

THE SATELLITE SERIES, LINK BY LINK

The Bit's Path

Satellite links, end to end

A satellite link is a division of labor. Someone has to supply the power, the antenna area, the processing, the money and the risk, and every system splits them differently between the user's end, the satellite and the ground. This book follows one bit along the real paths of a link, hop by hop, and gives the reader the Link Ledger: two pages that record what a link must deliver, whether each hop closes, and what evidence stands behind every number.

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CONTENTS

BEFORE THE PATH

Reader's Brief: the Link Ledger and Six Questions

Prologue: One Picture in 1962, One Message in 2026

PART I: WHERE, HOW FAR, WHICH BAND

01 What Must Be Delivered

02 Orbits and Passes

03 Bands and Antennas

PART II: DOES THE HOP CLOSE

04 The Hop Budget

05 Modulation and Coding

06 Delay, Doppler and Acquisition

PART III: THROUGH THE SATELLITE AND DOWN TO THE SCREEN

07 Framing

08 The Payload: Transparent, Regenerative, Crosslinked

09 Optical Links

10 From the Gateway to the Screen

PART IV: WHO CAN INTERFERE, AND HOW TO CHECK A CLAIM

11 The Security of a Link

12 Reading a Link End to End

Epilogue: Who Supplies the Margin Next

APPENDICES

A The Link Ledger: Blank, Field Guide and Index

B The Decibel and the Budget Sheet

C Glossary

D Dated Register of Volatile Facts, as of the book's date

E Sources

BEFORE THE PATH

Reader's Brief: the Link Ledger and Six Questions



Every satellite link asks the same question of the people who build it: who supplies the margin? This book follows one bit from the user's end, up to a satellite, down to the ground and on to a screen, and at every station it asks who pays for the bit's safe arrival in power, antenna area, processing, money and risk.

The question of the series

A satellite link is a division of labor. Three parties can carry the load: the user's end, the satellite, and the ground. In 1962 a ground station with a horn antenna seven stories high did almost all of the work, and the satellite was a small sphere with a 2 watt transmitter. In 2026 a phone in a pocket cannot grow a larger antenna, so the satellite has to carry the load instead.

Each system in this book is read the same way: how was the work divided between user, space and ground, what limits drove that split, and did it work? Three verdicts are kept apart. The link may work while the service fails, and the service may work while the business fails.

One form, two pages

The tool of the book is a two-page form called the Link Ledger. Page 1 describes the service in ten fields: the requirement, the ends and the path, the orbit, the band and the permission to use it, capacity, who owns each end, trust, how the link fails and how anyone would see it, the shape of the cost, and the numbers that carry the argument. Page 2 is the hop budget: one block for each radio or optical hop, as many pages as the hops need, adding gains and losses in decibels until it shows whether the receiver gets what it needs, and by how much.

A worked form comes in one of three classes. A **full** form has both pages. A **service** form has page 1 only, and says why there is no budget; often the reason is that the operator does not publish the waveform. A **budget** form has page 2 only. Figure R.1 shows the form in brief.

FIGURE R.1

The Link Ledger in brief: ten fields on page 1, one budget per hop on page 2

Page	Field or line	What goes in it
Header	Id, date, system, status, class	One id per link; status Planned, In service, Suspended, Retired or Failed; class full, service or budget
1	1 Requirement	What must be delivered, by when: size, deadline, rate, coverage, availability, terminal limits
1	2 Ends and path	The two ends, and whether the satellite repeats, regenerates, crosslinks or stores the signal
1	3 Orbit and time	Altitude, passes or continuous view, delay
1	4 Band and permission	Frequency of each hop; who holds the right to use it, and where
1	5 Capacity	Rate up and down, peak and sustained, and who shares it
1	6 Who owns each end	Space segment, ground segment, customer relationship, the exit
1	7 Trust	Who can command, listen or interfere
1	8 How it fails, and how we would see it	The failure mode and the signal that shows it
1	9 Cost shape	What is paid, when, and what the price leaves out
1	10 Evidence	The numbers that carry the argument, each with its class, source and date

Page	Field or line	What goes in it
2	Transmit	Transmitter output, feeder loss, antenna gain (EIRP)
2	Losses	Free space, atmosphere and rain, polarization and pointing
2	Receive	Receive gain or G/T, system noise temperature
2	Bandwidth, interference, coding	Information rate (for Eb/N0), symbol rate (for Es/N0) or noise bandwidth (for C/N); the step to C/(N+I); modulation, code, implementation loss
2	Required and margin	Required Eb/N0 or Es/N0 (dB), or C/N0 (dBHz), for a stated error rate, its source, the margin, the operating point

The blank form, reduced; the full blank pages with the field guide are in Appendix A.

Author's form, following the series' Link Ledger.

Six questions

The ten fields answer six questions. They are the questions an engineer, an architect or a buyer should ask of any satellite service, before the first purchase order.

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?

"Close" has a precise meaning in this book. A hop closes when the signal quality at the receiver is above what the receiver needs, at a stated operating point: a rate, a direction, an elevation angle, the weather, and the availability the link was designed for. A hop never

simply "closes". In the hypothetical model hop of chapter 4, for example, it closes at 64 kbit/s, upward, at 30 degrees elevation, in open sky, for a stated error rate, with 3 dB to spare; at another operating point the same hop does not.

The decibel in one page

Radio engineers add instead of multiplying. A **decibel** (dB) is ten times the base-ten logarithm of a power ratio. Gains and losses are power ratios, and multiplying ratios becomes adding their decibels, which is why a hop budget is a column of numbers with a sum at the bottom.

Decibels worth remembering

Decibels	Power ratio	Read it as
+3 dB	about 2	twice the power
+10 dB	10	ten times the power
+20 dB	100	a hundred times
-3 dB	about 0.5	half the power
-160 dB	one part in 10^{16}	close to the free-space path loss of 159 dB at 1.9 GHz over about 1,075 km, from a phone to a low orbit satellite (chapter 4)

A unit after "dB" names the reference. **dBW** is power relative to one watt and **dBm** relative to one milliwatt, so 30 dBm is 0 dBW, and the nominal 23 dBm of a power class 3 phone is about 0.2 watt. **dBi** is antenna gain relative to an ideal antenna that radiates equally in every direction. **dB/K** is the unit of G/T, a receiver's antenna gain divided by its noise temperature in kelvin: the single number that says how well a receiving station hears. Appendix B gives the formulas.

A budget ends in one of three ratios, and the form names which. **C/No**, carrier to noise density in dBHz, describes the hop before any waveform is chosen. Subtract the **information rate** in decibels and it becomes **Eb/No**, the energy per useful bit: Eb/No = C/No less 10 log10(information rate). Count that rate at the same point as the threshold it is compared with: a modem's threshold usually counts the bits entering its code, framing included, not the application's payload. Subtract the **symbol rate** instead and it becomes **Es/No**, the energy per transmitted symbol: Es/No = C/No less 10 log10(symbol rate), which is also C/N in a noise bandwidth equal to the symbol rate. The two differ by the bits each symbol carries after the code. Use the one the source of the required value uses: the

DVB-S2 standard tables Es/N0, so chapter 4's Ka band example writes a symbol rate of 100 Mbaud and a required Es/N0, while its phone uplink writes an information rate and a required Eb/N0.

Where each number comes from

Every number on a worked form carries one of seven classes, a source and a date. The date is the day the source was read for this book; when a measurement was made, or a history written, the source says so.

The seven classes

Class	It means
measured	Read from an instrument or a log, by a named party, on a date
calculated	Follows from stated inputs by a formula the book gives
simulated	A named model with named settings produced it
operator claim	The operator or supplier stated it; no independent check is known to the book's sources
standard	A published standard or regulation gives it, clause or table named
assumption	No primary source read yet; printed "assumption, to verify", with what would settle it
published history	An official agency history or audit report, or labeled scholarship, reports it; the work and the page are named

These seven are the only classes in the book. Where it helps, a label in brackets says what carried the fact: trade press reporting what an operator said is still an operator claim; a regulator's order or authorization, such as an FCC grant, is classed as standard, labeled a regulatory document; an operator's own application or securities filing is an operator claim. An operator claim is never promoted to a measurement. Where an operator does not publish a number, the form says "not published", or the budget solves for it: "the G/T the satellite must have for this hop to close". No number in this book was measured by its author.

The **bench link** that runs through the chapters, a weather satellite's broadcast received on a dipole, is an exercise for the reader: a link small enough to predict on paper and then try with a receive-only radio. The author has not run it, and no argument in the book rests on it; its ledger says "measured: none yet" and is printed as a prediction to be tested.

What the form does not do

The form gives a structured first assessment. It does not qualify a service. Coverage over a country, capacity under load, availability over a year, interference from other systems and the legal right to transmit all need analysis that two pages cannot hold. What the form does is show where that analysis is missing, which questions go to the supplier, and which go to a specialist. A filled form with honest gaps is worth more than a brochure with none.

The modern examples are **illustrative, not a market survey**. They were chosen because a primary source for them could be read on the book's date: a regulator's order, an operator's filing or support page, a standard, or a peer-reviewed measurement. Several systems a buyer would also weigh, among them OneWeb, Telesat's Lightspeed and today's Inmarsat fleet, are named but not worked, because no such source for them was read; chapter 10 says which. Most of the regulatory examples are from the United States, where the filings are public; the method of the form does not depend on the country.

Each numbered chapter ends with a **Monday rule**: one sentence a reader can act on the next working week. Each also carries a failure from the record, told from its sources, and a security note: who can interfere or command, how it would be seen, and how service is recovered.

Prologue: One Picture in 1962, One Message in 2026



Telstar 1 was launched in the early morning of 10 July 1962. On the first pass that Andover, Maine could use, the engineers there sent speech and television to an audience in Washington, and in the middle of the program word came that the French station at Pleumeur-Bodou was receiving picture and sound. The British station at Goonhilly Downs had the signal too, but could not use it, because of "a turnover in polarization at the antenna". The next day, television came back from both European stations. That account is from the builders' own report, published by the Bell System Technical Journal a year later.

A small satellite and a very large ground

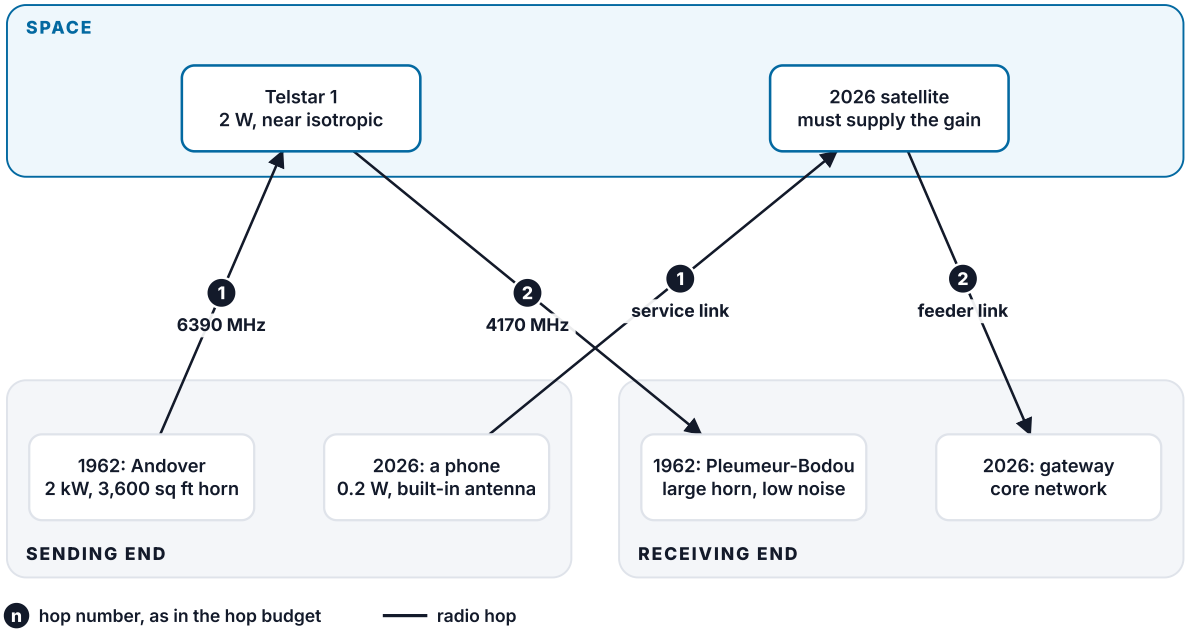
The satellite was a 34 inch sphere of about 170 pounds. Its repeater received a frequency-modulated carrier near 6390 MHz, shifted it down to an intermediate frequency, amplified it, and sent it back near 4170 MHz. It did not touch the modulation. In the language of this book it was a **transparent** satellite, a "bent pipe". Its radio output was 2 watts, through antennas its builders describe as approximately isotropic: they radiated about equally in every direction, so no gain was spent on pointing at Maine.

Everything that the satellite could not supply, the ground supplied. Andover had a horn reflector antenna with 3,600 square feet of aperture, 177 feet long, seven stories high and 380 tons, inside an inflated radome. It transmitted with 2 kilowatts. Its receiver began with a traveling-wave maser cooled in liquid helium, and the whole station's system noise temperature at zenith was 32 kelvin. The builders wrote that the research behind these parts, the study of sky noise, the maser, the low-noise horn and a better FM demodulator, reduced "the power requirement on the satellite by two or three orders of magnitude".

That is the first division of labor in this book. A 2 watt satellite could carry a television channel across the Atlantic because a ground station with a thousand times its transmit power, a giant aperture and a very low-noise receiver did the heavy work at both ends of the hop: the power going up, and the gain and the low noise coming down.

FIGURE P.1

1962 and 2026: the same chain of hops, with the margin supplied from opposite ends



In 1962 the ground station supplied the gain and the low noise; in 2026 the phone cannot grow, so the satellite must.

Author's diagram based on the Bell System Technical Journal, July 1963 (Telstar Table I), NASA SP-4217 chapter 6, and 3GPP TS 38.101-5 (power class 3, 23 dBm). The 2026 path is generic.

Minutes, not a service

Telstar flew an elliptical orbit, 952 km at its lowest and 5,651 km at its highest, once every 158 minutes. A transatlantic link needed the satellite above 7.5 degrees at Andover and at a European station at the same time. In the first weeks that happened three or four times a day, for 10 to 20 minutes each. Seven weeks later, with the orbit's high point further north, there were four or five such passes a day, of 20 to 40 minutes.

Inside those windows the link worked. In the following months Bell Laboratories ran more than 250 technical tests and some 400 demonstrations, and showed transatlantic television 47 times, five of them in color. Measured against its own aim, an experiment to prove a wideband repeater in orbit, Telstar did what it was built to do. Measured against a different requirement, continuous service, it could not: between passes there was no link at all. The company's answer to that requirement was not a better Telstar but many of them. NASA's history records that AT&T's operational plan was to consist of 50 to 120 active satellites, with about 25 ground stations.

THE SYSTEM'S FAILURE

The radiation belts that Explorer 1 had found four years earlier were worse along Telstar's orbit than its designers had expected. The builders' own radiation paper records that particles injected into the belts by United States and Soviet high-altitude nuclear explosions, a possibility not considered when the experiments were conceived, played a major role in the radiation damage. Telemetry showed a much higher density of energetic electrons than anticipated. One of the satellite's two command decoders failed in August 1962. In the fourth week of November the command channel began to act erratically, and after the 1,242nd orbit, on 23 November 1962, it stopped responding. The engineers' working hypothesis, stated in their report, was radiation damage to transistors in the command decoder. They devised special codes that bypassed the suspect transistors, sent one successfully on 20 December 1962, and by early January Telstar again responded to its normal commands. From 14 February 1963 the command system degraded again, and on 21 February the satellite misinterpreted a command and disconnected most of its electronics from its power supply; when the report was written, it had not responded since. The repeater had worked; the ability to tell it what to do had not lasted. The lesson the source supports is narrow and lasting: a satellite that cannot be commanded is a satellite that cannot be managed, whatever its radio can still do.

