4
EGNOS commissioned for aviation March 2011; MSAS commissioned 2007; GAGAN commissioned December 2013; KASS commissioned 2024; SouthPAN early services 2022, aviation services planned 2028; SDCM under development; BDSBAS in test, undergoing certification (FAA's summary of other providers)	2025-11-27 (fact sheet)	FAA, SBAS worldwide fact sheet	2026-11-23	operator claim (FAA summary)	4
GAGAN certified by India's civil aviation regulator for RNP 0.1 on 2013-12-30 and APV-1 on 2015-04-21	2015-04-21	ISRO, Satellite Navigation Services	2026-11-23	operator claim	4

Fact	As of	Source	Read	Kind	Ch
BeiDou: free precise positioning service for China and neighboring areas through 3 geostationary satellites, better than 30 cm horizontal and 60 cm vertical, convergence under 30 minutes; no percentile stated	2022-11-04	BeiDou white paper	2026-11-23	operator claim	4
Trimble RTX tiers and delivery; Swift Skylark tiers and delivery, as stated on the operators' pages	page as read	Trimble RTX; Swift Navigation Skylark	2026-11-23	operator claim	4

Navigation service events and announcements

Fact	As of	Source	Read	Kind	Ch
GPS: UTC message off by 13 microseconds after a ground software upload on 2016-01-26, while SVN 23 was removed from service; the problem "did not appear to have affected" positioning, in the report's words	2016-01-26	Inside GNSS, 2016-01-29	2026-11-23	operator claim (trade press)	5
GPS minus UTC changed from 17 to 18 seconds at the leap second	2016-12-31	GPS SPS Performance Standard, 5th edition	2026-11-23	standard	5
Galileo open service interrupted: notices of 11, 13 and 18 July 2019 in one report; total failure 10 to 17 July in a later one	2019-07	Inside GNSS, 2019-07-18 and 2019-09-19	2026-11-23	operator claim (trade press)	6
Galileo message authentication (OSNMA) operational	2025-07-24	Inside GNSS, 2025-07-24	2026-11-23	operator claim (trade press)	6
EASA bulletin on navigation outages, SIB 2022-02R3: areas named; no immediate airworthiness action	2024-07-08 (report)	Inside GNSS (trade press); the bulletin itself not read	2026-11-23	standard, as reported by trade press	6
European Union: signal authentication service announced "from 2027"; interference monitoring service announced for 2026 to 2027; low orbit positioning constellation announced for the mid term	2025-09-10	European Commission, SPEECH/25/2072	2026-11-23	operator claim	6

Fact	As of	Source	Read	Kind	Ch
WWVB: 60 kHz time code; about 100 microseconds with the path delay removed	2025-12-17 (page update)	NIST, Radio Station WWVB	2026-11-23	operator claim	5, 6

Navigation systems sought and not sourced

Each row is a fact the plan of this book called for and the chapter does not print, because its primary source could not be read on the date given. The chapter says so where the fact would have stood.

Fact sought	Primary source sought	Date sought	Result
GPS: total operational satellites in 2026; first GPS IIIF launch date; exact day of the first NAVSTAR launch	US Coast Guard Navigation Center constellation status; Space Force and Space Systems Command pages	2026-11-23	Not read
GLONASS: satellites in operation today; code-division signals; return to a full constellation; the broadcast data error of April 2014	Russian Information and Analysis Center for PNT status page; Roscosmos; IGS	2026-11-23	Not read
Galileo: usable satellites today; a dated count of satellites in orbit (ESA's overview gives one without its date); Open Service signal frequencies and interface document issue; Open Service and HAS service definition figures; exact OSNMA declaration day; time scale and frame names	European GNSS Service Centre; EU Agency for the Space Programme; ESA	2026-11-23	Not read
BeiDou: signal names and frequencies; interface documents; open service performance standard; current count	China Satellite Navigation Office site	2026-11-23	Not read
QZSS: satellites in service; service start; launches of recent satellites; orbits; signals; SLAS, CLAS and MADOCA-PPP figures; performance standards	Cabinet Office QZSS site; JAXA releases; the builder's pages	2026-11-23	Not read
NavIC: number of satellites providing positioning today	ISRO notices	2026-11-23	Not stated in the pages read

Fact sought	Primary source sought	Date sought	Result
Korean Positioning System: plan, first launch, service year	Korea Aerospace Research Institute; ministry pages	2026-11-23	Not read
WAAS Performance Standard (edition, time to alert, continuity); commissioning day	FAA GNSS library	2026-11-23	Not read; the July 2003 month is from the FAA fact sheet
EGNOS, MSAS, KASS, SouthPAN, SDCM and BDSBAS: each provider's own status page and satellites	Each provider's site	2026-11-23	Not read; FAA summary used instead
Hexagon TerraStar and SmartNet terms; NOAA National Geodetic Survey real-time guidelines and CORS network	Operator pages; NOAA NGS	2026-11-23	Not read

Sensing missions and fleets: launches, counts and status

The same rules hold for Earth observation. A launch is not a service, and a commercial operator's count is printed only as the operator gave it, with its date; where the operator gave no total, the row says so.

Fact	As of	Source	Read	Kind	Ch
Landsat 9 launched 2021-09-27, 705 km; "as many as 750 scenes per day" (other official pages say "more than 700" and "740")	pages as read	USGS, Landsat 9	2026-11-23	operator claim	7, 12
Landsat 7: scan line corrector failed 2003-05-31; science data until 2024-01-19; decommissioned 2025-06-04	2025-06-04	USGS, Landsat 7	2026-11-23	operator claim	8

Fact	As of	Source	Read	Kind	Ch
Landsat 5: launched 1984-03-01; decommissioned 2013-06-05	2013-06-05	USGS, Landsat 5	2026-11-23	operator claim	7, 13
Landsat 10 (formerly Landsat Next): launch expected in 2031	page as read	USGS, Landsat Next page	2026-11-22	operator claim	7, 13
Sentinel-1: 1A launched 2014-04-03; 1B launched 2016-04-25, no radar data since 2021-12-23; 1C launched 2024-12-05; 1D launched 2025-11-04. Whether 1A still operates: not checked	page as read	Copernicus SentiWiki, S1 Mission	2026-11-22	operator claim	9, 12
GOES-19 operational as GOES-East from 2025-04-07; GOES-18 as GOES-West from 2023-01-04; GOES-16 and GOES-17 in on-orbit storage	status page as read	NOAA OSPO, GOES status	2026-11-23	operator claim	10
Meteosat-9, 10 and 11 operated; Meteosat-12 launched 2022-12-13, imager data pre-operational from 2024-09-23; Meteosat-13 launched 2025-07-01	pages as read	EUMETSAT, MSG and MTG pages	2026-11-23	operator claim	10
Metop-B and Metop-C operational; Metop-SGA1 launched 2025-08-13, in commissioning when read	page as read	EUMETSAT, Metop series	2026-11-23	operator claim	10