Telstar's Link Ledger, LL-1962-01, starts here. Page 1 records the requirement, the ends, the orbit, the band and the failure above; page 2, the budget of the two hops and of the circuit they make together, follows in chapter 4.

LINK LEDGER · LL-1962-01 · SERVICE LEDGER

1962-07-10 System: Telstar 1: one television channel across the Atlantic through a transparent satellite

Retired | Class: full | Budget: see this ledger's page 2

1 Requirement	Carry one television channel with sound, or the equivalent of 600 one way telephone channels, between Andover, Maine and stations in France and Britain while the satellite is in view of both. An experiment: commercial grade quality was the aim, not a contract.
2 Ends and path	Andover, Maine: a 3,600 square foot horn reflector, a 2 kW transmitter and a maser receiver. Stations at Pleumeur-Bodou (France) and Goonhilly Downs (Britain), built by those countries' telecommunications agencies. **Path:** Transparent: the satellite receives the FM carrier, shifts it to an intermediate frequency, amplifies it and sends it down without changing the modulation.
3 Orbit and time	Elliptical: perigee 514 nautical miles (952 km), apogee 3,051 nautical miles (5,651 km), inclined 44.8 degrees, period 158 minutes. **Time:** Passes, not continuous: at first three or four transatlantic passes a day of 10 to 20 minutes, later four or five of 20 to 40 minutes (antennas above 7.5 degrees). About 19 ms for one ground to satellite leg at apogee, straight up (calculated).
4 Band and permission	**Uplink.** 6389.58 MHz; experimental, license record not read **Downlink.** 4169.72 MHz, beacon 4079.73 MHz; telemetry 136.05 MHz, command about 123 MHz
5 Capacity	**Up.** One FM carrier: television, or 600 one way telephone channels simulated by noise, or 12 two way channels. **Down.** The same carrier repeated; 25 MHz of RF bandwidth at the ground station, 50 MHz in the satellite. At 5,000 nautical miles the picture showed a slight impairment.
6 Who owns each end	**Space segment.** AT&T: Bell Laboratories built it; NASA launched it and was reimbursed **Ground segment.** Andover: AT&T. Pleumeur-Bodou and Goonhilly: the French and British stations **Customer relationship.** None: an experiment **The exit.** Not applicable
7 Trust	Commands from the ground near 123 MHz. How commands were protected is not described in the source read.
8 How it fails, and how we would see it	Radiation: one command decoder failed in August 1962; commands stopped on 23 November 1962. Heavy rain: 130 K, which the paper puts at 4 dB less C/N than a clear day at zenith (its 32 K zenith value implies 6.1 dB). **How we would see it:** Telemetry on 136.05 MHz (radiation, temperatures, solar cell output), and the command channel refusing commands.
9 Cost shape	AT&T paid for the satellites and stations and reimbursed NASA 6 million dollars for launch and tracking.
10 Evidence	2 W in the satellite; 2 kW on the ground (operator claim) BSTJ July 1963, Table I, 2026-11-23 32 K at zenith; 130 K in heavy rain (measured) Bell Laboratories, 1962; BSTJ July 1963, 2026-11-23 Passes of 10 to 40 minutes (operator claim) BSTJ July 1963, section IV, 2026-11-23 Margin 7.5 dB above threshold (calculated) page 2 of this ledger, 2026-11-23

Inputs are the Bell System's published values; the free-space losses are recalculated.

RECONSTRUCTION · 1962 TO 1965 · THE REPORT FROM OUT OF REACH

The message	None.
The link	Telstar, Early Bird
Note	Told without the insurer: the satellite replaced a cable for the telephone company, not for the customer.

A reconstruction: the insurer is invented and illustrative. The link is the documented service of that year.

The hops of a link

Telstar's path had two radio hops. The first, the **uplink**, ran from Andover's horn up to the satellite near 6390 MHz. The second, the **downlink**, ran from the satellite down to the European station near 4170 MHz. The satellite in between did not decode anything. It shifted the frequency, amplified, and passed on whatever arrived, including the noise that the uplink had picked up on the way.

That last detail is the reason this book counts hops instead of links. Each hop has its own distance, its own frequency, its own transmitter and its own receiver, and so its own budget. Through a transparent satellite the noise of both hops reaches the receiver: the circuit is weaker than either hop alone (chapter 4 derives the rule). The builders' own figures show it. At a range of 5,000 nautical miles they gave a carrier-to-noise ratio of 17.5 dB at the satellite and 15 dB at the ground, and wrote that the up path reduced the overall ratio by about 2 dB. Chapter 4 works that arithmetic line by line.

The path does not end at the receiving antenna either. In 1962 the first demonstration at Andover was also televised for the national networks; in 2026 a message goes from a gateway into a mobile operator's core network, and from there to someone's screen. The strip at the top of each chapter marks where on that path the chapter sits: the user's end, the hop up, the satellite, the hop down, the ground, the screen.

2026: a phone with no tower in reach

Now move the user's end. Picture someone in 2026 standing in a valley where no mobile tower reaches, holding an ordinary phone. The phone is the opposite of Andover. A handset of power class 3, the class that the 3GPP standards support for satellite access, has a nominal maximum output of 23 dBm, about 0.2 watt, with a tolerance of 2 dB either way and before any power reduction. For testing, the standard assumes a reference antenna of 0 dBi: the same gain as an ideal antenna radiating equally in every direction. A real phone's antenna does worse in some directions, and the user's head and hand take more. The phone cannot grow a horn, cool its receiver in helium, or aim itself at the sky.

So the question of 1962 comes back turned around. If the margin cannot come from the user's end, it has to come from somewhere else: a satellite with a very large antenna, more processing in orbit, a narrower requirement, or all three. Whether that person's message can get out, on which network, on which phone, and from which date, is a question with a dated answer, and chapter 12 gives it as far as the record allows. The prologue only poses it.

The same five things, divided differently

Both links need the same five things. Only the split changes.

Who supplied what, 1962 and 2026

What the link needs	1962, Telstar	2026, a phone to a satellite
Transmit power	Ground: 2 kW at Andover; satellite: 2 W	User: at most about 0.2 W nominal, set by the power class
Antenna area	Ground: a 3,600 square foot horn	Satellite, unless the requirement is cut instead: the phone's antenna cannot grow
Low noise	Ground: a maser and a 32 K station	Satellite: its receiver, warm and in sunlight
Processing	Ground: the FM demodulator	Phone and network (in the satellite or on the ground, by design): coding, timing and Doppler correction (chapters 5, 6 and 8)
Money and risk	One telephone company, its own funds	Satellite operators, phone makers, mobile networks and their investors

The rest of the book follows one bit along that path, hop by hop, and asks at each hop who supplies the margin.

CHAPTER ONE

What Must Be Delivered



On 15 November 2022 Apple switched on a service that let the four models of its iPhone 14 lineup send an emergency message to a satellite, in the United States and Canada, from places outside cellular and Wi-Fi coverage. What it offered was a short emergency message, a questionnaire and a location, sent with the phone held toward open sky, in "as little as 15 seconds in clear conditions". The decision this chapter changes is the order of work: the requirement comes first, written as numbers, and every choice of orbit, band and vendor follows from it.

The requirement in six numbers

A link is built to move some bits, from somewhere to somewhere, by some time. Before anyone says "low orbit" or "Ka band", the requirement can be written as six numbers, each with a unit and a date.

Six numbers, before any radio is chosen (the answers are illustrative examples)

Number	The question	An example of the answer
Message size	How many bits per transaction?	A 160 character text, or a 3 megabyte photo
Deadline	By when must it arrive?	Within a minute; within a day
Rate, up and down	How many bits per second, in each direction, at the busy hour?	10 kbit/s up, 1 Mbit/s down
Coverage	Where must it work: which places, at what elevation of the sky?	Anywhere at sea between two latitudes
Availability	What share of time, averaged over what period, at which place?	99 percent of each month, at the user's site
Terminal limits	What power, antenna, pointing and battery does the user's end allow?	A phone, held by hand, no pointing

The last number often matters most and is written down least. A ship can carry a stabilized dish; a phone cannot. A ground station can burn kilowatts; a sensor buried in a field lives on a battery. The terminal limit decides how much of the margin the user's end can supply, and therefore how much the satellite and the ground must supply instead.

Three kinds of link

Direction and rate sort satellite links into three families, shown in Figure 1.1. A **two way conversation** needs both directions at once, at the rate of speech or better, with a short enough delay for people to take turns. A **one way broadcast to everyone**, like a navigation signal, has no uplink at all: the satellite does not know who is listening, and the user of an open navigation service needs a receiver but no license, no subscription and no transmitter. (The operator still uploads data and commands to its satellites from its own control stations; the user does not.) A **one way firehose**, like an imaging satellite, makes data whether or not a station is in view, stores it on board, and pours it down to a few stations when they come into view.

FIGURE 1.1

Three kinds of link: a conversation, a broadcast to everyone, and a firehose to a few

	Two way conversation	One way broadcast	One way firehose
Example	Iridium voice call, 1998	GPS navigation signal	Sentinel-1 radar imaging
Direction	Both ways, through the satellite	Satellite to every receiver; no user uplink	Satellite to a few ground stations, plus a small command uplink
The far end	One caller, through a gateway	Anyone; the satellite does not know the receiver exists	The operator's own stations, or a relay satellite
What decides the rate	Speech, in both directions at once	A slow, repeated stream of orbit and clock data (its rate is in chapter 5)	What the instrument makes, stored on board (capacity 1,410 Gbit) until a station is in view
Orbit	780 km	About 20,200 km	693 km
What the user supplies	A handset that can reach the satellite	A receiver; no license, no subscription, no uplink	Nothing: the user is the operator

Direction and rate decide the requirement long before an orbit or a band is chosen.

Iridium Form 10-K405 for 1998; GPS.gov archive, Space Segment; Copernicus SentiWiki, S1 Mission (read 2026-11-22).

Each family pushes the requirement toward a different design. A conversation punishes delay and needs a path in both directions. A broadcast must be received by the weakest acceptable receiver, so the signal is designed for it. A firehose needs storage, large ground antennas and many minutes of contact, and the delay of the radio path matters far less to it than the minutes of contact.

Availability is a statistic

"Available 99.9 percent of the time" is a sentence with three missing words: over what period, at which place, and counting which outages. The arithmetic is simple. Over an average year of 365.25 days, or 8,766 hours, 99 percent leaves about 88 hours without service, 99.9 percent about 8.8 hours, and 99.99 percent about 53 minutes. Over a single 30 day month the same 99.9 percent allows about 43 minutes.

The period matters because outages are not spread evenly. Heavy rain arrives in a few storms, and a low orbit satellite's gaps arrive between passes. A link that meets 99.9 percent over a year can still fail for an afternoon. The length of the longest outage, and how often it comes, is often the number the user actually needs: a pipeline monitor might tolerate ten minutes, while a voice call might not survive ten seconds, and the requirement should say which case it is.

Place matters because the budget changes with the sky. Rain, the elevation of the satellite and obstructions differ from one site to the next. An availability with no place attached describes no one in particular. And each extra "nine" is bought with margin: more transmit power, more antenna, a lower rate in bad weather, or a second path. Chapter 4 shows what one rain percentile costs in decibels for one hop.

Capacity is shared

A satellite beam is a shared medium, like a cell of a mobile network. A rate in a brochure is usually a peak: one user, best conditions, nobody else in the beam. The requirement should say what it needs at the busy hour, when many users in the same beam want service at once, and whether it can live with a lower rate when they do. Peak, sustained and contended rates are three different numbers. Field 5 of the ledger asks for all three, and asks who else shares the capacity. Where the operator does not publish them, the honest entry is "not published".

Cutting the requirement until the link closes

The 2022 emergency service is a lesson in choosing the requirement. A phone has a small antenna, little transmit power and no dish to aim; at most the user turns it. What was offered was what such a phone could do: a short message, sent slowly, from open sky, with the user turning the phone as the screen directs. The release lists the parts of the requirement that the design kept: a short questionnaire answered "with a few simple taps", a location, and delivery either "directly to emergency services that are equipped to receive text messages" or to relay centers "with Apple-trained emergency specialists" who contact the emergency answering point.

Every constraint that was accepted bought margin. A short message needs few bits, so the rate can be low, and a low rate needs little signal per second. Open sky avoids the loss of walls and roofs. Asking the user to point the phone means the design does not have to work at every orientation of the phone. The link numbers behind those choices (transmit power, the satellites' G/T, the waveform) are not stated in the sources read, so its ledger below is a service ledger, page 1 only. It is still useful: it shows which requirement was written, who owns each end, and which numbers a reviewer would have to ask for.

RECONSTRUCTION · 2022 · THE REPORT FROM OUT OF REACH

The message	A policyholder's emergency text.
The link	Phone to satellite, emergency service only
Note	Safety, not a claim: the scene shows an emergency message only; what else the service carried is not stated.

A reconstruction: the insurer is invented and illustrative. The link is the documented service of that year.

LINK LEDGER · LL-2022-01 · SERVICE LEDGER

2022-11-15

System: Emergency SOS via satellite on the iPhone 14 lineup (Apple; Globalstar as satellite operator)

In service | Class: service only

1 Requirement	From outside cellular and Wi-Fi coverage, get a short emergency message, the answers to a short questionnaire and the user's location to emergency services: directly where they accept text, otherwise through a relay center. Open sky; the phone shows where to point it.
2 Ends and path	An iPhone 14 model (the maker's own components and software), and emergency services that accept text or relay centers whose specialists, trained by the maker, contact the emergency answering point. **Path:** Not published for this service; the operator's filings describe its first generation satellites as bent pipe.
3 Orbit and time	Low orbit; the first generation flew at 1,414 km. Which satellites carry this service is not stated in the sources read. **Time:** "As little as 15 seconds" to send and receive in clear conditions; times "vary based on location, site conditions, and other factors" (operator claim).
4 Band and permission	**Phone to satellite and back.** The satellite operator's licensed mobile satellite spectrum (the partnership filing names "satellite spectrum and regulatory rights"); carriers not published
5 Capacity	**Up.** Short text messages and a location; rate not published. **Down.** Short replies; rate not published. The satellite operator allocates 85 percent of its current and future network capacity to the service (Form 8-K, 2022-09-07).
6 Who owns each end	**Space segment.** Globalstar, the satellite operator for the service **Ground segment.** Globalstar's gateways, ten of them new for this partnership **Customer relationship.** Apple; free for two years from activation **The exit.** Not published
7 Trust	Not published: who may command the satellites, how messages are protected, and how jamming would be detected are not stated in the sources read.
8 How it fails, and how we would see it	Without open sky or pointing, the connection waits or fails; the phone's guide shows it. Only in the countries the maker lists, on supported phones. **How we would see it:** The user sees it: the phone's pointing guide and the time to connect. The operator's own monitoring is not published.
9 Cost shape	No charge to the user for two years from activation. The phone maker pays the satellite operator recurring service fees and most of the capital spending (Form 8-K, 2022-09-07).
10 Evidence	Available 2022-11-15, US and Canada, iPhone 14 lineup; as little as 15 seconds operator claim Apple Newsroom, 2022-11-15, 2026-11-23 85 percent of network capacity; 10 new gateways operator claim Globalstar 8-K, 2022-09-07, 2026-11-23 1,414 km, bent pipe operator claim Globalstar 10-K, 2001, 2026-11-23 Status: 21 countries and regions; free for two years from activation operator claim Apple Support, 2026-10-05, 2026-11-24

Service only, no hop budget: the waveform, the satellites' figures and the phone's transmit power for this service are not published.

THE SYSTEM'S FAILURE

Iridium began commercial phone service on 1 November 1998. By August 1999 Iridium LLC was operating under Chapter 11 of the US Bankruptcy Code, as Motorola's annual report for 1999 states. The satellites stayed in orbit; in December 2000 a new company, Iridium Satellite LLC, acquired them from the bankrupt one.

Iridium's own annual report for 1998, filed in the spring of 1999, gives part of the reason in its own words. Subscriber levels and revenues had been "significantly below Iridium's prior estimates", which it attributed to "an initial lack of availability of phones and pagers, a shortage of fully-trained and motivated service providers and sales personnel and lack of effective marketing coordination". The phone had "an initial retail price of at least $3,000". Suggested call prices were expected to be about 25 to 30 percent above land-based calling options. And the filing warned that "in densely packed urban areas or inside buildings with steel construction and metal coated glass", including most hotels and professional buildings, "no meaningful satellite voice service is available".

The lesson is bounded by those words. This was a commercial failure with several causes, and the filing does not single out one. One engineering reading, which is this book's and not the filing's conclusion: the requirement the system was built to did not include the inside of a hotel or an office tower, and by the company's own warning such places were outside the service.

SECURITY NOTE

Who can interfere or command. A requirement that omits "who may command this system, and who may listen to it" is incomplete. Field 7 of the ledger is filled before the budget, not after: it names who can command the satellite, whose keys protect the traffic, and who could transmit into the same band. For the 2022 service none of this is stated in the sources read, and the ledger says so. **How it is seen.** Write down, with the requirement, the signal that would show an attack or an outage: a log at the relay center, a rise in failed connections in one region, a user's complaint. **How it is recovered.** Name the fallback in the requirement itself: another network, another path, or a stated time to restore.

Monday rule: write the requirement as six numbers with a date (size, deadline, rate up and down, coverage, availability with its period and place, terminal limits) before anyone names an orbit or a vendor.

CHAPTER TWO

Orbits and Passes



On 14 February 1963 Syncom 1 was launched toward the 24 hour orbit that Arthur C. Clarke had described in 1945. It went silent when the motor meant to circularize its orbit fired. Five months later Syncom 2 reached a 24 hour orbit and carried a single two way telephone channel. The decision this chapter changes is the first one after the requirement: where the satellite will be, for how long it can be seen, and how far away it is when it can.

Altitude, period and speed

A satellite in a circular orbit has no choice about its speed. Gravity at its altitude sets one speed at which it falls around the Earth instead of into it, and that speed sets the time for one orbit, the **period**. Higher means slower and longer. The numbers below are calculated from the altitude, a spherical Earth of radius 6,371 km and the standard gravitational parameter of the Earth; Appendix B gives the formula.

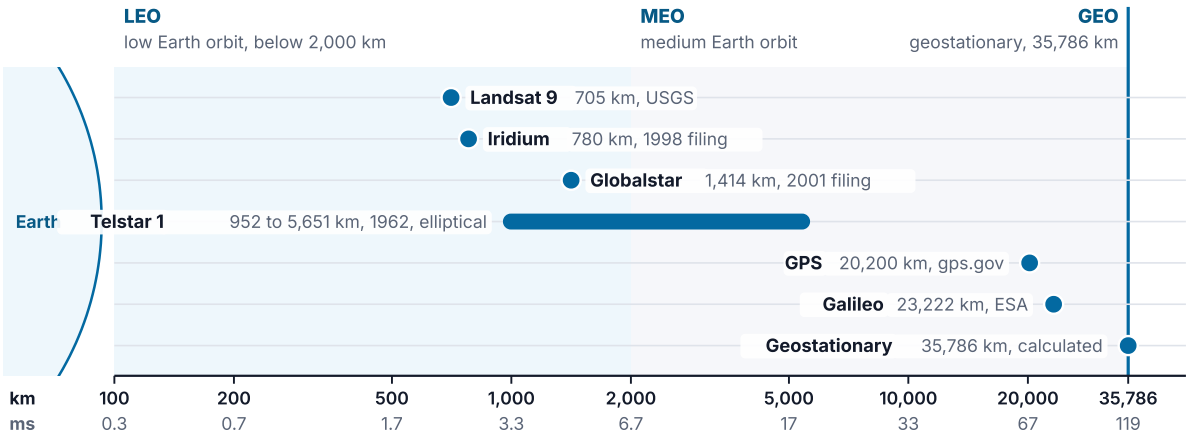
Altitude, speed, period and the delay of one leg straight up (circular orbits, calculated)

Example	Altitude	Speed	Period	One way, straight up
A low orbit example	550 km	7.6 km/s	96 minutes	1.8 ms
Iridium, per its 1998 filing	780 km	7.5 km/s	100 minutes	2.6 ms
Globalstar, per its 2001 filing	1,414 km	7.2 km/s	114 minutes	4.7 ms
GPS, about	20,200 km	3.9 km/s	about 12 hours	67 ms
Galileo	23,222 km	3.7 km/s	14.1 hours	77 ms
Geostationary	35,786 km	3.1 km/s	one sidereal day	119 ms

Three families follow. **Low Earth orbit** (LEO), below about 2,000 km, gives short distances and short delays, and a satellite that crosses the sky in minutes. **Medium Earth orbit** (MEO), where the navigation systems fly, gives periods of half a day or so: GPS satellites circle the Earth twice a day, as the program's own description puts it. **Geostationary orbit** (GEO), 35,786 km above the equator (the conventional value, measured from the equatorial radius, not from the 6,371 km mean radius of the table), has a period equal to the Earth's rotation, so the satellite hangs over one point and a fixed dish need not move. A fourth family, the **highly elliptical orbit**, swings low and fast on one side of the Earth and high and slow on the other; inclined and oriented so that its high point lies over the north, it spends most of its time over high latitudes. Telstar 1's orbit, 952 by 5,651 km, was elliptical for a plainer reason: its launch vehicle could not lift it into a high circular orbit, and its builders chose a high apogee over the North Atlantic instead.

FIGURE 2.1

Altitude sets the period and the delay of each leg



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

Named systems at their published altitudes; the second axis gives the light time straight up, one way.

USGS, Landsat 9; Iridium Form 10-K405 for 1998; Globalstar Form 10-K for 2001; Bell System Technical Journal, July 1963; GPS.gov archive; ESA, What is Galileo; geostationary altitude the conventional 35,786 km above the equatorial radius. Read 2026-11-22 and 2026-11-23.

Speed is quoted with its altitude, always. "Satellites move at 7.6 km/s" is true at 550 km and false at 1,414 km. The delay of one leg is quoted the same way: the 119 ms of a geostationary leg is the straight-up value, and a station far from the point under the satellite sees more. Chapter 6 gives the delay of a whole circuit and of a reply.

Footprint, elevation and slant range

From the ground, a satellite's position is described by two angles: its **azimuth**, the compass direction, and its **elevation**, the angle above the horizon. The distance from the station to the satellite is the **slant range**. It is shortest when the satellite is straight overhead, at 90 degrees, and grows quickly toward the horizon.

For a satellite at 550 km, the slant range is 550 km overhead, about 993 km at 30 degrees, about 1,815 km at 10 degrees and about 2,704 km at the horizon. The signal travels five times as far at the horizon as overhead, and the free-space loss of a radio path grows with the square of the distance, so that difference alone costs 20 times the base-ten logarithm of 4.9, about 14 dB (chapter 4 shows the formula). Near the horizon the signal also crosses more air, more rain and more of the ionosphere, and buildings, trees and hills get in the way.

That is why links are designed to a **minimum elevation**. Telstar's transatlantic link counted a pass only while the satellite was above 7.5 degrees at both stations. The minimum elevation sets the **footprint**: the area of the ground from which the satellite is above that elevation. It is a geometric limit; the beams, the budget and, for a transparent satellite, a gateway in view can make the usable area smaller. For the 550 km example with a 10 degree minimum, the footprint is a circle of about 1,660 km radius around the point under the satellite. Raise the minimum elevation and the footprint shrinks; lower it and the budget gets worse at the edge.

A pass: rise, culmination, set

A low orbit satellite crosses a station's sky in a **pass**. It rises above the minimum elevation, climbs to its highest point, the **culmination**, and sets. The best pass goes straight overhead. For a satellite at 550 km and a 10 degree minimum, an overhead pass lasts about 7.9 minutes; counted from horizon to horizon it lasts about 12.2 minutes. Both are calculated for a non-rotating Earth; a real pass also depends on its direction and on the Earth's rotation, and a pass that misses the zenith is usually shorter. Figure 2.2 shows how fast the geometry changes during one overhead pass.

FIGURE 2.2

One pass at 550 km: the slant range and the delay change by a factor of three in four minutes

Elevation	Time from the highest point	Slant range	One way delay
10 degrees (rise or set)	about 4.0 minutes	1,815 km	6.1 ms
20 degrees	about 2.7 minutes	1,294 km	4.3 ms
30 degrees	about 1.9 minutes	993 km	3.3 ms
45 degrees	about 1.2 minutes	749 km	2.5 ms
60 degrees	about 0.7 minutes	627 km	2.1 ms
90 degrees (overhead)	0	550 km	1.8 ms

An overhead pass of a satellite at 550 km above 10 degrees elevation, calculated for a non-rotating Earth; real passes also depend on the Earth's rotation, and most miss the zenith.

Calculated: slant range from altitude and elevation with an Earth radius of 6,371 km, the circular speed from the WGS 84 gravitational parameter, and the speed of light (Appendix B).

Four minutes from rise to culmination, the distance falls from about 1,815 km to 550 km and the one way delay from about 6 ms to under 2 ms. Every line of the hop budget that depends on distance moves with it. A low orbit link is not one budget; it is a budget that changes every second, and the design must hold at the worst point of the pass it is required to use.

The number that matters to a user is not "coverage" but **contact time**: minutes per day, at one site, above the minimum elevation. Telstar's builders measured their system that way: three or four usable transatlantic passes a day of 10 to 20 minutes at first, and four or five of 20 to 40 minutes once the orbit's high point had moved north.

Continuous coverage

A link that must work all the time needs a satellite in view all the time. There are two common ways to get it, and mixtures of them. One geostationary satellite sees a large part of the Earth, about 42 percent of its surface according to NASA's history of the period, from a fixed point in the sky. Or many low satellites follow each other so closely that one rises before the last one sets.

The second way needs many satellites. Iridium's filing describes 66 satellites in six orbital planes at about 780 km, plus spares in orbit. AT&T's own plan in the early 1960s for an operational system after Telstar was 50 to 120 satellites. The count depends first on the footprint: the lower the orbit, the smaller each footprint and the more satellites it takes to tile the Earth with no gaps. Low orbit buys short delay and a stronger signal for the same power, and pays for them in the number of satellites, the handover from one to the next, and the ground or crosslinks needed to connect them.

Continuous coverage from low orbit has a cost that the user feels: **handover**. If an overhead pass at 550 km is usable for about 8 minutes, a 30 minute call needs at least four satellites in turn, and usually more, because most passes are shorter than the overhead one. Each change of satellite is a moment where the link must be re-established without the user noticing. Iridium carried calls between satellites over links in orbit; Globalstar brought every call down to a gateway in view. Chapter 8 compares the two designs; here the point is only that the orbit decided that both had to solve the problem.

Geostationary orbit has a cost of its own, and it grows with latitude. The satellite sits over the equator, so a station far north or south looks at it low over the horizon. For a station on the same meridian as the satellite, the elevation is about 44 degrees at 40 degrees latitude, about 22 degrees at 60 degrees, about 12 degrees at 70 degrees, and the satellite drops below the horizon beyond about 81 degrees latitude (calculated for a spherical Earth). Low elevation means a longer path, more air and rain, and more obstruction, which is the case for the highly elliptical orbits that spend their slow, high part over the northern latitudes.

> **WHAT HASN'T CHANGED**
>
> In 1962 Telstar's builders drew "lunes of mutual visibility" to find when Maine and western Europe could both see the satellite, and they wrote that as the height gets lower, "the net result is fewer and shorter useful passes". Every low orbit link since has faced the same geometry. The tools changed; the question is still how many minutes a day both ends can see the same satellite.

Inclination, polar and sun-synchronous orbits

The **inclination** is the angle between the orbit's plane and the equator. The point under the satellite never goes further from the equator than the inclination (or 180 degrees less the inclination, for an orbit inclined beyond 90 degrees). The footprint reaches somewhat further than that track, but the inclination still decides, to a first approximation, who can be served at all. Telstar's builders wanted the highest inclination their launch could give, because their two ends were in Maine and western Europe; they got 44.8 degrees.

A **polar orbit**, at 90 degrees, passes over both poles, and the Earth turning beneath it brings every longitude under its track; a near-polar orbit's track reaches the latitude of its inclination (or 180 degrees less it), and its footprint reaches further. A **sun-synchronous orbit** is a near-polar orbit whose plane turns slowly with the seasons, so the satellite crosses the equator, going north or going south, at about the same local solar time on every orbit; imaging satellites use it for steady lighting. It does not by itself bring the satellite over a given place every day. Landsat 9, for example, flies a sun-synchronous orbit at 705 km and 98.2 degrees, and returns over the same ground every 16 days, according to the US Geological Survey. That interval is the orbit's **repeat cycle**. How often a given site can be imaged, the revisit, also depends on the swath, the latitude, any pointing and the number of satellites; for an imaging mission both are part of the requirement, as much as the rate.

Where is it now? Element sets and tracking

An antenna can only point at a satellite whose position it can predict. For most satellites the position is published as an **element set**: a small group of numbers describing the orbit at a stated moment, its **epoch**. A **propagator** is the program that carries the orbit forward from the epoch to the time of the pass. For satellites tracked by the United States, the common public format is the two-line element set, read by a propagator called SGP4, and both are widely used in published research on constellations.

An element set ages. One study of large constellations, which used public element sets with SGP4, assumed a position error growing by 1 to 3 km per day; that is the study's working figure, not a general rate. The practical rule follows: the prediction is only as good as the element set is fresh, and a satellite that has just maneuvered may not match its old elements at all.

A ground antenna follows the satellite in one of three ways, often in combination. It can point from the prediction alone. It can **step track**, nudging the antenna and keeping the direction that gives the stronger signal. Or it can use **monopulse** tracking, comparing signals from several feeds at once to measure the pointing error directly. Andover in 1962 used all of these ideas: pointing from a tape drive, an autotrack on the satellite's beacon, and slaving to a precision tracker. Its builders wrote that the fine tracking was capable of holding the beam within 0.005 degree of the satellite.

Drag, radiation and the end of a satellite

Low orbit is not empty. The thin upper atmosphere drags on a satellite and takes energy from its orbit, which lowers it (on the lower orbit it then moves faster), until it re-enters; much of it burns up, though not always all of it. Drag depends on the density of that air, and the density rises when the Sun is active and when a geomagnetic storm heats the upper

atmosphere. Drag is a cost at low altitude, and it is also a benefit: a dead satellite there comes down on its own, and the lower the orbit, the sooner; higher up, it can stay for decades or longer.