Fact	As of	Source	Read	Kind	Ch
NOAA-21 afternoon primary, NOAA-20 secondary, Suomi-NPP tertiary	status page as read	NOAA OSPO, JPSS status	2026-11-23	operator claim	10
COSMO-SkyMed: CSG-3 launched 2026-01-03; the page's count of satellites in operation carries no date and is not printed	2026-01-03	Italian Space Agency, COSMO-SkyMed	2026-11-23	operator claim	9
SAOCOM 1A launched 2018-10-07; 1B launched 2020-08-30	2020-08-30	CONAE, SAOCOM	2026-11-23	operator claim	9
COSMIC-2: six satellites launched 2019-06-25	2019-06-25	UCAR COSMIC Program	2026-11-23	operator claim	11
ICEYE: 76 satellites launched in total; the number operating is not published in the release read	2026-07-07	ICEYE release, Transporter-17	2026-11-22	operator claim	9, 13
Planet: 10 high-resolution Pelican satellites in orbit; total fleet not stated in the releases read	2026-07-31	Planet results release (reprint)	2026-11-22	operator claim	8
BlackSky: fifth third-generation satellite deployed; total in orbit not stated	2026-11-05	BlackSky, Form 8-K exhibit 99.1	2026-11-22	operator claim	8, 12
Vantor: six WorldView Legion satellites launched in the 18 months before the post; older fleet not stated	2025-10-02	Vantor blog	2026-11-22	operator claim	8, 13

Fact	As of	Source	Read	Kind	Ch
Umbra: Umbra-13 and Umbra-14 launched; number in orbit not verified	2026-10-20	Via Satellite (trade press)	2026-11-22	operator claim (trade press)	9
Satellogic: Merlin.01 launched; total fleet not stated	2026-10-01	Satellogic results release (reprint)	2026-11-22	operator claim	8, 14
HawkEye 360: clusters 15 and 16 (six satellites) launched; total not stated	2026-10	HawkEye 360 results release (reprint)	2026-11-22	operator claim	11, 12
Spire: 29 satellites launched in 2026 up to July; total in orbit not stated	2026-07	Spire, second quarter 2026 results	2026-11-22	operator claim	11
Landsat 6 failed to reach orbit (1993); Landsat 7 launched April 1999	1993 to 1999	USGS, Landsat Satellite Missions	2026-11-22	published history	7
Landsat 9 Collection 2 Level-1 and Level-2 data in the commercial cloud	2022-02-15	USGS, Landsat 9	2026-11-23	operator claim	12
Landsat 9 product times: Level-1 4 to 6 hours after acquisition; Level-2 about 3 days	pages as read	USGS, Collection 2 pages	2026-11-23	operator claim	7, 12, 14
PRISMA launched 2019-03-22 to 615 km	2019-03-22	Italian Space Agency, PRISMA	2026-11-23	operator claim	8
GOES-17 launched 2018-03-01; its imager listed operational with a limitation; replaced as GOES-West 2023-01-04	status page as read	NOAA OSPO, GOES status	2026-11-23	operator claim	10

Fact	As of	Source	Read	Kind	Ch
GOES Rebroadcast: 96 receive stations at 68 sites	2020-12	NOAA OSPO, GOES Rebroadcast page	2026-11-23	operator claim	10
Meteosat-12 imager: a "serious anomaly during the commissioning phase" delayed the data release	2024-09-23	EUMETSAT release	2026-11-23	operator claim	10
SMAP launched 2015-01-31; radar failure in July 2015 (news item on the mission site)	2015-07	NASA JPL, SMAP	2026-11-23	operator claim	11
SWOT launched 2022-12-16; TROPOMI launched October 2017 on Sentinel-5 Precursor	2022-12-16	NASA JPL, SWOT; TROPOMI team	2026-11-23	operator claim	11
Planet: first second-generation Pelican launched July 2026, expected to reach "up to 30 cm class imagery"	2026-07	Planet results release (reprint)	2026-11-22	operator claim	8

Sensing suppliers and services: changes of owner, name, terms and status

Fact	As of	Source	Read	Kind	Ch
Landsat archive available for download at no cost to users	2008	USGS, Landsat Data Access	2026-11-23	operator claim	13
Azure Orbital Ground Station retired: notice 2024-10-03; public spacecraft access ended 2024-10-28; private spacecraft 2024-12-18	2024-12-18	Microsoft retirement notice (archived)	2026-11-22	operator claim	12

Fact	As of	Source	Read	Kind	Ch
Spire completed the sale of its maritime business to Kpler	2025-04-25	Spire release	2026-11-22	operator claim	11, 13
IonQ completed its acquisition of Capella Space	2025-07-15	Capella release	2026-11-22	operator claim	9, 13
Maxar Intelligence rebranded as Vantor	2025-10-02 (post)	Vantor blog	2026-11-22	operator claim	13
Capella License Agreement, version 2.1	2026-05	Capella, license PDF	2026-11-24	operator claim	13, 14
ICEYE legacy product formats: final availability	2026-12-31	ICEYE SAR product specification 6.0.8	2026-11-23	operator claim	12, 13
Reseller price list for satellite and radar imagery last modified	2025-07-08	Apollo Mapping price list	2026-11-24	operator claim (reseller)	13, 14
Planet: Sweden's first sovereign reconnaissance satellite launched May 2026	2026-07-31 (quarter end)	Planet results release	2026-11-22	operator claim	1
ICEYE: seven European governments have procured sovereign radar systems	2026-07-07	ICEYE release, Transporter-17	2026-11-22	operator claim	1, 9, 13
Planet: Germany awarded a dedicated-capacity tender worth up to 25 million euros over five years	2026-08	Planet results release (reprint)	2026-11-22	operator claim	13
Satellogic: about 37 million dollars for three satellites sold in orbit	2026-09-30 (quarter end)	Satellogic results release (reprint)	2026-11-22	operator claim	13

Sensing systems and terms sought and not sourced

Fact sought	Primary source sought	Date sought	Result
Sentinel-1 modes, swaths and repeat intervals; cause and end of Sentinel-1B; end of Sentinel-1A; Sentinel-2, 3, 5P and 6 dates; Copernicus product levels	ESA; Copernicus SentiWiki; Copernicus Data Space Ecosystem	2026-11-23	Not read
Replacement of the Copernicus Open Access Hub and its closing date	Copernicus notices; Data Space documentation	2026-11-23	Not read; Chapter 12 uses another case
Copernicus data regulations in their current text	EUR-Lex: Delegated Regulation 1159/2013; Regulation 2021/696	2026-11-24	Not read; the Commission's legal notice used
NISAR, ALOS-2, ALOS-4, RADARSAT Constellation Mission	JPL, NASA, ISRO, JAXA, Canadian Space Agency	2026-11-23	Not read
Harmonized Landsat and Sentinel-2, EnMAP, ECOSTRESS, Cartosat-3, Resourcesat-2A native sampling, ALOS-3, KOMPSAT-3A, Gaofen	NASA, DLR, JPL, ISRO, JAXA, KARI and Chinese agency pages	2026-11-23	Not read or not stated
CYGNSS, SMOS, ASCAT, ICESat-2, Sentinel-6, MethaneSAT	NASA, ESA, EUMETSAT, EDF	2026-11-23	Not read
Landsat 9 downlink rate; Landsat 9 Data Users Handbook	USGS; NASA	2026-11-23	Not stated in the pages read; handbook not read
World weather satellite register; EUMETCast; GOES-R direct broadcast power	WMO OSCAR; EUMETSAT; GOES-R program documents	2026-11-23	Not read

Fact sought	Primary source sought	Date sought	Result
Total fleets of Planet, Capella, Umbra, BlackSky, Satellogic, HawkEye 360, Spire; ICEYE satellites operating	Operators' own pages and releases	2026-11-22 to 24	Not stated in pages read
Optical tasking terms (Planet, BlackSky, Satellogic); price and license pages of UP42, SkyWatch, Satellogic and ICEYE	Operators' and platforms' pages	2026-11-23 and 24	Not read or not found
CEOS analysis-ready data specifications; STAC specification; OGC API standards	ceos.org; stacspec.org; ogc.org	2026-11-23	Not read

APPENDIX E

Sources

Every dated fact in this book was checked against the source listed for its chapter in November 2026. Primary sources come first: original papers, standards, treaties and regulations, regulator filings and orders, official reports, operator documents and institutional histories. Trade press is labeled as such. Every number in a Link Ledger also carries one of seven evidence classes: measured, calculated, simulated, operator claim, standard, assumption (to verify) or published history. This list holds 298 chapter source entries, including repeated works and notes on the illustrative case. It is drawn from the book's claim tables, which pair each claim with its source and the date it was checked; those tables are part of the book's sources.