Higher up, the satellite meets the radiation belts, the zones of trapped particles that Explorer 1's data revealed in 1958. Telstar crossed them on every orbit, and the prologue tells what that did to its command decoder. How a satellite is disposed of at the end of its life, and who requires it, belongs to the book of this series on licensing and debris, covered in depth later in this series.

> **THE SYSTEM'S FAILURE**
>
> In February 2022 a geomagnetic storm struck a batch of Starlink satellites shortly after their launch, and many of them re-entered early, as a peer-reviewed paper and a survey both record. Storms of this kind raise the density of the upper atmosphere and with it the drag on a low satellite.
>
> The lesson is bounded and physical. Low altitude buys a short delay and a satellite that comes down on its own if it fails. It pays in drag, and a storm can raise that drag faster than a young satellite can climb away from it.
>
> Orbits can also be lost before they are reached. Syncom 1, in February 1963, went silent when the motor meant to circularize its orbit fired, according to NASA's history. The orbit is part of the link, and getting there is part of the risk.

The bench link: a satellite with a published orbit

The bench link of this book, an exercise for the reader that the author has not run, is a weather satellite, Meteor-M N2-4, which broadcasts images in its LRPT format near 137.9 MHz, at 80 kbit/s, according to the World Meteorological Organization's satellite database. It was launched on 29 February 2024. It is a one way broadcast: anyone in view with a suitable antenna and a receive-only radio can listen, and the station transmits nothing.

Its orbit comes from a public element set (SatNOGS DB, NORAD 59051, epoch 23 November 2026, 07:06 UTC), the one the bench link's ledger in chapter 12 uses: a mean altitude of about 824 km, an inclination of 98.7 degrees and a period of about 101 minutes. From those numbers the geometry follows by the formulas of this chapter. The slant range is 824 km overhead and about 2,415 km at 10 degrees elevation, and an overhead pass above 10 degrees lasts about 11 minutes, calculated for a non-rotating Earth. The bench link's ledger, LL-2026-03, starts here with page 1; its hop budget follows in chapter 12. The satellite's transmit power and antenna pattern were not found in a primary document, so that page solves for what the link needs instead.

This chapter's part of the exercise is a step written as what it requires, because nothing has been recorded. Predicting a pass needs a current public element set for the satellite, a propagator, and the station's coordinates and minimum elevation. The output is a table: the time of rise, of culmination and of set, the highest elevation, and the slant range at each. That table is the prediction that a later recording will be checked against, line by line. Measured: none yet.

LINK LEDGER · LL-2026-03 · SERVICE LEDGER

2026-11-23 System: Meteor-M N2-4 LRPT at 137.9 MHz to a dipole and a receive-only radio (the bench link)

Planned | Class: full | Budget: see this ledger's page 2

1 Requirement	Decode one pass of the 80 kbit/s LRPT weather broadcast on a dipole and a receive-only radio, with 3 dB of margin at 20 degrees elevation in clear sky. Measured: none yet.
2 Ends and path	Meteor-M N2-4 (launched 2024-02-29), a Russian polar weather satellite, and a fixed station that sends nothing. LRPT frames carry Reed-Solomon error-correction coding (decoder documentation). **Path:** Direct broadcast: one hop, satellite to station. No uplink, gateway or subscription.
3 Orbit and time	Sun-synchronous, 824 km mean, 98.7 degrees, 101.2 minutes (calculated from SatNOGS element set NORAD 59051, epoch 2026-11-23 07:06 UTC). **Time:** Overhead pass: 15.6 minutes above the horizon, 7.7 above 20 degrees. Delay 2.7 to 11.2 ms. Doppler up to 3.0 kHz, at most 27 Hz per second.
4 Band and permission	**Downlink.** 137.1, 137.9 or 137.9125 MHz (WMO OSCAR); the station transmits nothing. Rules on receiving: not assessed
5 Capacity	**Up.** None. **Down.** 80 kbit/s listed (WMO OSCAR), the same for every station in view.
6 Who owns each end	**Space segment.** Roscosmos and Roshydromet (as a peer-reviewed survey lists them) **Ground segment.** The station's owner **Customer relationship.** None: an open broadcast **The exit.** None; the broadcast may change or stop without notice
7 Trust	The operator is authorized to command the satellite; command protection is not documented. No source read establishes broadcast authentication, so a frame's origin is unassured; a stronger signal can overshadow it, encrypted or not.
8 How it fails, and how we would see it	Site noise, a low pass, or a stale element set. At the quiet-site EIRP a residential site is 4.3 dB short. **How we would see it:** Sync lock and Reed-Solomon error counts per frame against elevation; recorded carrier against the predicted Doppler.
9 Cost shape	A dipole and a receive-only radio; no service fee. Parts are not priced on this page.
10 Evidence	137.9 MHz, 80 kbit/s, RHCP operator claim WMO OSCAR, 2026-11-22 Orbit and passes in field 3 calculated element set, 2026-11-23, 2026-11-23 EIRP needed 5.3 to 12.5 dBW; residential 4.3 dB short calculated page 2, 2026-11-23 3 dB margin (a choice); received signal: none yet *assumption* a dated recording settles the signal, 2026-11-23

A first assessment, not a qualification. EIRP is solved for, since no document read gives it.

SECURITY NOTE

Who can interfere or command. Public element sets exist for many satellites, and orbits are predictable. Anyone with an element set knows when a low orbit satellite will be over a site, and so does anyone who wants to listen to it or transmit at it. The authority to command belongs to the operator; whether anyone else could get a command accepted is a security property that needs its own proof (chapter 11). For a receive-only station, the near risk is not a command but a wrong input. **How it is seen.** A stale or wrong element set points an antenna at empty sky, and on a signal meter that looks exactly like a link failure. Compare the predicted and the received carrier: if the timing or the Doppler is off, suspect the prediction before the radio. **How it is recovered.** Fetch a fresh element set from the publisher, keep its epoch in the log next to every pass, and let the antenna's tracking take over from the prediction once the signal is found.

Monday rule: for any low orbit link, ask the supplier for contact minutes per day and the longest gap, at your site and minimum elevation, not for "coverage".

CHAPTER THREE

Bands and Antennas



Soon after 1971 an eight foot radar from the Second World War, converted to C band, was installed on the liner Queen Elizabeth 2 for a live test of satellite calls from the high seas. The test was a public relations success, and it needed two whole transponders of an Intelsat IV satellite for one voice link, one for each direction. By 1976 the ships of the Marisat service carried a one meter dish on a stabilized platform and talked in L band, and one satellite served the ships of a whole ocean region. The difference was not cleverness alone. It was a choice of band and of antenna, made together. This chapter shows what each frequency and each aperture buys, what it costs, and why the choice cannot be made without asking who holds the right to use the band.

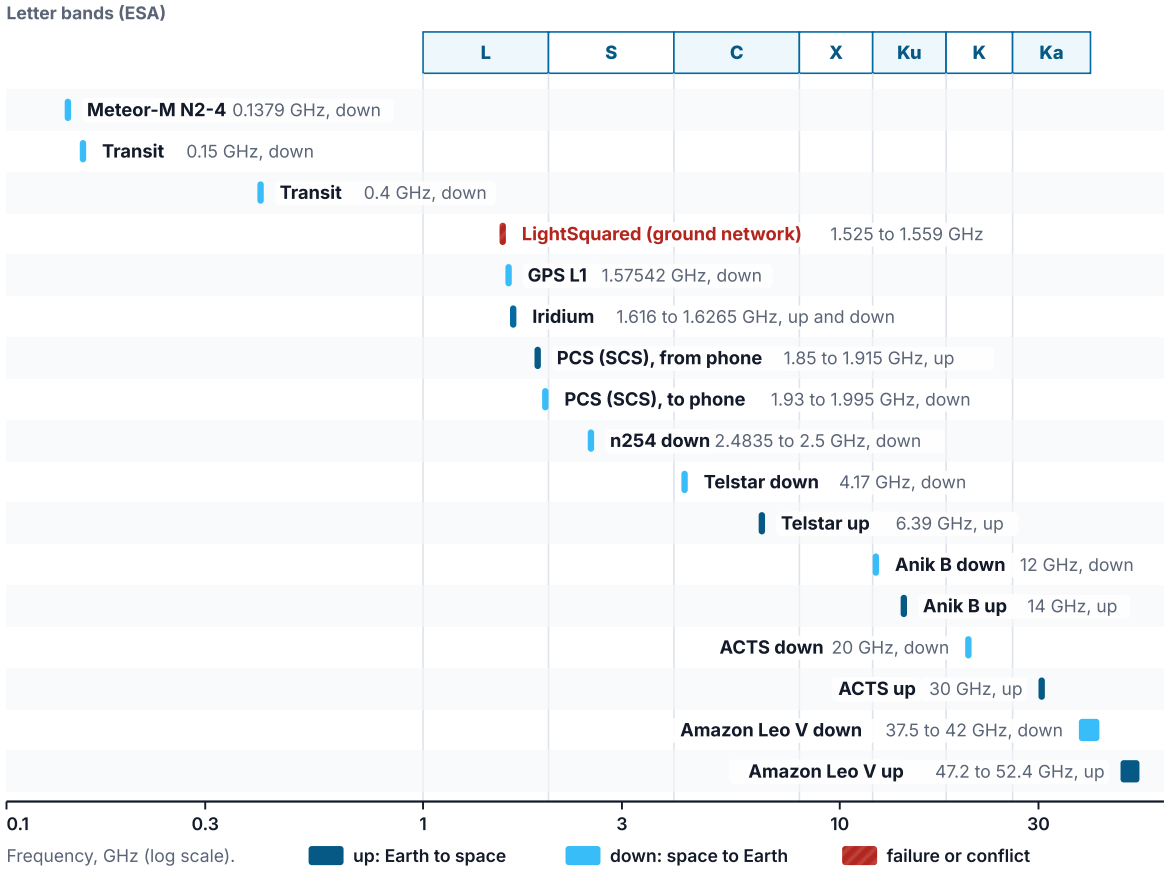
Frequency, wavelength and the band names

A radio wave has a frequency, the number of cycles per second, and a wavelength, the distance between two crests. The two are tied by the speed of light: wavelength equals the speed of light divided by the frequency. At 1.6 GHz (1.6 billion cycles per second) the wavelength is 18.7 cm; at 12 GHz it is 2.5 cm; at 30 GHz it is 1.0 cm. Many properties that matter in this chapter, the gain of an antenna, the width of its beam, what rain does to the wave, depend on the wavelength compared with something else: the antenna, the raindrop. Others, such as absorption by gases and the effects of the upper atmosphere, have their own laws, given later.

Satellite engineers name ranges of frequency with letters. The European Space Agency gives L band as 1 to 2 GHz, S band 2 to 4, C band 4 to 8, X band 8 to 12, Ku band 12 to 18, K band 18 to 26 and Ka band 26 to 40 GHz. The older names VHF and UHF belong to a separate scheme that overlaps the letter bands, and above Ka band the names Q and V are used; the boundaries of those names vary between documents, so this book quotes the frequency itself. Light is a different case with different rules; Chapter 9 owns it.

FIGURE 3.1

Each band carries a different kind of system, from 137 MHz weather pictures to V band broadband



One named system per region of the spectrum (Telstar 1962, Anik B 1978, ACTS 1993, the Amazon Leo authorization 2026); uplinks dark, downlinks light; the red bar is the terrestrial band whose ground transmitters were found to impact GPS receivers.

Sources: ESA, Satellite frequency bands (read 2026-11-22); WMO OSCAR, Meteor-M N2-4 (page of 2026-01-23); Johns Hopkins APL Technical Digest 19(1); IS-GPS-200N; Iridium Form 10-K405 for 1998; FCC 89 FR 34148 (2024); 3GPP NTN overview; Bell System Technical Journal 42(4), 1963; NASA SP-4217 ch. 6 and 14; FCC DA 12-214 (2012); FCC DA 26-553 (2026).

Figure 3.1 puts one real system on each part of the axis. The weather satellite Meteor-M N2-4 sends its pictures near 137.9 MHz. Transit, the United States Navy's navigation satellites of the 1960s, sent two tones at 150 and 400 MHz. GPS broadcasts at 1575.42 MHz. Iridium's handsets talk between 1616 and 1626.5 MHz, sending and receiving in turn on the same band (time division). Telstar in 1962 listened near 6390 MHz and answered near 4170 MHz. Canada's Anik B of 1978 carried 14 GHz up and 12 GHz down. NASA's ACTS of 1993 used 30 GHz up and 20 GHz down. In 2026 the FCC granted Amazon Leo, in part, V band

authorizations within 37.5 to 42 GHz down and 47.2 to 52.4 GHz up; an FCC order of 5 June 2026 lists the granted bands, and part of the request was deferred. The edges are envelopes, not one continuous band.

Antennas: gain, area and beamwidth come together

An antenna does not add power. It concentrates power in some directions at the expense of others. Its **gain** is how much stronger it radiates toward its best direction than an imaginary antenna that radiates equally in every direction, the isotropic antenna. Gain is quoted in dBi, decibels relative to that isotropic antenna.

On receive, the same antenna has an **effective area**: the area of the passing wave from which it collects power. Gain and effective area are two views of one property. The effective area equals the gain, as a plain ratio rather than in decibels, times the square of the wavelength, divided by four pi. Even an ideal isotropic antenna has such an area: it is the target the passing wave must hit to deliver its power. A perfect isotropic antenna at 1.9 GHz collects from about 20 cm^2; at 1.6 GHz, from about 28 cm^2. A dish of physical area A and wavelength λ reaches a gain of about efficiency times $4\pi A/\lambda^2$. The efficiency is the share of the physical area the antenna really uses after illumination taper, spillover, blockage and surface errors: at most one for an ideal aperture, less in practice. This chapter assumes 0.6 for its examples, an assumption to check for any real antenna.

The third view is the **beamwidth**, the angle across which the antenna's gain stays within half of its peak. High gain means a narrow beam. For a circular aperture with uniform illumination the half-power beamwidth is about 1.03 times the wavelength divided by the diameter, in radians; a real feed that tapers its illumination toward the rim widens the beam a little and lowers the gain. Gain and pointing therefore come together. A 40 dBi dish, with a beam about 1.5 degrees wide, has to be aimed within a fraction of a degree, and something has to keep it aimed: a motor, a stabilized platform on a ship, or electronics.

FIGURE 3.2

The same aperture gains about 8 dB from 12 to 30 GHz, and its beam narrows to match

Band (frequency)	Wavelength	10 cm aperture: gain, beam	1 m dish: gain, beam	Diameter for 30 dBi
L (1.6 GHz)	18.7 cm	about 2 dBi, most of the sky (indicative only: half a wavelength wide)	22.3 dBi, 11.0 degrees	2.4 m
Ku (12 GHz)	2.5 cm	19.8 dBi, 14.7 degrees	39.8 dBi, 1.5 degrees	33 cm
Ka (30 GHz)	1.0 cm	27.7 dBi, 5.9 degrees	47.7 dBi, 0.6 degrees	13 cm

Gain at an assumed aperture efficiency of 0.6 and half-power beamwidth for uniform illumination, calculated; a tapered feed gives a slightly wider beam and lower gain.

Author's calculation: gain = efficiency x (pi D / wavelength)^2 with efficiency 0.6 (assumption); beamwidth = 1.029 wavelength / D radians (uniform circular aperture). The formulas hold for apertures many wavelengths across.

Figure 3.2 shows the trade for two apertures at three bands. The same 1 m dish has 22.3 dBi at 1.6 GHz, 39.8 dBi at 12 GHz and 47.7 dBi at 30 GHz, with beams of about 11, 1.5 and 0.6 degrees. At 1.6 GHz an antenna 10 cm across is only about half a wavelength wide; the dish formula gives about 2 dBi there only as an indication, and the beam covers most of the sky.

Antennas come in a few families, described here in their typical forms. A **reflector** (a dish) collects the wave onto a feed and gives high gain cheaply, and is usually pointed mechanically. A **helix** or a **patch** is typically small, low in gain and wide in beam, and suits a handset or a small spacecraft. A **phased array** is a grid of small elements, usually flat, whose signals are combined with controlled delays, so that the beam is steered electronically, without moving parts. An array pays for that freedom: as the beam is steered away from the direction straight out of the panel, the panel looks smaller to the wave, each element's own pattern falls off, and the gain drops. This is called **scan loss**, and a supplier's gain figure for an array means little until it says at which steering angle it was stated.

What a higher band buys, and what it costs

A higher band buys three things. The first is room for bandwidth, if the regulator allocates it: an allocation of 500 MHz is under 4 percent of Ka band and half of the whole L band, and bandwidth is what carries bits. The second is gain from the same aperture: at a fixed size and efficiency, gain grows with the square of the frequency, so moving from 12 to 30 GHz adds about 8 dB to a dish of a given diameter. The free-space loss between ideal antennas grows by the same 8 dB. So if one end keeps a fixed gain, such as a handset's small antenna, the other end's fixed-size dish only pays for the extra path loss; if both ends keep their physical size, both gain and the link improves; if both keep their gain, the link loses the 8 dB. The third follows from the second: a satellite's antenna of a given size makes a narrower beam at a higher frequency. Narrow **spot beams** let the same frequencies be used again in beams that do not overlap, which is called **frequency reuse**, and that multiplies the capacity of one satellite.

The costs come as a set. A narrow beam must be pointed, at both ends. Parts are harder to make well at short wavelengths: surface errors of a dish must stay small compared with the wavelength. And the atmosphere, which hardly notices L band, takes a growing share of the signal as the frequency rises, as the next sections show. A link at Ka band is designed for rain the way a building is designed for wind.

What a lower band buys: an antenna that needs no aiming

A lower band buys a simple antenna. At 1.6 GHz an antenna a few centimeters across has a beam wide enough to see most of the sky. It needs little or no pointing, no motor and no installer, and it keeps working while the user walks or turns, apart from the nulls of its pattern and what the body or the vehicle blocks. That is why the handheld end of satellite services is usually in L or S band: the Iridium handset, the GPS receiver, and the phone that talks directly to a satellite in 2026. Marisat's ships sat between the two: L band, but with a 1 m dish that needed a stabilized platform.

The price is gain, and with it capacity. It is tempting to say that a lower band needs a smaller antenna. The opposite is true for the same gain: to reach 30 dBi a dish must be about 2.4 m across at 1.6 GHz, 33 cm at 12 GHz and 13 cm at 30 GHz (Figure 3.2). A lower band suits a small antenna only because the system accepts low gain at that end and makes it up elsewhere: more power or a bigger antenna on the satellite, a low data rate, or both.

Marisat shows the trade being made on purpose. NASA's history of the program records that the L band capability of the satellite was limited, so the size of the ship's antenna had to be weighed with care: too large and no shipowner would buy it, too small and the system's channel capacity would be too low to pay. European planners expected a practical ship antenna to have very low gain. COMSAT chose a one meter L band dish on a low-cost

stabilized platform developed by Scientific-Atlanta, and ordered 200 units to seed the market. One meter at 1.6 GHz is about 22 dBi under this chapter's assumed efficiency, modest by Ku band standards, and far above the very low gain the European plan expected.

RECONSTRUCTION · LATE 1970S · THE REPORT FROM OUT OF REACH

The message	A casualty report from a ship at sea.
The link	Marisat, then the Inmarsat system from 1982
Note	Marine insurance is the insurer's oldest line.

A reconstruction: the insurer is invented and illustrative. The link is the documented service of that year.

The scene above is a reconstruction. The service it relies on is documented: NASA's history states that Marisat opened commercial service in the Atlantic and Pacific regions in the summer of 1976 through stations at Southbury, Connecticut and Santa Paula, California, with a combined telephony and telex system, and added the Indian Ocean through Yamaguchi, Japan in November 1978.

LINK LEDGER · LL-1976-01 · SERVICE LEDGER

1976 System: Marisat, ship to shore (telephone and telex) Retired Class: service only

1 Requirement	Telephone and telex between merchant ships at sea and the shore network: Atlantic and Pacific regions from summer 1976, Indian Ocean from November 1978. A ship pays for a terminal; the Navy pays for UHF channels on the same satellites.
2 Ends and path	A ship terminal with a 1 m L band dish on a stabilized platform; one satellite per ocean region; a shore station at Southbury, Connecticut, Santa Paula, California, and from 1978 Yamaguchi, Japan. **Path:** Transparent: one 4 MHz transponder per direction, C band to L band shore to ship, L band to C band ship to shore.
3 Orbit and time	Geostationary: one satellite over each ocean region in service, the third first held as a ground spare. **Time:** About a quarter second one way through the satellite, half a second for a reply, before the shore network.
4 Band and permission	**Ship to satellite, satellite to ship.** L band, maritime allocation of the 1971 Space Conference; frequencies not in the source read **Shore station links.** C band; COMSAT under FCC instructions, United States, and KDD, Japan
5 Capacity	**Up.** Channel counts not in the source read. Up to 75 percent of each satellite's capacity was at UHF for the United States government. **Down.** As up: three L band power levels let commercial service grow as the Navy withdrew from UHF. Shared by every ship in an ocean region; a ship gets a channel on demand, not a fixed rate.
6 Who owns each end	**Space segment.** Marisat joint venture: COMSAT General (manager), RCA 8 percent, Western Union International 3.41 percent, ITT 2.3 percent **Ground segment.** COMSAT shore stations; Yamaguchi under an agreement with KDD **Customer relationship.** The shipowner, who buys or leases the terminal **The exit.** Operations moved to Inmarsat on 1 February 1982
7 Trust	The operator commands the satellites from the ground; the U.S. Navy leases UHF channels on the same satellites. The source describes no encryption of the commercial traffic.
8 How it fails, and how we would see it	One satellite per ocean region: its loss ends that region's service until a spare is in place. At sea, ship motion and pointing; at the shore, weather on the C band link. **How we would see it:** Not documented in the source read; expected: the ship terminal loses the carrier, the shore station sees a carrier drop, and a telex sender sees no answer.
9 Cost shape	Three satellites from Hughes, just over 40 million dollars (1973); Navy, 27.9 million dollars (1972); first ship terminals 50,000 to 75,000 dollars (all NASA SP-4217, ch. 21); tariffs not read.
10 Evidence	4 MHz per transponder, C to L and L to C published history NASA SP-4217, ch. 21, 2026-11-23 1 m L band ship antenna published history NASA SP-4217, ch. 21, 2026-11-23 Service summer 1976; to Inmarsat 1 February 1982 published history NASA SP-4217, ch. 21, 2026-11-23 About a quarter second one way calculated Light time, 2026-11-23

Service only, no hop budget: the ship terminal's gain and noise temperature, the satellite's L band power and the channel rates are not in the source read.

The atmosphere, band by band

Between the satellite and the ground the wave crosses two different layers. The lower one, the troposphere, holds the weather: gases, cloud and rain. The upper one, the ionosphere, holds free electrons charged by the sun. They act on opposite ends of the spectrum. ITU-R Recommendation P.618, the international method for Earth to space paths, states that absorption by gases and absorption, scattering and depolarization by rain and cloud are especially important above about 10 GHz, while ionospheric effects may be important particularly below 1 GHz.

Rain grows with frequency. ITU-R Recommendation P.838 gives the coefficients for the loss per kilometer of path through rain as a function of frequency and rain rate. Computed from them for a heavy rain of 25 mm per hour and a circularly polarized wave, the loss is about 0.001 dB per km at 1.5 GHz, 0.01 dB at 4 GHz, 1.0 dB at 12 GHz, 2.5 dB at 20 GHz and 4.7 dB at 30 GHz. A few kilometers of such rain on the path cost a Ka band link many decibels and an L band link nothing worth counting. How often such rain falls at a given place is a separate question, answered by the prediction method of P.618 from the local rain statistics, for a stated percentage of the year; Chapter 4 shows what a stated rain loss does to the margin; an availability needs the site's own statistics.

Gases (oxygen and water vapor) absorb a little at all frequencies; P.618 says the effect may normally be neglected below 10 GHz and grows above it, especially at low elevation, though not smoothly: water vapor and oxygen absorb in lines, with windows between them, so the band matters as well as the frequency. **Cloud** adds its own smaller loss at the higher bands. **Tropospheric scintillation**, fast fading from small changes in the refractive index of the air, matters above about 10 GHz at low elevation.

The ionosphere works the other way. Its free electrons delay the signal, bend it and, near the geomagnetic equator after sunset, make it flicker: P.618 tabulates peak-to-peak ionospheric scintillation of more than 20 dB at 1 GHz, about 10 dB at 3 GHz and about 4 dB at 10 GHz in those conditions. The electrons also rotate the plane of a linearly polarized wave, an effect called **Faraday rotation**. For a high electron content and 30 degrees of elevation, P.618 gives about 30 full rotations at 100 MHz, 108 degrees at 1 GHz, 12 degrees at 3 GHz and about 1 degree at 10 GHz. Rotation, delay and absorption fall with the square of the frequency; scintillation falls too, by its own law; and P.618 calls all of them negligible above 10 GHz.

Transit made the ionosphere useful. Its satellites sent two related frequencies, 150 and 400 MHz, because the ionosphere delays the two by different amounts, and comparing them removes most of the error; the builder's own history, in the Johns Hopkins APL Technical Digest, records the reason. GPS repeats the idea with more than one frequency. Low elevation makes every effect worse: the path through the air is longer.

FIGURE 3.3

The weather troubles the high bands and the ionosphere troubles the low ones

Frequency	Rain, 25 mm/h (dB per km)	Gases	Faraday rotation (one way)	Ionospheric scintillation (equator, night, high sunspot number)
0.1 GHz	method starts at 1 GHz	normally neglected	about 30 rotations	see ITU-R P.531
1 GHz		normally neglected	108 degrees	more than 20 dB peak to peak
1.5 GHz (L)	0.001	normally neglected		
3 GHz (S)		normally neglected	12 degrees	about 10 dB peak to peak
4 GHz (C)	0.014	normally neglected		
10 GHz (X)		becomes significant above 10 GHz	1.1 degrees	about 4 dB peak to peak
12 GHz (Ku)	1.0	grows with frequency	negligible above 10 GHz	negligible above 10 GHz
20 GHz (K)	2.5	grows with frequency	negligible	negligible
30 GHz (Ka)	4.7	grows with frequency	negligible	negligible

Rain loss computed from ITU-R P.838-3 at an illustrative 25 mm/h, circular polarization; Faraday rotation from ITU-R P.618-14 Table 1 for a high electron content and 30 degrees elevation; scintillation from the same table for the conditions in the column head; blank where the source gives no value at that frequency.

ITU-R P.838-3 (2005), Table 5 and equations 1, 4 and 5, computed for tau = 45 degrees; ITU-R P.618-14 (2023-08), clause 1, clause 2.1 and Table 1. Rain loss is per kilometer of rain on the path, not per link.

Polarization

A radio wave's electric field points in a direction, its **polarization**. In a linearly polarized wave it stays in one plane; in a circularly polarized wave it turns once per cycle, clockwise or counterclockwise. Two waves of orthogonal polarization (two crossed linear planes, or left and right hand circular) can share a frequency, and many satellites use that to carry twice the traffic in the same band. The price is that rain and ice crystals depolarize the wave a little, so some of each signal leaks into the other: a form of interference that grows in the weather that already weakens the signal.

Polarization also explains why the mobile bands favor circular waves. Faraday rotation turns a linear wave by an amount that depends on the electrons along the path, and a handset held at any angle has no fixed orientation. A circularly polarized wave stays circular however far the ionosphere rotates it, so no rotation mismatch arises; the handset's own pattern and the user's body still cost decibels. GPS transmits right-hand circular polarization (IS-GPS-200N), and its own specification measures the minimum received signal with a linearly polarized antenna, which takes half of a circular wave's power: 3 dB, a line that appears in Chapter 5's budget.

Permission is part of the band

A frequency is not free to use because a radio can tune to it. The International Telecommunication Union allocates bands to services worldwide, national regulators license their use, and operators coordinate with neighbors in orbit and on the ground before they transmit. Power limits protect other users. This book treats licensing in one page; a later book in this series covers it in depth. One point from history and one from 2026 are enough here.

Maritime satellite service received only a footnote in a small piece of VHF spectrum at the first ITU space conference in 1963. NASA's history records that only the next space conference, in 1971, gave the maritime services a piece of L band, placed next to the aeronautical allocation so that one satellite could serve both. Marisat existed because that allocation did.

In 2026 a phone can reach a satellite on two spectrum roads, and they are different in law, not only in frequency. On the first road, a satellite operator uses a mobile carrier's own terrestrial spectrum under the carrier's license. In the United States this is the FCC's Supplemental Coverage from Space framework, published in the Federal Register on 30 April 2024 and effective 30 May 2024; it lists the 600, 700 and 800 MHz bands, Broadband PCS and the AWS-H block, and licenses the phones by rule. On the second road, the satellite uses spectrum allocated to the mobile satellite service. 3GPP defined satellite bands for it: n255 in L band and n256 in S band in Release 17, and n254, with the phone transmitting at

1610 to 1626.5 MHz and the satellite at 2483.5 to 2500 MHz, in Release 18. Standards, device support, spectrum rights and each operator's own design are four separate questions; a phone that supports a band is not yet a phone with a service.

FIGURE 3.4

A phone reaches a satellite on two spectrum roads, and they differ in law, not only in frequency

	Road 1: a carrier's terrestrial spectrum	Road 2: mobile satellite spectrum
Bands	600, 700, 800 MHz, Broadband PCS (1850 to 1915 and 1930 to 1995 MHz), AWS-H	n255 (L band), n256 (S band) in Release 17; n254 (1610 to 1626.5 up, 2483.5 to 2500 MHz down) in Release 18
Whose right	The terrestrial licensee's spectrum, leased to a satellite operator that also holds its own satellite authorization	The satellite operator's own authorization in a band allocated to the mobile satellite service
The phone	Licensed by rule as an earth station (FCC)	Must support the service's band and air interface (the 3GPP satellite features, for a 3GPP service)
Rule	FCC Supplemental Coverage from Space, 89 FR 34148, effective 2024-05-30	National licenses under ITU allocations; 3GPP defines the bands, not the right to use them

The two roads as of November 2026, United States framework and 3GPP bands; an approved band is not yet a service in a given country.

Federal Register 89 FR 34148 (2024-04-30); FCC fact sheet and draft order DOC-400678 (2024-02-22), GN Docket 23-65; 3GPP, Non-Terrestrial Networks overview (read 2026-11-22).

THE SYSTEM'S FAILURE

LightSquared, 2011 to 2012: a band is also its neighbors. LightSquared held a mobile satellite license with an ancillary terrestrial component, permission to add ground base stations in its L band spectrum. In January 2011 the FCC's International Bureau granted it a conditional waiver toward a terrestrial broadband network. The concern, in the FCC's words, was overload interference from those ground operations into other bands, including the GPS bands. On 14 February 2012 NTIA, which speaks for federal spectrum users, wrote to the FCC that, based on federal testing, the proposed network "will impact GPS services" and that there is currently "no practical way to mitigate the potential harmful interference" from planned terrestrial operations in the 1525 to 1559 MHz band. The next day the Bureau proposed to vacate the waiver and to suspend the terrestrial authorization indefinitely (FCC public notice DA 12-214, 15 February 2012).