Reader's Brief: The Link Is Necessary, Not Sufficient

- IS-GPS-200N, Navstar GPS Space Segment/Navigation User Segment Interfaces (2022-08-01) https://www.gps.gov/sites/default/files/2025-07/IS-GPS-200N.pdf

Prologue: A Clock Overhead, a Camera Overhead

- NOAA NESDIS, Celebrating 65 Years of the World's First Weather Satellite https://www.nesdis.noaa.gov/news/celebrating-65-years-of-the-worlds-first-weather-satellite
- Johns Hopkins APL Technical Digest vol. 19 no. 1 (1998), Danchik, An Overview of Transit Development https://secwww.jhuapl.edu/techdigest/Content/techdigest/pdf/V19-N01/19-01-Danchik.pdf
- Same paper
- ESA, What is Galileo? https://www.esa.int/Applications/Satellite_navigation/Galileo/What_is_Galileo; ISRO, Satellite Navigation Services https://www.isro.gov.in/SatelliteNavigationServices.html; NASA ILRS, GLONASS https://ilrs.gsfc.nasa.gov/missions/satellite_missions/current_missions/g125_general.html
- Lockheed Martin news release, 21 April 2026 https://news.lockheedmartin.com/2026-04-21-Lockheed-Martin-Launches-GPS-III-Satellite,-Paving-the-Way-for-Next-Generation-GPS-IIIF-Spacecraft
- ESA, Two new Galileo satellites enter service (24 July 2026) https://www.esa.int/Applications/Satellite_navigation/Two_new_Galileo_satellites_enter_service
- Copernicus SentiWiki, S1 Mission https://sentiwiki.copernicus.eu/web/s1-mission
- NOAA NESDIS, Celebrating 50 Years of GOES https://www.nesdis.noaa.gov/our-satellites/currently-flying/goes-east-west/celebrating-50-years-of-goes

Chapter 1. Two Kinds of Service That Need Nothing From You

- GPS.gov, Selective Availability https://gps.gov/selective-availability
- Copernicus SentiWiki, S1 Mission https://sentiwiki.copernicus.eu/web/s1-mission
- IS-GPS-200N, Navstar GPS Space Segment/Navigation User Segment Interfaces (2022-08-01) https://www.gps.gov/sites/default/files/2025-07/IS-GPS-200N.pdf
- IS-GPS-200N
- GPS Standard Positioning Service Performance Standard, 5th edition, April 2020 https://www.gps.gov/sites/default/files/2025-07/2020-SPS-performance-standard.pdf
- US Space Force Mission Delta 31 briefing to the CGSIC, 21 April 2026 https://www.gps.gov/sites/default/files/2026-04/Mediate%2020260421_CGSIC%20MD%2031_FINAL.pdf
- GPS SPS Performance Standard, 5th edition, April 2020

- US Geological Survey, Landsat 9 https://www.usgs.gov/landsat-missions/landsat-9 NASA Science, Landsat 9
- ICEYE, ICEYE launches four new satellites aboard Transporter-17 https://iceye.com/newsroom/press-releases/iceye-launches-four-new-satellites-aboard-transporter-17
- Planet Labs, Planet Reports Financial Results for First Quarter of Fiscal Year 2027 https://investors.planet.com/news/news-details/2026/Planet-Reports-Financial-Results-for-First-Quarter-of-Fiscal-Year-2027/default.aspx

Chapter 2. How a Receiver Finds Itself

- IS-GPS-200N, Navstar GPS Space Segment/Navigation User Segment Interfaces (2022-08-01) https://www.gps.gov/sites/default/files/2025-07/IS-GPS-200N.pdf
- Author's calculation: 4.4647E-10 x 86,400 s, times the speed of light
- IS-GPS-200N
- IS-GPS-705J (2022-08) https://www.gps.gov/sites/default/files/2025-07/IS-GPS-705J.pdf
- IS-GPS-800J (2022-08) https://www.gps.gov/sites/default/files/2025-07/IS-GPS-800J.pdf
- Author's calculation from the clauses above
- GPS Standard Positioning Service Performance Standard, 5th edition, April 2020 https://www.gps.gov/sites/default/files/2025-07/2020-SPS-performance-standard.pdf
- GPS SPS Performance Standard, 5th edition
- GPS.gov archive, Space Segment https://archive.gps.gov/systems/gps/space/
- Author's calculation (speed of light 299,792.458 km/s)
- Johns Hopkins APL Technical Digest vol. 19 no. 1 (1998), Danchik, An Overview of Transit Development https://secwww.jhuapl.edu/techdigest/Content/techdigest/pdf/V19-N01/19-01-Danchik.pdf
- NASA ILRS, GLONASS https://ilrs.gsfc.nasa.gov/missions/satellite_missions/current_missions/g125_general.html
- ESA, What is Galileo? https://www.esa.int/Applications/Satellite_navigation/Galileo/What_is_Galileo
- ISRO, Satellite Navigation Services https://www.isro.gov.in/SatelliteNavigationServices.html
- Author's calculation

Chapter 3. The Systems: Four Global, Two Regional

- Lockheed Martin news release, 21 April 2026 https://news.lockheedmartin.com/2026-04-21-Lockheed-Martin-Launches-GPS-III-Satellite,-Paving-the-Way-for-Next-Generation-GPS-IIIF-Spacecraft
- US Space Force Mission Delta 31 briefing to the CGSIC, 21 April 2026 https://www.gps.gov/sites/default/files/2026-04/Mediate%2020260421_CGSIC%20MD%2031_FINAL.pdf
- GPS Standard Positioning Service Performance Standard, 4th edition, September 2008 https://www.gps.gov/sites/default/files/2025-07/2008-SPS-performance-standard.pdf
- GPS SPS Performance Standard, 5th edition, April 2020 https://www.gps.gov/sites/default/files/2025-07/2020-SPS-performance-standard.pdf
- GPS SPS Performance Standard, 4th edition (2008)
- NASA, Global Positioning System History https://www.nasa.gov/general/global-positioning-system-history/
- GPS.gov archive, Space Segment https://archive.gps.gov/systems/gps/space/
- GPS.gov, Space Segment https://www.gps.gov/space-segment
- IS-GPS-200N https://www.gps.gov/sites/default/files/2025-07/IS-GPS-200N.pdf
- IS-GPS-705J https://www.gps.gov/sites/default/files/2025-07/IS-GPS-705J.pdf
- GPS.gov, Interface Control Documents and Interface Specifications https://www.gps.gov/interface-control-documents-icds-interface-specifications-iss
- GPS SPS Performance Standard, 5th edition (2020)
- NASA International Laser Ranging Service, GLONASS https://ilrs.gsfc.nasa.gov/missions/satellite_missions/current_missions/g125_general.html
- Russian Information and Analysis Center for PNT, About GLONASS https://glonass-iac.ru/en/about_glonass/
- European Commission, IP/16/4366, "Galileo goes live!", 14 December 2016 https://ec.europa.eu/commission/presscorner/api/documents?reference=IP/16/4366&language=en
- European Commission, MEMO/16/4382, Galileo Initial Services, 14 December 2016
- ESA, What is Galileo? https://www.esa.int/Applications/Satellite_navigation/Galileo/What_is_Galileo
- ESA, Two new Galileo satellites enter service, 24 July 2026 https://www.esa.int/Applications/Satellite_navigation/Two_new_Galileo_satellites_enter_service