The top of that band sits 16.42 MHz below the GPS L1 carrier at 1575.42 MHz. A GPS signal arrives near the ground at a specified minimum of -158.5 dBW (Chapter 5), below the noise of the receiver; a ground transmitter nearby does not have to be strong by its own standards to dwarf it. The finding the public notice states is about GPS receivers and devices, not about the transmitter's own band. The lesson, kept to what the record supports: permission to transmit in its own band did not settle the question, because the GPS receivers and devices assessed in federal testing could not reject the neighbor's signal. The 16.42 MHz is a distance from carrier to band edge, not a guard band anyone guaranteed.

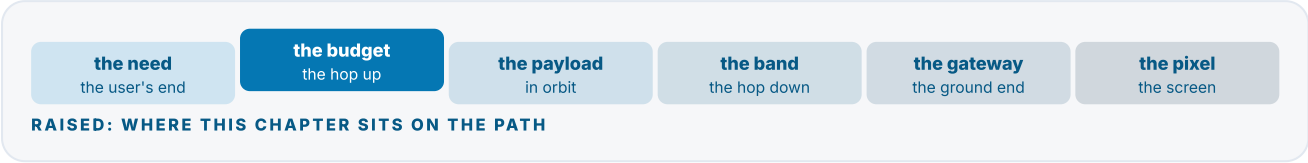
SECURITY NOTE

Who can interfere or command. A wide-beam, low-gain antenna hears everything in view: the wanted satellite, other satellites, and any transmitter on the ground within its beam, including a deliberate one. A narrow beam rejects signals by angle. **How it is seen.** Rain and interference both lower the demodulator's signal quality, C/(N+I), and a power reading alone does not tell them apart. Context gives clues, not proof: rain tends to fade the links that pass through the same storm and follows the weather; interference tends to appear on some frequencies or beams and not others; a beacon or a second site helps tell them apart. **How it is recovered.** For rain, margin, adaptive coding and site diversity; for interference, finding the source (geolocation by the operator), a change of frequency, and regulatory action, which Chapter 11 covers.

Monday rule: for every hop of a service you depend on, ask which band it uses, who holds the right to use that band in your country, and what antenna the terminal really has.

CHAPTER FOUR

The Hop Budget



In July 1963 the Bell System Technical Journal printed the design of Telstar 1, launched a year earlier, and on page 795 it put the whole radio argument for the satellite into one short table. Ten lines for the path up from Andover, Maine, seven for the path down, and at the bottom of each a single number: the carrier-to-noise ratio. Everything else in the issue, the horn reflector with its 3,600 square foot aperture, the maser cooled in liquid helium, the tube in the satellite, served those two numbers. This chapter teaches the table. Its one decision: no rate is accepted without the budget behind it.

One line of additions, stated at named places

A hop is one radio path from one transmitter to one receiver: a phone to a satellite, or a satellite to a dish. Its budget follows the power from the transmitter's output to the decoder's input and asks one question at the end: is the signal strong enough, compared with the noise, for the receiver to recover the bits at the stated error rate?

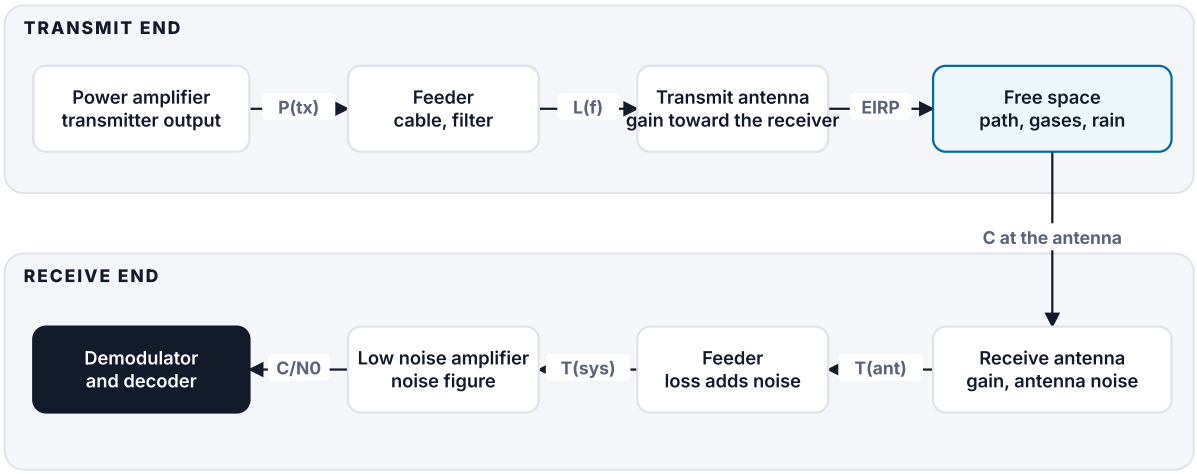
Powers multiply along the path. The transmitter's power is multiplied by the antenna's gain, divided by the spreading of the wave over distance, divided again by every loss in the air, then multiplied by the receiving antenna's gain. In decibels, ten times the base-10 logarithm of a ratio, each multiplication becomes an addition (Appendix B teaches the unit). A budget is therefore one column of signed numbers: gains with a plus sign, losses with a minus sign, each with its unit and its source.

Each line is stated at a place, and the places must agree. The **reference plane** is the point in the chain to which a number is referred, whether it was measured, calculated or assumed. A transmitter's power can be given at the amplifier's output or at the antenna's connector, and the cable between them can cost a decibel or two. The **EIRP**, the equivalent isotropically radiated power, is the power an ideal antenna radiating equally in all directions would need to put the same signal toward the receiver: transmitter output, less the feeder loss, plus the antenna gain. On the receive side, the antenna's gain and the system's noise temperature are

summarized as one number, G/T, and that number is only meaningful at one named plane. A common error mixes planes: the gain reduced by the feeder loss, as at the receiver input, with a noise temperature already referred back to the antenna terminal. At the antenna terminal the feeder sits only in the noise temperature; at the receiver input it also reduces the gain. Both give the same G/T; mixing them counts the feeder twice or not at all. Figure 4.1 shows the chain and where each line belongs.

FIGURE 4.1

A hop budget is only as good as its reference planes: where each line is measured, and what it includes



The transmit chain ends in the EIRP; the receive chain begins at the antenna and is summarized by G/T at one named plane; every line of the budget belongs to one stretch of this chain.

Author's diagram based on the budget conventions of Appendix B (ITU-R P.525-5 for free space; T(sys) = T(ant) + (L - 1) T(p) + L T(r) at the antenna terminal).

A feeder loss before the first amplifier does two kinds of harm. It removes signal, and because a lossy cable at room temperature radiates noise, it adds noise at the most sensitive point of the chain; Appendix B gives the formula that counts both once. This is why the 1962 ground station placed its transmitter's power stage and its maser receiver close to the antenna feed, as the Bell System paper records.

Distance: free-space loss and the slant range

In every worked budget of this chapter the largest line is the spreading of the wave. Free-space loss between two ideal antennas is 20 log10(4 pi d / lambda), with the distance d and the wavelength lambda in the same unit; ITU-R Recommendation P.525-5 (November 2024)

gives this form and an equivalent one in megahertz and kilometers. It grows with the square of the distance and the square of the frequency, so it is quoted for both at once.

Three reference values, all calculated with that formula and repeated in Appendix B:

- At 2 GHz, 550 km straight up costs 153.3 dB.
- At the same frequency, 5 km costs 112.4 dB.
- The gap between them is 40.8 dB, which is 20 log10 of the distance ratio of 110.

Both values are free space. A real cell on the ground usually loses more than free space, through buildings, terrain and the ground itself, so the gap is a reference for the distance alone, not a comparison of two real links. It still explains the direction of the problem: a phone that reaches a tower a few kilometers away has some forty decibels less to spare when the same phone talks to a satellite overhead, before any other line is counted.

A satellite is rarely overhead. The **slant range** is the distance at a stated elevation angle, and it grows quickly toward the horizon. A satellite at 600 km is 600 km away straight up, 1,075 km away at 30 degrees and 1,932 km away at 10 degrees. Going from straight up to 30 degrees costs 5.1 dB at any frequency. A geostationary satellite, at 35,786 km above the equator, is 37,778 km from a dish that sees it at 40 degrees, and at 19.7 GHz that path costs 209.9 dB.

Noise: temperature, G/T, and the maser of 1962

The receiver's enemy is noise, and noise is measured as a temperature. Every resistor, every lossy cable and every patch of warm ground in an antenna's view adds thermal noise whose power in a given bandwidth is proportional to its temperature in kelvin: N = k T B, with k Boltzmann's constant, fixed exactly by the SI since 2019, and B the bandwidth. The **system noise temperature** collects all of it at one reference plane: the antenna's own noise, which depends on what the antenna sees, and the receiver's, which depends on its first amplifier.

The receiving end's figure of merit is **G/T**, antenna gain divided by system noise temperature, in dB/K. With it, the carrier-to-noise density at the receiver is one line of additions: C/N0 = EIRP less the free-space loss, less the other losses, plus G/T, less Boltzmann's constant in decibels. Subtracting that constant, a negative number, adds 228.6 dB.

Telstar's designers put almost all of the hop's strength on the ground. The Bell System paper describes a horn reflector at Andover with a 3,600 square foot aperture, a maser amplifier at its input, and a system noise temperature of 32 K at the zenith; its budget used 50 K at the worst range. With 58 dB of antenna gain, that is a G/T of 41.0 dB/K. The satellite was the opposite. Its antennas were nearly isotropic, with about 0 dB of gain, and its receiver had an

equivalent noise figure that Bell Laboratories measured at 16.5 dB, plus or minus 2 dB. Looking at a warm Earth, that receiver's system noise temperature works out at 12,954 K. Figure 4.2 sets the two ends of 1962 beside the model phone link of this chapter, line by line.

FIGURE 4.2

1962 and 2026 on the same lines: in 1962 the ground supplied the gain and the low noise; in the model phone link the satellite must

Line	Telstar 1 downlink, 1962	Model phone uplink, 2026 (hypothetical)
Transmitter output	35 dBm, one traveling-wave tube	23 dBm, power class 3 (nominal maximum)
Transmit antenna gain	0 dB, nearly isotropic	0 dBi reference; body and hand are a separate 3 dB loss line (assumption)
EIRP	3.2 dBW	-7.0 dBW at the reference antenna (-10.0 dBW after body and hand)
Range and free-space loss	9,260 km, 184.2 dB at 4169.72 MHz	1,075 km, 158.7 dB at 1.9 GHz
Receive antenna gain	58 dB, a 3,600 square foot horn	not known; inside the solved G/T
System noise temperature	50 K, a maser at the feed	not known; inside the solved G/T
Receive G/T	41.0 dB/K at Andover	3.6 dB/K required of the satellite
What it carried	one television channel, FM in 25 MHz	64 kbit/s of information
Who supplies the margin	the ground station	the satellite

Telstar 1's downlink (Bell System values, July 1963) beside the model phone uplink (hypothetical, chapter 4): the same budget lines, with the margin supplied at opposite ends.

Bell System Technical Journal, vol. 42 no. 4, July 1963 (Table V, p. 795; repeater paper, p. 833), read 2026-11-23; model ledger, this chapter. G/T at Andover calculated: 58 dB less 10 log10(50 K), both taken at the maser input, as the paper gives them.

The comparison is the series question in two columns. In 1962 the user's end was a national laboratory, so the ground supplied the gain and the low noise. In the model phone link the user's end is a phone in a hand, with a reference antenna gain of 0 dBi and a nominal maximum output of 23 dBm, so in this model the rest of the margin has to come from the satellite end.

From carrier to noise density to bits

C/N0 is the carrier power divided by the noise power density (noise per hertz); its unit is the hertz, written dBHz in decibels. It becomes a statement about bits in one of two ways. Divide by the information rate R, and the result is Eb/N0, the energy per bit over the noise density: Eb/N0 = C/N0 less 10 log10(R). Divide by the symbol rate instead, and the result is Es/N0, the energy per transmitted symbol: Es/N0 = C/N0 less 10 log10(symbol rate); it equals C/N in a noise bandwidth equal to the symbol rate, and it differs from Eb/N0 by 10 log10 of the information bits each symbol carries: it is higher when a symbol carries more than one information bit and lower when it carries fewer, as with QPSK at code rate 1/4. Or divide by any other bandwidth B, and the result is C/N in that bandwidth. A modulation and code then need a stated value of one of these for a stated error rate, and that value must have a source: a standard's table or a published curve.

The division by the rate is the reason the budget is a negotiation. At a fixed C/N0, every doubling of the rate costs 3 dB of Eb/N0. 64 kbit/s is 48.1 dBHz; 10 Mbit/s is 70.0 dBHz. Going from 64 kbit/s to 10 Mbit/s on the same link loses 21.9 dB of Eb/N0, and nothing about the radio has changed; whether it then fails depends on the margin it had. The rate is what the margin buys.

Interference is a line, not a remark. Other beams of the same satellite, other satellites and terrestrial transmitters add power that looks, at the decoder, much like noise. If the interference density I0 is 6 dB below the noise density N0, the step from C/N0 to C/(N0+I0) costs 1.0 dB; if the two are equal it costs 3.0 dB. Interference with structure, such as a strong narrow carrier or a pulsed source, needs an analysis of the waveform instead, and chapter 11 treats a deliberate interferer.

The model: one phone, one satellite, solved for the satellite

The worked hop of this chapter is hypothetical and labeled so. A phone of power class 3, the class that 3GPP TS 38.101-5 lists for its satellite bands n255 and n256 at 23 dBm with a tolerance of plus or minus 2 dB, sends 64 kbit/s of information to a satellite at 600 km, seen at 30 degrees, in open sky, at a carrier of 1.9 GHz. The losses are those a 3GPP study, TR 38.821, uses as evaluation assumptions: 2.2 dB of ionospheric scintillation, a 3 dB shadowing margin and 3 dB of polarization mismatch for a linearly polarized phone into

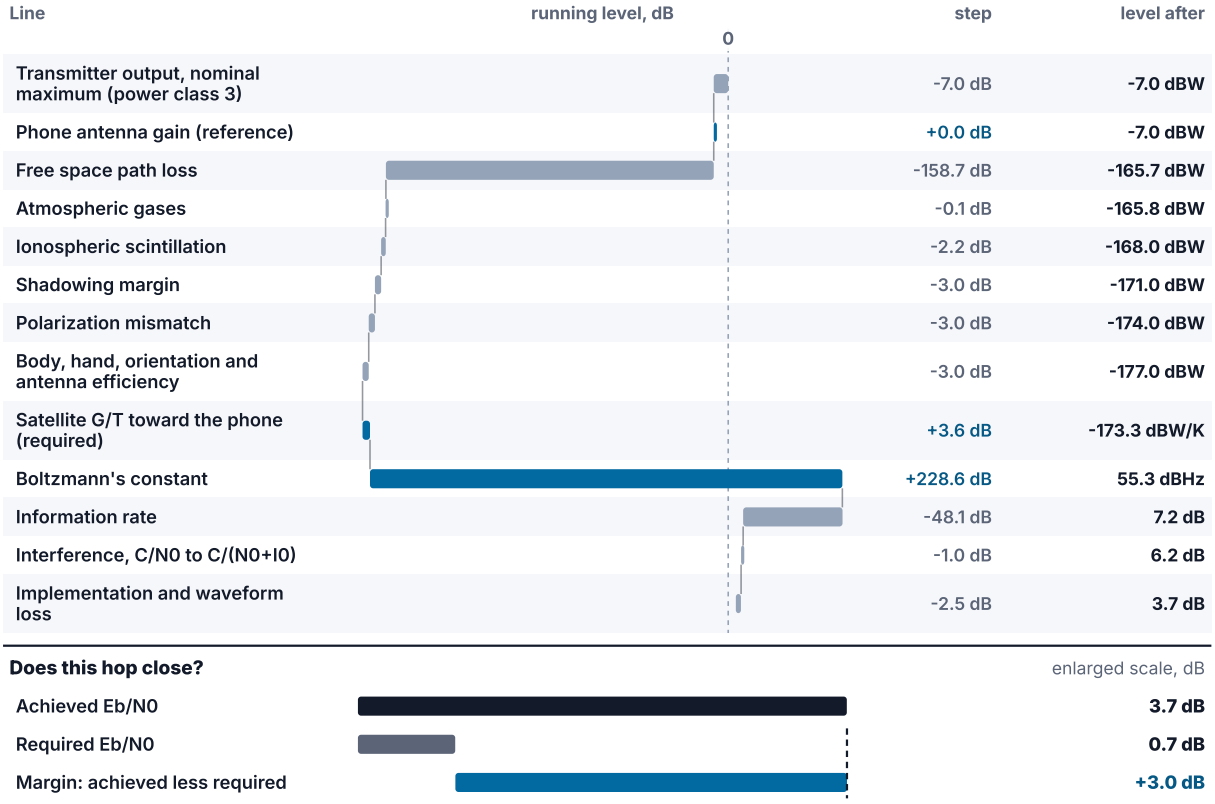
circular reception. Three inputs have no primary source yet and are printed as assumptions to verify: 3 dB for the hand, the head, the phone's orientation and its antenna's efficiency, interference 6 dB below the noise, and a 2.5 dB implementation loss.