- European Commission, SPEECH/23/341, 24 January 2023
- European Commission, SPEECH/25/2072, 10 September 2025
- European Commission, SPEECH/26/228, 27 January 2026
- European Commission, MEX/21/1602, 6 April 2021
- State Council Information Office, China's BeiDou Navigation Satellite System in the New Era, 4 November 2022 https://english.www.gov.cn/archive/whitepaper/202211/04/content_WS63647de9c6d0a757729e249d.html
- Same white paper
- ISRO, Satellite Navigation Services https://www.isro.gov.in/SatelliteNavigationServices.html
- ISRO-IRNSS-ICD-SPS-1.1, Signal in Space ICD for SPS, version 1.1, August 2017 https://www.isro.gov.in/media_isro/pdf/SateliteNavigation/irnss_sps_icd_version1.1-2017.pdf
- ISRO-NAVIC-ICD-SPS-L1-1.0, version 1.0, August 2023 https://www.isro.gov.in/media_isro/pdf/SateliteNavigation/NavIC_SPS_ICD_L1_final.pdf
- ISRO, NVS-02 Spacecraft On-Orbit Observations https://www.isro.gov.in/NVS-02-Spacecraft-On-Orbit-Observations.html
- ISRO, IRNSS-1F completes 10-year mission, 13 March 2026 https://www.isro.gov.in/IRNSS-F_successfully.html
- ISRO, Final Orbit manoeuvring of NVS03 spacecraft, 4 November 2026 https://www.isro.gov.in/Final_Orbit_manoeuvring_of_NVS03_spacecraft.html
- Experimental Validation of Sensor Fusion-based GNSS Spoofing Attack Detection Framework for Autonomous Vehicles, arXiv 2401.01304 (preprint, not peer reviewed) https://arxiv.org/abs/2401.01304
- Author's reasoning from the counts above and the four-satellite fix of chapter 2
- State Council Information Office, China's BeiDou Navigation Satellite System in the New Era (2022-11-04), full text re-read

Chapter 4. Accuracy and Integrity: Augmentation, Corrections and Monitoring

- Author's calculation; carrier from IS-GPS-200N (2022-08-01) https://www.gps.gov/sites/default/files/2025-07/IS-GPS-200N.pdf
- Property of the normal distribution
- FAA, SBAS worldwide fact sheet, rev. 2025-11-27 https://www.faa.gov/about/office_org/headquarters_offices/ato/service_units/techops/navservices/gnss/library/factsheets/sbas_worldwide-reduced.pdf
- FAA, WAAS Quick Facts, rev. 2025-11-27 https://www.faa.gov/about/office_org/headquarters_offices/ato/service_units/techops/navservices/gnss/library/factsheets/waas-qfacts-reduced.pdf
- FAA, Satellite Navigation, WAAS, How It Works https://www.faa.gov/about/office_org/headquarters_offices/ato/service_units/techops/navservices/gnss/waas/howitworks
- FAA, WAAS Program Overview, 14 June 2021 https://www.faa.gov/sites/faa.gov/files/about/office_org/headquarters_offices/ato/WAAS_Program_Status_Update_Jun_2021.pdf
- FAA William J. Hughes Technical Center, WAAS Performance Analysis Report 98, October 2026 https://www.nstb.tc.faa.gov/reports/FAA_WAAS_PAN_Report_98_v1.0.pdf
- FAA specification FAA-E-2892, as quoted in WAAS Performance Analysis Report 98
- ICAO State letter AN 7/62.1.4-21/41, 6 July 2021, proposed amendment to Annex 10 Vol. I https://www.icao.int/sites/default/files/APAC/GBAS-SBAS/041e_Amendment-to-Annex-10-Vol-I-DFMC_GLONASS_BDS.pdf
- FAA Technical Center, ARAIM Performance Analysis Report 2, February 2021 https://www.nstb.tc.faa.gov/reports/2020_Q2_araim_report_v1.0.pdf
- ISRO, Satellite Navigation Services https://www.isro.gov.in/SatelliteNavigationServices.html
- European Commission, SPEECH/23/341 (2023-01-24); MEX/25/3110 (2025-12-17) https://ec.europa.eu/commission/presscorner/
- State Council Information Office, China's BeiDou Navigation Satellite System in the New Era, 4 November 2022 https://english.www.gov.cn/archive/whitepaper/202211/04/content_WS63647de9c6d0a757729e249d.html
- Trimble, Trimble RTX https://positioningservices.trimble.com/en/rtx
- Swift Navigation, Skylark Precise Positioning Service https://www.swiftnav.com/skylark
- Swift Navigation, RTK for Automotive Autonomy https://www.swiftnav.com/automotive
- RTCM, Publications https://www.rtcm.org/publications

Chapter 5. Time as a Service

- Inside GNSS, "GPS Glitch Caused Outages, Fueled Arguments for Backup", 2016-01-29 https://insidegnss.com/gps-glitch-caused-outages-fueled-arguments-for-backup/
- IS-GPS-200N (2022-08-01), NAVSTAR GPS Space Segment/Navigation User Segment Interfaces https://www.gps.gov/sites/default/files/2025-07/IS-GPS-200N.pdf
- US government, GPS Standard Positioning Service Performance Standard, 5th edition, April 2020 https://www.gps.gov/sites/default/files/2025-07/2020-SPS-performance-standard.pdf
- Same, 5th edition
- IETF RFC 5905, Network Time Protocol Version 4 https://www.rfc-editor.org/rfc/rfc5905
- NASPI Time Synchronization Task Force, Time Synchronization in the Electric Power System, NASPI-2017-TR-001 (PNNL-26331), March 2017 https://www.naspi.org/node/608
- Same report
- ITU-T Recommendation G.8272 (07/2025), Timing characteristics of primary reference time clocks https://www.itu.int/rec/T-REC-G.8272-202507-I/en
- ITU-T Recommendation G.8272.1 (01/2024), Timing characteristics of enhanced primary reference time clocks https://www.itu.int/rec/T-REC-G.8272.1-202401-I/en
- ITU-T Recommendation G.8271 (03/2020), Time and phase synchronization aspects of telecommunication networks https://www.itu.int/rec/T-REC-G.8271-202003-I/en
- FINRA Rule 4590, Synchronization of Member Business Clocks https://www.finra.org/rules-guidance/rulebooks/finra-rules/4590
- FINRA Rule 6820, Clock Synchronization https://www.finra.org/rules-guidance/rulebooks/finra-rules/6820
- Commission Delegated Regulation (EU) 2017/574 https://eur-lex.europa.eu/eli/reg_del/2017/574/oj
- European Space Agency, What is Galileo? https://www.esa.int/Applications/Satellite_navigation/Galileo/What_is_Galileo
- Federal Register vol. 85, no. 32, 2020-02-18, page 9359 https://www.govinfo.gov/link/fr/85/9359
- NIST, Radio Station WWVB, updated 2025-12-17 https://www.nist.gov/pml/time-and-frequency-division/time-distribution/radio-station-wwvb
- Oligeri, Sciancalepore, Di Pietro, GNSS Spoofing Detection via Opportunistic IRIDIUM Signals, ACM WiSec 2020 https://doi.org/10.1145/3395351.3399350 (arXiv 2006.10284)
- https://www.iridium.com/services/iridium-pnt/
- Calculated, Appendix B