The required value comes from the DVB-S2 standard, ETSI EN 302 307-1, Table 13: QPSK with a rate 1/4 LDPC code needs an ideal Es/N0 of -2.35 dB at 0.490243 bit per symbol for a packet error ratio of 1e-7, which is an Eb/N0 of 0.7 dB. It is a stand-in. The 3GPP uplink uses its own waveform and block error targets, and the gap between the stand-in and the real threshold is not known to be small until a link-level result for that waveform exists. The 2.5 dB implementation line carries the difference, and the total of 3.2 dB is a placeholder, not necessarily a conservative one.

No operator figure for a satellite's G/T toward one phone has been found in a primary source for this book. So the budget does not guess it. It solves for it: the G/T at which this hop keeps a 3 dB design margin is 3.6 dB/K. That number is a statement about what a hypothetical satellite must have, not about any real one. It sits 2.5 dB above the G/T that TR 38.821 assumes for its first set of low orbit satellite parameters at 2 GHz (1.1 dB/K), and 8.5 dB above its second set (-4.9 dB/K). Figure 4.3 draws the hop, line by line.

FIGURE 4.3

One hop, line by line: the model phone uplink keeps its 3 dB design margin only because the satellite G/T was solved for it



Required for: quasi error free (packet error ratio 1e-7) on the standard's ideal curve. Dashed line: the design minimum margin, 3.0 dB. Operating point: 64 kbit/s, phone to satellite, 30 degrees elevation, open sky, clear conditions; one phone; availability not assessed.
Source of the required value: ETSI EN 302 307-1 V1.4.1, Table 13 (stand-in), 2026-11-23.

The baseline hop of the model ledger, from the phone's transmitter output to the margin over the required Eb/N0; every bar is one line of the hop budget.

Author's calculation; inputs from 3GPP TS 38.101-5 V17.8.0, 3GPP TR 38.821 V16.2.0 and ETSI EN 302 307-1 V1.4.1, read 2026-11-23; assumptions marked in the ledger.

A G/T does not give an antenna size without three more numbers: the system noise temperature, the losses when the beam is steered and at its edge, and the aperture efficiency. With noise temperatures of 350 to 800 K, losses of 1 to 3 dB and efficiencies of 0.7 to 0.5, all assumptions, the solved G/T needs 30.1 to 35.7 dBi of gain, an effective aperture of 2.0 to 7.3 square meters, and a physical area of 2.9 to 14.6 square meters. An effective aperture is not a deployed area, and the range is for 64 kbit/s to one phone.

The verdict is the uplink's alone. With a regenerative satellite, which decodes on board, it is the decoder's margin; with a transparent one it is an allocation, and the circuit's verdict needs the combined line of the next section.

Then two stresses, each against the frozen baseline. **Case A** raises the rate to 10 Mbit/s. It costs 21.9 dB and leaves the hop 18.9 dB below zero margin (case A of the ledger at the end of this chapter). **Case B** keeps 64 kbit/s and adds a stated 10 dB obstruction, standing for a wall or a roof; it leaves the hop 7.0 dB short. The obstruction is a stated number, not a measured building; a building entry model such as ITU-R P.2109 would give one for a named scene.

For scale only: case A would keep its 3 dB margin with a directional G/T toward the phone of 25.6 dB/K, which under the same three assumptions is a physical area of 450 to 2,281 square meters. With the phone's EIRP fixed, the required area in this model grows with the rate: from 64 kbit/s to 10 Mbit/s the rate rises 156.25 times, and so does the area. One operator, AST SpaceMobile, describes its Block 2 satellite in an SEC filing of 9 November 2026 as about 2,400 square feet, against about 700 for Block 1 (operator claim). That is one operator's design for its own bands, beams and rates, not a check on this model, and this model implies nothing about it.

Two hops through a transparent satellite

A transparent satellite repeats what it hears, noise included. The uplink's noise arrives at the ground receiver together with the downlink's, so the two hops do not each pass or fail on their own: their inverse carrier-to-noise ratios add, in linear terms, and only the combined line is compared with the requirement. The total is below the weaker hop. The rule holds for a linear repeater with independent noises; distortion and intermodulation in the repeater add further terms of the same form.

Telstar 1 is the worked case, from the Bell System's own Table V at its worst-case range of 5,000 nautical miles, 9,260 km, on both hops. Up from Andover: a 2 kW transmitter, 1 dB of waveguide, a 61 dB horn, and a satellite antenna of about 0 dB with a 2 dB feed loss in front of a receiver with that 16.5 dB noise figure. The C/N0 at the satellite is 90.6 dBHz, a C/N of 16.6 dB in the 25 MHz band. Down to Andover: the tube's 35 dBm output, less 0.2 dB in a separation network and 1.6 dB in the antenna and its cables, gives 33.2 dBm radiated; with 0 dB of antenna gain the EIRP is 3.2 dBW. Into the 58 dB horn at 50 K, the C/N0 is 88.6 dBHz, a C/N of 14.6 dB.

Combined, the circuit's C/N0 is 86.5 dBHz, 2.1 dB below the weaker hop. The paper says the up path reduces the overall carrier-to-noise ratio "by about 2 db", and its own printed values (17.5 and 15 dB) combine to 13.1 dB, a loss of 1.9 dB: the same result. For television the paper names the requirement. A conventional FM receiver begins to degrade at a carrier-to-noise ratio of 10 dB, and the frequency compression demodulator at Andover improved that threshold by about 5 dB, so the circuit needs about 5 dB of C/N in 25 MHz, a C/N0 of 79.0

dBHz. The circuit closes with 7.5 dB above that threshold, at 5,000 nautical miles, in clear sky, while the satellite is in view. Clearing the threshold is not the same as picture quality, which the paper treats separately; at that range it reports a slight impairment.

One line does not match the paper, and the difference is printed instead of hidden. Recalculated, the uplink's free-space loss at 6389.58 MHz over 9,260 km is 187.9 dB; Table V prints 187 dB. The downlink's 184.2 dB agrees with its printed 184. The budget keeps the calculated value, which is why the uplink's C/N here is 16.6 dB, not the paper's 17.5. Recomputing every line, including a famous journal's, is the habit this chapter asks for.

The same page also answers the opposite question. Ask the 1962 circuit for continuous service and it fails, not on any line of the budget, but because the satellite was in view of both sides of the Atlantic for minutes per pass. Telstar met its own aim, an experiment; the requirement decides whether a closing budget is enough.

Margin and availability

Margin is achieved less required, at one operating point (Reader's Brief). Rain, pointing error, interference, aging and implementation each take some of it. A margin is instantaneous; availability is a statistic over a year at a place, and one does not give the other without a propagation model and a design percentile.

The third worked hop shows how a modern system spends its margin. It is a geostationary Ka band spot beam to a 0.75 m consumer dish at 19.7 GHz, seen at 40 degrees, carrying one 100 Mbaud DVB-S2 carrier. It is representative, not one operator's system: the satellite's EIRP is solved (56.8 dBW for a 1 dB design margin in clear sky), and every terminal, rain and interference input is an assumption to verify.

- **Clear sky.** The dish's G/T is 20.1 dB/K and the C/(N+I) in the symbol rate bandwidth, which is Es/(N0+I0), is 12.2 dB: enough for 16APSK at code rate 3/4, 297 Mbit/s before pilots and higher-layer overhead, with the 1 dB design margin.
- **A stated 6 dB of rain.** The 6 dB is a sensitivity value, not a percentile of any site's rain statistics, and no availability is attached to it. It costs 7.1 dB of C/(N+I), because rain also radiates noise into the dish and its G/T falls by 3.1 dB. The terminal steps down the adaptive ladder to QPSK 3/5 and carries 119 Mbit/s with 1.8 dB of margin.
- **A stated 14 dB of rain.** At 14 dB even QPSK 1/4, the lowest mode of the table, is 1.9 dB short, and the link drops. How often either value occurs is a question for a named site, which this example does not have.

Interference behaves differently on this downlink. Rain lowers the carrier and the other beams' interference together, so their ratio holds: interference costs 2.3 dB of C/(N0+I0) in clear sky and 0.4 dB in the 6 dB rain, where thermal noise dominates. That holds only for

interference from the same satellite's beams arriving through the same rain; it is an assumption of these pages, and terrestrial or other-satellite interference need not fade with the wanted carrier: it may cross the same rain or none, and its path needs its own model. The three verdicts are therefore a sensitivity study: they show how the mode and the rate fall as rain grows, not how often the link is up. Turning 6 or 14 dB into an availability needs ITU-R P.618 with one site's rain statistics, its elevation and its polarization; that step is named here and not taken, because the site data were not read for this book.

"The link closes" keeps the meaning the Reader's Brief gives it, and no more: it does not say that a service will work for a user, that a beam has capacity for many users, or that a satellite has a G/T its operator did not publish.

THE SYSTEM'S FAILURE

Globalstar, 2007: one hop of two. In its annual report for 2006, filed in 2007, Globalstar reported that the S band antenna amplifiers on a number of its satellites were degrading, and that "the degradation of the two-way communication service is occurring at a rate faster than previously experienced". The filing explains the link: "The S-band antenna provides the downlink from the satellite to a subscriber's phone or data terminal. Degraded performance of the S-band antenna reduces the quality of two-way voice and data communication." It also states what survived: the degradation "does not affect adversely our one-way Simplex data transmission services, which utilize only the L-band uplink" from a terminal to the satellites. The filing gives the root cause as unknown. The lesson stays inside the source: a two-way service needs both directions to close, the satellite-to-user downlink and the user-to-satellite uplink are different hops with different hardware, and the product that kept working did not use the degraded one. (Its data still went on from the satellite to a gateway over the feeder link.)

Bench step, as a requirement. The bench link of this book, a weather satellite's low rate downlink near 137.9 MHz to a dipole, gets its own hop budget in chapter 12. Filling it needs the satellite's transmit power and antenna pattern from a primary document. Without them, the hop budget page of that ledger solves for the EIRP that would be needed and gives a range. It is an exercise for the reader; no recording exists yet.

SECURITY NOTE

Who can interfere or command. Anyone who can put power into the receiver's band and beam: a neighboring system by accident, a jammer on purpose. The budget is where that power is assessed, as a line with its geometry, its bandwidth and the victim antenna's discrimination, not as a slogan. **How it is seen.** As a C/(N0+I0) below what the thermal budget predicts at the same elevation and weather. A beacon, other beams and other sites help tell rain from interference, though the two can occur together. **How it is recovered.** By locating the source and coordinating or removing it; a margin is not a defense, since a stronger interferer takes any margin. Chapter 11 works one bounded case.

The worked hops

The model phone uplink, with its baseline and both stresses:

LINK LEDGER · LL-2026-01 · SERVICE LEDGER

2026-11-23 System: A phone uplink to a low orbit satellite near 1.9 GHz (hypothetical model ledger)

Planned Class: full **Budget: closes (baseline); stress cases A and B fail, as intended**

1 Requirement	Hypothetical, labeled so. One phone sends 64 kbit/s of information up to a low orbit satellite in open sky at 30 degrees elevation, with 3 dB of design margin. Stress cases: 10 Mbit/s (case A) and a stated 10 dB obstruction (case B).
2 Ends and path	A phone that supports 3GPP satellite access (power class 3) and one satellite in view. The satellite's onward path to a gateway is outside this ledger. **Path:** Not decided here: the uplink hop is the same for a transparent or a regenerative satellite. Only the service link up is budgeted.
3 Orbit and time	Low orbit at 600 km (the 3GPP LEO-600 evaluation case). Passes, not continuous: one satellite is in view for minutes. **Time:** Slant range 1,075 km at 30 degrees; one way delay on this hop 3.6 ms (2.0 ms straight up). Doppler up to 44 kHz at 1.9 GHz near the horizon (calculated, chapter 6).
4 Band and permission	**Uplink, phone to satellite.** 1.9 GHz, hypothetical; the 3GPP satellite band n256 uplink is 1980 to 2010 MHz. The n256 allocation does not cover 1.9 GHz, and the right to transmit depends on band, service, country and operator (in the United States, for example, the FCC proceeding GN Docket 23-65). Not assessed
5 Capacity	**Up.** 64 kbit/s of information for one phone (a requirement, not a measured rate). **Down.** Not budgeted here: the downlink is a separate hop. Sharing among phones in one beam is not modeled.
6 Who owns each end	**Space segment.** Not named (hypothetical) **Ground segment.** Not named **Customer relationship.** Not assessed **The exit.** Not assessed
7 Trust	Not assessed: hypothetical. A real ledger names who commands the satellite, whose keys protect the traffic, and how uplink jamming would be seen.
8 How it fails, and how we would see it	The silent failure: the budget closes outdoors and the user stands indoors. A stated 10 dB obstruction leaves the hop 7.0 dB short. **How we would see it:** Per-phone uplink signal quality and retransmission counts at the satellite or gateway, logged per pass and per beam.
9 Cost shape	Not assessed (hypothetical).
10 Evidence	23 dBm standard TS 38.101-5, Table 6.2.1-1, 2026-11-23 Eb/N0 0.7 dB calculated EN 302 307-1 Table 13 (stand-in), 2026-11-23 G/T 3.6 dB/K calculated solved here, 2026-11-23 Body, interference, implementation *assumption* to verify (page 2), 2026-11-23

A first assessment, not a qualification. Hypothetical system; no number is measured by the author. Assumptions are marked and must be verified; every budget line is recomputed by script.