Chapter 6. What a One Way Signal Can Promise: Jamming, Spoofing and Fallback

- European Commission, SPEECH/25/2072, Statement by Commissioner Kubilius, 2025-09-10 https://ec.europa.eu/commission/presscorner/api/documents?reference=SPEECH/25/2072&language=en
- European Commission, SPEECH/26/228, 2026-01-27 https://ec.europa.eu/commission/presscorner/api/documents?reference=SPEECH/26/228&language=en
- European Commission, IP/16/4366, "Galileo goes live!", 2016-12-14 https://ec.europa.eu/commission/presscorner/api/documents?reference=IP/16/4366&language=en
- European Space Agency, What is Galileo? https://www.esa.int/Applications/Satellite_navigation/Galileo/What_is_Galileo
- Inside GNSS, "Galileo OSNMA Looking Forward", 2026-01-21 https://insidegnss.com/?p=196179
- Inside GNSS, "Galileo Leads the Way in GNSS Spoofing Protection with OSNMA", 2025-07-24 https://insidegnss.com/galileo-leads-the-way-in-gnss-spoofing-protection-with-osnma/
- EUSPA and GSC web sites
- Motallebighomi, Sathaye, Singh, Ranganathan, Cryptography Is Not Enough: Relay Attacks on Authenticated GNSS Signals, arXiv 2204.11641 (2022) https://arxiv.org/abs/2204.11641
- Seco-Granados, Gomez-Casco, Lopez-Salcedo, Fernandez-Hernandez, Detection of Replay Attacks to GNSS based on Partial Correlations and Authentication Data Unpredictability, arXiv 2010.12502 (preprint, not peer reviewed)
- Yan, Wang, Bian, Meng, Signal Design and Compatibility Assessment for LEO Navigation Augmentation System, Engineering Proceedings 88, 17 (2025) https://doi.org/10.3390/engproc2025088017
- IS-GPS-200N https://www.gps.gov/sites/default/files/2025-07/IS-GPS-200N.pdf
- GPS Standard Positioning Service Performance Standard, 5th edition, April 2020 https://www.gps.gov/sites/default/files/2025-07/2020-SPS-performance-standard.pdf

- Inside GNSS, "EASA Issues Updated Advisory on GNSS Outages and Navigation Disruptions", 2024-07-08 https://insidegnss.com/easa-issues-updated-advisory-on-gnss-outages-and-navigation-disruptions/ (the bulletin itself could not be read)
- Morales-Ferre, Richter, Falletti, de la Fuente, Lohan, A Survey on Coping With Intentional Interference in Satellite Navigation for Manned and Unmanned Aircraft, IEEE Communications Surveys and Tutorials 22(1), 2020 https://doi.org/10.1109/comst.2019.2949178
- Inside GNSS, "Galileo Initial Services Have Now Been Restored", 2019-07-18 https://insidegnss.com/galileo-initial-services-have-now-been-restored/
- Inside GNSS, "Brussels View: Lessons to be Learned from Galileo Signal Outage", 2019-09-19 https://insidegnss.com/brussels-view-lessons-to-be-learned-from-galileo-signal-outage/
- GSC and EUSPA sites
- NASPI-2017-TR-001 (PNNL-26331), March 2017 https://www.naspi.org/node/608
- NIST, Radio Station WWVB, updated 2025-12-17 https://www.nist.gov/pml/time-and-frequency-division/time-distribution/radio-station-wwvb
- Oligeri, Sciancalepore, Di Pietro, ACM WiSec 2020 https://doi.org/10.1145/3395351.3399350

Chapter 7. The Buyer's First Questions: Observable, Resolution, Revisit, Latency

- US Geological Survey, Landsat 9 https://www.usgs.gov/landsat-missions/landsat-9
- US Geological Survey, Landsat 8 https://www.usgs.gov/landsat-missions/landsat-8
- US Geological Survey, Landsat Collection 2 https://www.usgs.gov/landsat-missions/landsat-collection-2
- US Geological Survey, Landsat Satellite Missions https://www.usgs.gov/landsat-missions/landsat-satellite-missions
- US Geological Survey, Landsat 10 (address landsat-next) https://www.usgs.gov/landsat-missions/landsat-next
- NOAA NESDIS, Celebrating 50 Years of GOES https://www.nesdis.noaa.gov/our-satellites/currently-flying/goes-east-west/celebrating-50-years-of-goes
- NOAA OSPO, GOES Rebroadcast (GRB) https://www.ospo.noaa.gov/operations/goes/grb/
- EUMETSAT, EUMETSAT releases pre-operational data from MTG imager (2024-09-23) https://www.eumetsat.int/eumetsat-releases-pre-operational-data-mtg-imager
- Copernicus SentiWiki, S1 Mission https://sentiwiki.copernicus.eu/web/s1-mission
- Italian Space Agency, PRISMA https://www.asi.it/en/earth-science/prisma/
- EUMETSAT, Metop series https://www.eumetsat.int/our-satellites/metop-series
- US Geological Survey, Landsat 1 https://www.usgs.gov/landsat-missions/landsat-1
- NOAA OSPO, GOES Instrument and Subsystem Performance Status https://www.ospo.noaa.gov/operations/goes/status.html
- Calculated: pixels per area scale with the inverse square of the sample distance
- Calculated: circular orbit with a period of one sidereal day (86,164 s), Earth's gravitational parameter 398,600 km3/s2 and equatorial radius 6,378 km (Appendix B)

Chapter 8. Optical, Thermal and Hyperspectral Sensing

- US Geological Survey, Landsat 7 https://www.usgs.gov/landsat-missions/landsat-7
- US Geological Survey, Landsat 1 https://www.usgs.gov/landsat-missions/landsat-1
- US Geological Survey, Landsat 9 https://www.usgs.gov/landsat-missions/landsat-9
- US Geological Survey, Landsat 8 and Landsat 9 pages https://www.usgs.gov/landsat-missions/landsat-8
- CNES, SPOT https://cnes.fr/en/projects/spot
- Italian Space Agency, PRISMA https://www.asi.it/en/earth-science/prisma/
- Calculated from the Rayleigh criterion (Appendix B); illustrative inputs, no real instrument
- Planet Labs, Planet Reports Financial Results for First Quarter of Fiscal Year 2027 https://investors.planet.com/news/news-details/2026/Planet-Reports-Financial-Results-for-First-Quarter-of-Fiscal-Year-2027/default.aspx
- Planet Labs, Q1 FY2027 release (above) and Q2 FY2027 release via Finviz https://finviz.com/news/388883/planet-reports-financial-results-for-second-quarter-of-fiscal-year-2027
- Satellogic, Satellogic Reports Third Quarter 2026 Financial Results, via Finviz https://finviz.com/news/420504/satellogic-reports-third-quarter-2026-financial-results

- SEC, BlackSky Technology Form 8-K exhibit 99.1 (2026-11-05) https://www.sec.gov/Archives/edgar/data/0001753539/000175353926000154/exhibit991-blackskyq32026e.htm
- Vantor, Welcome to the new frontier of spatial intelligence https://vantor.com/blog/welcome-to-the-new-frontier-of-spatial-intelligence/
- INPE, home page (Portuguese) https://www.gov.br/inpe/
- National Remote Sensing Centre, ISRO, home page https://www.nrsc.gov.in/

Chapter 9. Radar Sensing

- Copernicus SentiWiki, S1 Mission https://sentiwiki.copernicus.eu/web/s1-mission
- US Geological Survey, Volcano Hazards Program, InSAR: satellite-based technique captures overall deformation picture https://www.usgs.gov/programs/VHP/insar-satellite-based-technique-captures-overall-deformation-picture
- Guerra, Francisco, Villate, Aguado Agelet, Bertolami, Rajan, On small satellites for oceanography: A survey, Acta Astronautica (2016) https://doi.org/10.1016/j.actaastro.2016.06.007
- UrtheCast second-generation Earth observation sensors, ISPRS Archives XL-7/W3 (2015) https://doi.org/10.5194/isprsarchives-xl-7-w3-1069-2015
- Krieger, Zink, Moreira, TanDEM-X: A radar interferometer with two formation flying satellites, IAC-12-B4.7B.3 (2012), published in Acta Astronautica https://doi.org/10.1016/j.actaastro.2013.03.008
- ESA, Satellite frequency bands https://www.esa.int/Applications/Connectivity_and_Secure_Communications/Satellite_frequency_bands
- Calculated in this book: wavelength = speed of light over frequency; one cycle = half a wavelength for a two way path
- Agenzia Spaziale Italiana, COSMO-SkyMed https://www.asi.it/en/earth-science/cosmo-skymed/
- CONAE, SAOCOM https://www.argentina.gob.ar/ciencia/conae/misiones-espaciales/saocom
- nisar.jpl.nasa.gov; science.nasa.gov/mission/nisar; global.jaxa.jp/projects/sat/alos2 and alos4; eorc.jaxa.jp; asc-csa.gc.ca/eng/satellites/radarsat; isro.gov.in/NISAR.html
- ICEYE, ICEYE launches four new satellites aboard Transporter-17 https://iceye.com/newsroom/press-releases/iceye-launches-four-new-satellites-aboard-transporter-17
- ICEYE, SAR product specification https://sar.iceye.com/latest/productspecification/dataproducts/
- Capella Space, IonQ Completes Acquisition of Capella Space https://www.capellaspace.com/press-releases/ionq-completes-acquisition-of-capella-space-advancing-vision-for-space-based-quantum-communications
- Via Satellite, Umbra Secures Launch for Next 7 SAR Satellites With Increased Capabilities https://www.satellitetoday.com/imagery-and-sensing/2026/11/16/umbra-secures-launch-for-next-7-sar-satellites-with-increased-capabilities/
- IS-GPS-200N (the dual-frequency relation used in chapter 2), applied by the author

Chapter 10. Weather and Climate Data: Imagers, Sounders and the Products Built on Them

- NOAA Office of Satellite and Product Operations, GOES Instrument and Subsystem Performance Status https://www.ospo.noaa.gov/operations/goes/status.html
- NOAA NESDIS, Celebrating 50 Years of GOES https://www.nesdis.noaa.gov/our-satellites/currently-flying/goes-east-west/celebrating-50-years-of-goes
- NOAA NESDIS, Celebrating 65 Years of the World's First Weather Satellite https://www.nesdis.noaa.gov/news/celebrating-65-years-of-the-worlds-first-weather-satellite
- European Space Agency, Forty years of Meteosat https://www.esa.int/About_Us/ESA_history/Forty_years_of_Meteosat
- EUMETSAT, Meteosat Second Generation https://www.eumetsat.int/meteosat-second-generation
- EUMETSAT, Meteosat Third Generation https://www.eumetsat.int/meteosat-third-generation
- EUMETSAT, Meteosat Third Generation, launch hub link text
- EUMETSAT, EUMETSAT releases pre-operational data from MTG imager (2024-09-23) https://www.eumetsat.int/eumetsat-releases-pre-operational-data-mtg-imager
- EUMETSAT, Meteosat Third Generation imaging services https://www.eumetsat.int/meteosat-third-generation-imaging-services
- EUMETSAT, Meteosat Third Generation sounding services https://www.eumetsat.int/meteosat-third-generation-sounding-services
- EUMETSAT, Metop series https://www.eumetsat.int/our-satellites/metop-series
- NOAA Office of Satellite and Product Operations, JPSS status https://www.ospo.noaa.gov/operations/jpss/status.html

- World Meteorological Organization, WMO Unified Data Policy https://wmo.int/wmo-unified-data-policy
- EUMETSAT, Data policy https://www.eumetsat.int/legal-framework/data-policy
- NOAA Office of Satellite and Product Operations, GOES Rebroadcast (GRB) https://www.ospo.noaa.gov/operations/goes/grb/
- NOAA Office of Satellite and Product Operations, HRIT/EMWIN https://www.ospo.noaa.gov/operations/goes/hrit/index.html
- Calculated from about 2 x 35,786 km or more at the speed of light (Appendix B)
- Calculated from the NOAA OSPO status dates above
- Calculated: circular orbit with a period of one sidereal day (86,164 s), Earth's gravitational parameter 398,600 km3/s2 and equatorial radius 6,378 km (Appendix B)

Chapter 11. Other Sensors a Buyer Meets: Listening, Microwave, Altimetry and Gases

- UCAR COSMIC Program, COSMIC-2 https://www.cosmic.ucar.edu/what-we-do/cosmic-2
- UCAR COSMIC Program, GNSS radio occultation https://www.cosmic.ucar.edu/what-we-do/gnss-radio-occultation
- Spire Global, System and method for high-resolution radio occultation measurement through the atmosphere, US Patent 10,379,260 (2019) https://patents.justia.com/patent/10379260
- Spire Global, Spire Global Announces Second Quarter 2026 Results https://ir.spire.com/news-events/press-releases/detail/309/spire-global-announces-second-quarter-2026-results
- SES S.A., Apparatuses, systems and methods for obtaining information about electromagnetic energy emitted from the earth, US Patent 9,086,471 (2015) https://patents.justia.com/patent/9086471
- Clements, Ellis, Goodridge, Murrian, Psiaki, Humphreys, Single-Satellite-Based Geolocation of Broadcast GNSS Spoofers from Low Earth Orbit, arXiv 2503.17791 (preprint, not peer reviewed) https://arxiv.org/abs/2503.17791
- HawkEye 360, HawkEye 360 Announces Third Quarter 2026 Financial Results (press release via Finviz) https://finviz.com/news/422050/hawkeye-360-announces-third-quarter-2026-financial-results
- ITU, Recommendation ITU-R M.1371 https://www.itu.int/rec/R-REC-M.1371
- Spire Global, Spire Global Completes Sale of Maritime Business; Debt Eliminated https://ir.spire.com/news-events/press-releases/detail/251/
- Spire Global, AIS spoofing and dark-target detection methodology, US Patent 11,156,723 (2021) https://patents.justia.com/patent/11156723
- NASA JPL, SMAP https://smap.jpl.nasa.gov/
- NASA JPL, SWOT https://swot.jpl.nasa.gov/; and https://swot.jpl.nasa.gov/mission/overview/
- TROPOMI team, tropomi.eu https://www.tropomi.eu/
- Planet Labs, Planet Reports Financial Results for First Quarter of Fiscal Year 2027 https://investors.planet.com/news/news-details/2026/Planet-Reports-Financial-Results-for-First-Quarter-of-Fiscal-Year-2027/default.aspx
- science.nasa.gov/mission/cygnss; clasp-research.engin.umich.edu; earth.esa.int/eogateway/missions/smos; eumetsat.int/ascat; icesat-2.gsfc.nasa.gov; sealevel.jpl.nasa.gov; methanesat.org; edf.org

Chapter 12. From Photon to Product: Tasking, Downlink, Processing, Delivery, Acceptance

- US Geological Survey, Landsat 9 https://www.usgs.gov/landsat-missions/landsat-9
- Research record of USGS and NASA Landsat 9 pages (USGS Landsat 9; NASA Science, Landsat 9)
- US Geological Survey, Landsat Ground Network https://www.usgs.gov/landsat-missions/landsat-ground-network
- US Geological Survey, Landsat Collection 2 https://www.usgs.gov/landsat-missions/landsat-collection-2
- US Geological Survey, Landsat Collection 2 Level-1 Data https://www.usgs.gov/landsat-missions/landsat-collection-2-level-1-data
- US Geological Survey, Landsat Collection 2 Level-2 Science Products https://www.usgs.gov/landsat-missions/landsat-collection-2-level-2-science-products
- US Geological Survey, Landsat U.S. Analysis Ready Data https://www.usgs.gov/landsat-missions/landsat-us-analysis-ready-data
- Calculated in this book (spherical Earth, WGS 84 radius, Earth rotation ignored; slant range and central angle formulas of Appendix B)

- Copernicus SentiWiki, S1 Mission https://sentiwiki.copernicus.eu/web/s1-mission
- Capella Space support, How do I order with Capella? https://support.capellaspace.com/how-do-i-order-with-capella (dated 2025-06-06)
- Capella Space support, What are Capella's collection tiers? https://support.capellaspace.com/what-are-capellas-collection-tiers (dated 2025-06-06)
- Capella Space support, What is the tasking cancellation policy? https://support.capellaspace.com/what-is-the-tasking-cancellation-policy (dated 2025-06-06)
- Capella Space support, How are imagery products delivered? https://support.capellaspace.com/how-are-imagery-products-delivered (dated 2025-05-13)
- Capella Space, home page https://www.capellaspace.com/
- Umbra, Canopy API documentation https://docs.canopy.umbra.space/
- Umbra, Task lifecycle tutorial https://docs.canopy.umbra.space/docs/task-lifecycle-tutorial.md (updated 2025-09-23)
- Umbra, Scheduling best practices https://docs.canopy.umbra.space/docs/scheduling-best-practices.md (updated 2025-09-24)
- ICEYE, SAR product specification https://sar.iceye.com/latest/productspecification/tasking/; and https://sar.iceye.com/latest/productspecification/dataproducts/
- ICEYE, SAR data tasking https://www.iceye.com/defense-and-intelligence/sar-data/tasking
- US SEC, BlackSky Technology Form 8-K exhibit 99.1 (2026-11-05) https://www.sec.gov/Archives/edgar/data/0001753539/000175353926000154/exhibit991-blackskyq32026e.htm
- HawkEye 360, Third Quarter 2026 Financial Results (press release via Finviz) https://finviz.com/news/422050/hawkeye-360-announces-third-quarter-2026-financial-results
- Microsoft, Retirement: Azure Orbital Ground Station Retirement (message as archived) https://mc.merill.net/message/AZ-azure-orbital-ground-station-retirement
- Microsoft Learn, Azure Orbital Ground Station https://learn.microsoft.com/en-us/azure/orbital/about-ground-stations
- Calculated in this book from the notice's dates
- The first book of this series, LL-2016-01 (calculated, distance over the speed of light)
- dataspace.copernicus.eu; documentation.dataspace.copernicus.eu; scihub.copernicus.eu; stacspec.org; github.com/radiantearth/stac-spec; ogcapi.ogc.org; ceos.org/ard; developers.planet.com; planet.com; blacksky.com; satellogic.com
- Author's calculation (Appendix B.6 model)

Chapter 13. Open Programs and Commercial Suppliers: Licenses, Prices, Platforms and Rules

- Capella Space, Capella Consolidated License Agreement v2.1 05292026 (PDF) https://cdn.prod.website-files.com/6970b8a0eb7e9ae5e1a148f0/6a2367ddd1ca422d18b6afba_Capella%20Consolidated%20License%20Agreement%20v2.1%2005292026.pdf
- Capella License Agreement v2.1 (above)
- Capella Space, Legal and Compliance Information https://www.capellaspace.com/legal
- US Geological Survey, Landsat Data Access https://www.usgs.gov/landsat-missions/landsat-data-access
- European Commission, Legal notice on the use of Copernicus Sentinel Data and Service Information https://sentinels.copernicus.eu/documents/247904/690755/Sentinel_Data_Legal_Notice
- eur-lex.europa.eu, CELEX 32013R1159 and 32021R0696
- US Geological Survey, Landsat Next (now titled Landsat 10) https://www.usgs.gov/landsat-missions/landsat-next
- Apollo Mapping, Price List: Medium + High-Resolution Satellite, SAR and Aerial Imagery https://apollomapping.com/image_downloads/Apollo_Mapping_Imagery_Price_List.pdf
- Calculated in this book from the price list above
- Planet Labs, Planet Reports Financial Results for Second Quarter of Fiscal Year 2027 (press release via Finviz) https://finviz.com/news/388883/planet-reports-financial-results-for-second-quarter-of-fiscal-year-2027
- ICEYE, ICEYE launches four new satellites aboard Transporter-17 https://iceye.com/newsroom/press-releases/iceye-launches-four-new-satellites-aboard-transporter-17
- Satellogic, Satellogic Reports Third Quarter 2026 Financial Results (press release via Finviz) https://finviz.com/news/420504/satellogic-reports-third-quarter-2026-financial-results
- Vantor, Welcome to the new frontier of spatial intelligence https://vantor.com/blog/welcome-to-the-new-frontier-of-spatial-intelligence/

- Capella Space, IonQ Completes Acquisition of Capella Space https://www.capellaspace.com/press-releases/ionq-completes-acquisition-of-capella-space-advancing-vision-for-space-based-quantum-communications
- Spire Global, Spire Global Completes Sale of Maritime Business; Debt Eliminated https://ir.spire.com/news-events/press-releases/detail/251/
- ICEYE, SAR product specification 6.0.8 https://sar.iceye.com/latest/productspecification/dataproducts/
- United States Code, 51 U.S.C. 60121 and 60122 (2023 edition) https://www.govinfo.gov/app/details/USCODE-2023-title51/USCODE-2023-title51-subtitleVI-chap601
- Public Law 98-365, 98 Stat. 451 https://www.govinfo.gov/content/pkg/STATUTE-98/pdf/STATUTE-98-Pg451.pdf
- Umbra, Order from the Archive Catalog https://docs.canopy.umbra.space/docs/using-the-archive-catalog.md (updated 2026-08-03)
- up42.com/pricing; skywatch.com/pricing; satellogic.com/legal; iceye.com/terms-and-conditions

Chapter 14. Writing the Requirement and Reading the Offer

- ISRO, NVS-02 Spacecraft On-Orbit Observations (as cited in Chapter 3) https://www.isro.gov.in/NVS-02-Spacecraft-On-Orbit-Observations.html
- GPS Standard Positioning Service Performance Standard, 5th edition, April 2020 (as cited in Chapters 2 and 3) https://www.gps.gov/technical/ps/2020-SPS-performance-standard.pdf
- GPS SPS Performance Standard 2020 (as cited in Chapter 5)
- ITU-T Recommendation G.8271 (03/2020) https://www.itu.int/rec/T-REC-G.8271-202003-I/en (as cited in Chapter 5)
- US Geological Survey, Landsat 9 and Collection 2 Level-2 pages (as cited in Chapters 7 and 12) https://www.usgs.gov/landsat-missions/landsat-9
- Calculated: 9 x 30 m x 30 m = 8,100 square meters
- As cited in Chapter 12 and its claim table (ICEYE SAR product specification 6.0.8; ICEYE tasking page; Umbra documentation; Capella Space support articles and home page)
- Calculated in this book; the 0.6 is an assumption for illustration, not a published figure
- Apollo Mapping, Price List: Medium + High-Resolution Satellite, SAR and Aerial Imagery https://apollomapping.com/image_downloads/Apollo_Mapping_Imagery_Price_List.pdf
- Calculated from the price list above
- Satellogic, Satellogic Reports Third Quarter 2026 Financial Results (press release via Finviz) https://finviz.com/news/420504/satellogic-reports-third-quarter-2026-financial-results
- GPS SPS Performance Standard 2020 (as cited in Chapter 3 and Appendix D)
- ESA, Two new Galileo satellites enter service, 24 July 2026 https://www.esa.int/Applications/Satellite_navigation/Two_new_Galileo_satellites_enter_service
- Capella Space, Capella Consolidated License Agreement v2.1 05292026 (PDF) https://cdn.prod.website-files.com/6970b8a0eb7e9ae5e1a148f0/6a2367ddd1ca422d18b6afba_Capella%20Consolidated%20License%20Agreement%20v2.1%2005292026.pdf
- Capella License Agreement v2.1 (above)
- The first book of this series, The Bit's Path, chapter 12
- ICEYE, SAR product specification, Tasking https://sar.iceye.com/latest/productspecification/tasking/ (no version or date shown on the page when re-read)

Epilogue: What Moves Next

- European Commission, SPEECH/25/2072, 2025-09-10 https://ec.europa.eu/commission/presscorner/api/documents?reference=SPEECH/25/2072&language=en
- Calculated (Appendix B); US Geological Survey, Landsat 9 https://www.usgs.gov/landsat-missions/landsat-9

Appendix B. Formulas and Check Values

- BIPM, The International System of Units (SI Brochure), 9th edition, 2019
- NGA, World Geodetic System 1984 (WGS 84), NGA.STND.0036
- IS-GPS-200N https://www.gps.gov/sites/default/files/2025-07/IS-GPS-200N.pdf
- GPS Standard Positioning Service Performance Standard, 5th edition, April 2020 https://www.gps.gov/sites/default/files/2025-07/2020-SPS-performance-standard.pdf

- Calculated with the matrix form in B.3 (calculated by the author from the stated geometries)
- IETF RFC 5905 https://www.rfc-editor.org/rfc/rfc5905
- NASPI-2017-TR-001 (PNNL-26331), March 2017 https://www.naspi.org/node/608
- Calculated from the formulas and inputs printed in B.4 to B.6
- US Geological Survey, Landsat 9 https://www.usgs.gov/landsat-missions/landsat-9
- Guerra, Francisco, Villate, Aguado Agelet, Bertolami, Rajan, On small satellites for oceanography: A survey, Acta Astronautica (2016) https://doi.org/10.1016/j.actaastro.2016.06.007
- Derived in B.7 from the two relations above; a primary statement was sought (NASA Earthdata SAR page) and could not be read
- Copernicus SentiWiki, S1 Mission (Sentinel-1 C band), as cited in chapter 9
- Calculated in B.6 from Kepler's third law with the WGS 84 constants of B.1
- Calculated in B.6 (slant range formula with the mean radius of B.1; distance over the speed of light)
- Calculated in B.6 (same method as the 705 km row)
- The issuing bodies' own sites (FCC and eCFR, EUR-Lex, BIPM, IERS, EASA, MARAD, FAA, USGS)

Appendix C. Glossary

- IS-GPS-200N, Navstar GPS Space Segment/Navigation User Segment Interfaces (2022-08-01) https://www.gps.gov/sites/default/files/2025-07/IS-GPS-200N.pdf
- GPS Standard Positioning Service Performance Standard, 5th edition, April 2020 https://www.gps.gov/sites/default/files/2025-07/2020-SPS-performance-standard.pdf
- GPS.gov, Selective Availability https://gps.gov/selective-availability
- Johns Hopkins APL Technical Digest vol. 19 no. 1 (1998), Danchik, An Overview of Transit Development https://secwww.jhuapl.edu/techdigest/Content/techdigest/pdf/V19-N01/19-01-Danchik.pdf

Appendix D. Dated Register: Systems, Fleets, Service Status, and Systems Sought and Not Sourced

- As listed in the claim tables of chapter 3 (GPS.gov Space Segment; Space Force CGSIC briefing 2026-04-21; Lockheed Martin release 2026-04-21; GPS SPS Performance Standard 2008 and 2020; glonass-iac.ru About GLONASS; European Commission IP/16/4366, SPEECH/23/341, SPEECH/25/2072, SPEECH/26/228; ESA pages; BeiDou white paper 2022-11-04; ISRO notices and interface documents)
- As listed in the claim table of chapter 4 (FAA fact sheets of 2025-11-27; FAA WAAS Performance Analysis Report 98; FAA WAAS Program Overview 2021-06-14; ISRO; BeiDou white paper; Trimble; Swift Navigation)
- As listed in the claim tables of chapters 7 to 12 (USGS Landsat 5, 7, 9 and Landsat Next pages; Copernicus SentiWiki S1 Mission; NOAA OSPO GOES and JPSS status; EUMETSAT MSG, MTG and Metop pages; ASI COSMO-SkyMed; CONAE SAOCOM; UCAR COSMIC-2)
- US Geological Survey, Landsat 5 https://www.usgs.gov/landsat-missions/landsat-5
- As listed in the claim tables of chapters 8, 9, 11 and 13 (operator releases, SEC exhibit, Via Satellite)
- As listed in the claim tables of chapters 12 and 13
- As listed in the claim tables of chapters 1, 2 and 3
- As listed in the claim tables of chapters 5 and 6
- As listed in the claim tables of chapters 1 and 7 to 13
- State Council Information Office, China's BeiDou Navigation Satellite System in the New Era (2022-11-04)
- https://www.navcen.uscg.gov/gps-constellation

THE SERIES

Every Bit Lands

Every Bit Lands is a series about satellites, end to end: how each system divides the work between the user's end, the satellite and the ground, whether each hop closes, and what one engineer can use, rent and build. This is its sixth book. Each book stands on its own.

Also by the author:

OTHER SERIES

From Terminal to Agent
Every Boundary Holds

From Code to Glass
Every Pixel Matters

From Tally to Token
Every Record Counts

From Warehouse to Lakehouse
Every Record Counts

Data on Every Desk
Every Record Counts

Governing Rust by Contract
GDCD in Code

AI Foundry by Contract
GDCD on Azure

From Bit to Pixel
Every Pixel Matters

From Silicon to Screen
Every Pixel Matters

The Model as Reader
Every Record Counts

What a Value Means
Every Record Counts

The Contract Decides
GDCD Field Guides

Governing Azure by Contract
GDCD on Azure

From Bronze to Gold
The Medallion Series

FIELD GUIDES

Ten Engineers, the Output of Thirty
Field guide

The Fifth Mind
Field guide

Every Pixel Matters
Field guide

The Forge and The Universe
Field guide

Who Is the Agent?
Field guide

The Agent Loop
Field guide

The Mesh
Field guide

The Crystal and The Ocean
Field guide

The Story of Azure
Field guide

The Security You Can Watch
Field guide

Juan Cardena

Enterprise AI & Agentic Systems Architect · blog.jcardena.com

Download the latest edition and the blank Link Ledger and the budget sheet at blog.jcardena.com/en/ebooks/eyes-and-clocks.

Every Bit Lands · Book 6 · Eyes and Clocks.