LINK LEDGER · LL-2026-01 · HOP BUDGET · THE BASELINE

Baseline · Uplink at 64 kbit/s, open sky

Phone (power class 3) to Low orbit satellite, 600 km · 1.9 GHz · 1,075 km slant range · reference plane: the phone's antenna connector; the satellite's G/T is referred to its antenna terminal

Part	Line	Value	dB, and the level after	Evidence	Source and date
TRANSMIT POWER AND ANTENNA GAIN	Transmitter output, nominal maximum (power class 3)	23 dBm	**-7.0** level -7.0 dBW	standard	3GPP TS 38.101-5 V17.8.0, Table 6.2.1-1, 2026-11-23
	Phone antenna gain (reference)	0 dBi	**+0.0** level -7.0 dBW	standard	TS 38.101-5, clause 6.1 (test convention), 2026-11-23
LOSSES	Free space path loss	1,075 km at 1.9 GHz	**-158.7** level -165.7 dBW	calculated	ITU-R P.525-5; Appendix B, 2026-11-23
	Atmospheric gases	0.1 dB	**-0.1** level -165.8 dBW	assumption	Assumption: ITU-R P.676, to verify, 2026-11-23
	Ionospheric scintillation	2.2 dB	**-2.2** level -168.0 dBW	standard	3GPP TR 38.821, Table 6.1.3.2-1 (study value), 2026-11-23
	Shadowing margin	3 dB	**-3.0** level -171.0 dBW	standard	TR 38.821, Table 6.1.3.2-1 (study value), 2026-11-23
	Polarization mismatch	3 dB	**-3.0** level -174.0 dBW	standard	TR 38.821, clause 6.1.1.1 (study value), 2026-11-23
	Body, hand, orientation and antenna efficiency	3 dB	**-3.0** level -177.0 dBW	assumption	Assumption: phone patterns, to verify, 2026-11-23
RECEIVE SENSITIVITY	Satellite G/T toward the phone (required)	3.6 dB/K	**+3.6** level -173.3 dBW/K	calculated	Solved for the 3 dB margin, 2026-11-23
	Boltzmann's constant	-228.6 dBW/K/Hz, subtracted	**+228.6** level 55.3 dBHz	standard	SI 2019, exact, 2026-11-23
BANDWIDTH	Information rate	64 kbit/s	**-48.1** level 7.2 dB	assumption	Requirement (a choice), 2026-11-23
INTERFERENCE	Interference, C/N0 to C/(N0+I0)	I0/N0 = -6 dB	**-1.0** level 6.2 dB	assumption	Assumption: operator analysis, to verify, 2026-11-23
CODING	Modulation and code	QPSK, LDPC rate 1/4 (DVB-S2 curve as representative)		standard	EN 302 307-1, Table 13 (stand-in), 2026-11-23
	Implementation and waveform loss	2.5 dB	**-2.5** level 3.7 dB	assumption	Assumption: link-level result, to verify, 2026-11-23
REQUIRED SIGNAL QUALITY	Required Eb/N0 (DVB-S2 ideal curve, stand-in)	Es/N0 -2.35 dB at 0.49 bit per symbol	**0.7**	calculated	ETSI EN 302 307-1 V1.4.1, Table 13 (stand-in), 2026-11-23
RESULT	**Achieved Eb/N0: the sum of the lines above**		**3.7**	calculated by this ledger	
	Required Eb/N0 for quasi error free (packet error ratio 1e-7) on the standard's ideal curve		**0.7**	from the line above	
	Margin: achieved less required		**+3.0**	design minimum 3.0 dB	

Closes: margin +3.0 dB (design minimum 3.0 dB)

Operating point. 64 kbit/s, phone to satellite, 30 degrees elevation, open sky, clear conditions; one phone; availability not assessed
Required Eb/N0, 0.7 dB: source. ETSI EN 302 307-1 V1.4.1, Table 13 (stand-in), 2026-11-23

Assumptions. Hypothetical. The G/T is solved: the satellite's directional G/T toward this phone, with scan, beam edge and pointing inside it. Assumes full phone power, successful acquisition and Doppler pre-compensation, and noise-like interference. Not covered: fast fading, rain, sharing, the downlink, availability.

LINK LEDGER · LL-2026-01 · HOP BUDGET · CASE A OF THE BASELINE

Case A: Uplink at 10 Mbit/s, a broadband rate

Phone (power class 3) to Low orbit satellite, 600 km · 1.9 GHz · 1,075 km slant range

Part	Line	Value	dB, and the level after	Evidence	Source and date
The other 13 lines are as in the baseline: not repeated here, and counted in the sums below.					
RECEIVE SENSITIVITY	Satellite G/T (baseline value)	3.6 dB/K	**+3.6** level -173.3 dBW/K	*calculated*	Frozen at the baseline value, 2026-11-23
BANDWIDTH	Information rate	10 Mbit/s	**-70.0** level -14.7 dB	*assumption*	Requirement (a choice), 2026-11-23
RESULT	**Achieved Eb/N0: the sum of the lines above**		**-18.2**	calculated by this ledger	
	Required Eb/N0 for quasi error free (packet error ratio 1e-7) on the standard's ideal curve		**0.7**	from the line above	
	Margin: achieved less required		**-18.9**	design minimum 3.0 dB	

Does not close: short by 18.9 dB, and by 21.9 dB against the design minimum of 3.0 dB

Operating point. 10 Mbit/s, phone to satellite, 30 degrees, open sky; satellite G/T frozen at the baseline value
Required Eb/N0, 0.7 dB: source. ETSI EN 302 307-1 V1.4.1, Table 13 (stand-in), 2026-11-23
Line that fails. Information rate: 10 Mbit/s costs 21.9 dB against 64 kbit/s, so the hop ends 21.9 dB below the 3 dB design margin

LINK LEDGER · LL-2026-01 · HOP BUDGET · CASE B OF THE BASELINE

Case B: Uplink at 64 kbit/s behind a stated 10 dB obstruction

Phone (power class 3) to Low orbit satellite, 600 km · 1.9 GHz · 1,075 km slant range

Part	Line	Value	dB, and the level after	Evidence	Source and date
The other 14 lines are as in the baseline: not repeated here, and counted in the sums below.					
LOSSES	Obstruction (stated)	10 dB	**-10.0** level -187.0 dBW	*assumption*	Assumption: ITU-R P.2109, to verify, 2026-11-23
RECEIVE SENSITIVITY	Satellite G/T (baseline value)	3.6 dB/K	**+3.6** level -183.3 dBW/K	*calculated*	Frozen at the baseline value, 2026-11-23
RESULT	**Achieved Eb/N0: the sum of the lines above**		**-6.3**	calculated by this ledger	
	Required Eb/N0 for quasi error free (packet error ratio 1e-7) on the standard's ideal curve		**0.7**	from the line above	
	Margin: achieved less required		**-7.0**	design minimum 3.0 dB	

Does not close: short by 7.0 dB, and by 10.0 dB against the design minimum of 3.0 dB

Operating point. 64 kbit/s, phone to satellite, 30 degrees, a stated 10 dB obstruction; satellite G/T frozen at the baseline value
Required Eb/N0, 0.7 dB: source. ETSI EN 302 307-1 V1.4.1, Table 13 (stand-in), 2026-11-23
Line that fails. Obstruction: 10 dB against a 3 dB design margin leaves the hop 7.0 dB short of zero margin

Telstar 1 as a transparent circuit, from the Bell System's published values (page 1 of this ledger is in the prologue):

LINK LEDGER · LL-1962-01 · HOP BUDGET · HOP 1 OF 2

Hop 1 · Uplink, Andover to Telstar 1

Andover, Maine (horn reflector, 2 kW) to Telstar 1 (transparent repeater) · 6389.58 MHz · 9,260 km (5,000 nautical miles) · reference plane: the ground transmitter's output; the satellite's noise referred to its receiver input

Part	Line	Value	dB, and the level after	Evidence	Source and date
TRANSMIT POWER AND ANTENNA GAIN	Transmitter output, 2 kW	63 dBm	**+33.0** level 33.0 dBW	operator claim	BSTJ 1963, Table V, 2026-11-23
	Ground waveguide loss	1 dB	**-1.0** level 32.0 dBW	operator claim	BSTJ 1963, Table V, 2026-11-23
	Ground antenna gain (horn reflector)	61 dB	**+61.0** level 93.0 dBW	operator claim	BSTJ 1963, Table V, 2026-11-23
LOSSES	Free space path loss	9,260 km at 6389.58 MHz	**-187.9** level -94.9 dBW	calculated	ITU-R P.525-5, 20 log10(4 pi d f / c), with Table V's range, 2026-11-23
RECEIVE SENSITIVITY	Satellite antenna gain	0 dB	**+0.0** level -94.9 dBW	operator claim	BSTJ 1963, Table V, 2026-11-23
	Satellite antenna feed loss	2 dB	**-2.0** level -96.9 dBW	operator claim	BSTJ 1963, Table V, 2026-11-23
	System noise temperature (noise figure 16.5 dB, 290 K at the antenna)	12,954 K	**-41.1** level -138.0 dBW/K	calculated	From the noise figure Bell Laboratories measured (BSTJ 1963, Table V note), 2026-11-23
	Boltzmann's constant	-228.6 dBW/K/Hz, subtracted	**+228.6** level 90.6 dBHz	standard	SI Brochure, 9th ed. (2019): k = 1.380649e-23 J/K exactly; 10 log10 k, 2026-11-23
RESULT	**Achieved C/N0: the sum of the lines above**		**90.6 dBHz**	calculated by this ledger	

No verdict for this hop alone: see the combined line

Assumptions. Table V's own range and lines; polarization and pointing losses, which the paper puts at about 0.1 dB each, are left out as in Table V.

LINK LEDGER · LL-1962-01 · HOP BUDGET · HOP 2 OF 2

Hop 2 · Downlink, Telstar 1 to Andover

Telstar 1 (traveling-wave tube, nearly isotropic antenna) to Andover, Maine (horn reflector, maser) · 4169.72 MHz · 9,260 km (5,000 nautical miles) · reference plane: the tube's output in the satellite; the ground noise referred to the maser input

Part	Line	Value	dB, and the level after	Evidence	Source and date
TRANSMIT POWER AND ANTENNA GAIN	Traveling-wave tube output	35 dBm	**+5.0** level 5.0 dBW	operator claim	BSTJ 1963, repeater paper, p. 833, 2026-11-23
	Separation network loss	0.2 dB	**-0.2** level 4.8 dBW	operator claim	BSTJ 1963, repeater paper, p. 833, 2026-11-23
	Transmitting antenna and cables loss (radiated power 33.2 dBm)	1.6 dB	**-1.6** level 3.2 dBW	operator claim	BSTJ 1963, repeater paper, p. 833, 2026-11-23
	Satellite antenna gain (EIRP 3.2 dBW)	0 dB	**+0.0** level 3.2 dBW	operator claim	BSTJ 1963, Table V, 2026-11-23
LOSSES	Free space path loss	9,260 km at 4169.72 MHz	**-184.2** level -181.0 dBW	calculated	ITU-R P.525-5, 20 log10(4 pi d f / c), with Table V's range, 2026-11-23
RECEIVE SENSITIVITY	Ground antenna gain (horn reflector)	58 dB	**+58.0** level -123.0 dBW	operator claim	BSTJ 1963, Table V, 2026-11-23
	System noise temperature (maser, at this range)	50 K	**-17.0** level -140.0 dBW/K	operator claim	BSTJ 1963, Table V, 2026-11-23
	Boltzmann's constant	-228.6 dBW/K/Hz, subtracted	**+228.6** level 88.6 dBHz	standard	SI Brochure, 9th ed. (2019): k = 1.380649e-23 J/K exactly; 10 log10 k, 2026-11-23
RESULT	**Achieved C/N0: the sum of the lines above**		**88.6 dBHz**	calculated by this ledger	

No verdict for this hop alone: see the combined line

Assumptions. Table V's range and its 50 K system temperature at that range (32 K at zenith). Table V uses 33 dBm for the satellite; the repeater paper's 33.2 dBm after the tube's output losses is used here.

LINK LEDGER · LL-1962-01 · COMBINED LINE · TRANSPARENT CIRCUIT, TELEVISION

Line	Value	Evidence	Source and date
Hop 1 · Uplink, Andover to Telstar 1: achieved C/N0	**90.6 dBHz**	from that hop's page	
Hop 2 · Downlink, Telstar 1 to Andover: achieved C/N0	**88.6 dBHz**	from that hop's page	
Combined C/N0: the inverse ratios add	**86.5 dBHz**	calculated by this ledger	
Required C/N0 for an FM television picture above the threshold of the frequency compression demodulator (about 5 dB C/N in 25 MHz)	**79.0 dBHz**	calculated	BSTJ 1963, p. 796: FM threshold 10 dB less about 5 dB, 2026-11-23
Margin: combined less required	**+7.5 dB**	design minimum 0.0 dB	

Closes: margin +7.5 dB

Operating point. television, FM in a 25 MHz band, Andover up and back down to Andover, 5,000 nautical miles on both hops, clear sky, 50 K at the ground receiver; only while the satellite is in view
Required C/N0, 79.0 dBHz: source. BSTJ 1963, p. 796: FM threshold 10 dB less about 5 dB, 2026-11-23

Two passing hops are not a passing circuit: a transparent satellite repeats the noise of the first hop into the second.

The hop pages of the representative Ka band forward link, its clear sky baseline and the two rain cases, are in Appendix B, section B.9.

Monday rule: do not accept a rate without the budget behind it: both directions, the reference plane, the required signal quality and its source, the margin, and the availability it was designed for.

CHAPTER FIVE

Modulation and Coding



The GPS interface specification, in its revision of August 2022, promises a civil signal of at least -158.5 dBW near the ground, at the output of a 3 dBi reference antenna, from any satellite above 5 degrees of elevation. Spread over the two megahertz that signal occupies, that is about 17.6 dB below the noise of an ordinary receiver: the signal is weaker than the hiss it arrives in, and the receiver still reads it, every second, for free. Chapter 4 ended with a margin, a number of decibels left over at a stated operating point. This chapter asks how many bits fit in that margin, and shows that the answer is a choice: of symbols, of code, of rate, and of how much of the channel is spent on telling the receiver where the bits are.

Symbols and bits

A radio does not send bits. It sends **symbols**: short stretches of carrier, each with an amplitude and a phase chosen from a fixed set of points called a **constellation**. The receiver decides which point each symbol was closest to, or, with a modern code, estimates how likely each point was, and turns that back into bits. The number of points sets the bits per symbol. **BPSK** (binary phase shift keying) has two points, opposite in phase, and carries 1 bit per symbol. **QPSK** has four and carries 2. **8PSK** has eight on one circle and carries 3. Beyond that, putting more points on one circle packs them too close, so **APSK** (amplitude and phase shift keying) places them on two or more rings: 16APSK carries 4 bits per symbol, 32APSK carries 5.

More points means more bits from the same symbol rate and the same bandwidth, and it means less room between points, so the receiver needs a stronger signal compared with the noise to tell them apart. The measure is **Es/No**, the energy per symbol divided by the noise density, in decibels; divide out the information bits each symbol carries after the code and it becomes **Eb/No**, the energy per useful bit. Figure 5.1 gives the price from the DVB-S2 standard, which publishes the Es/No each of its modes needs for quasi error-free reception in an ideal channel.

FIGURE 5.1

At code rate 3/4, each extra bit per symbol costs 2.3 to 3.9 dB more Es/N0

Constellation	Bits per symbol	Mode (rate 3/4)	Information bits per symbol	Ideal Es/N0 (dB)	Eb/N0 (dB)
BPSK	1	not in DVB-S2 at 3/4			
QPSK	2	QPSK 3/4	1.487	4.03	2.3
8PSK	3	8PSK 3/4	2.228	7.91	4.4
16APSK	4	16APSK 3/4	2.967	10.21	5.5
32APSK	5	32APSK 3/4	3.703	12.73	7.0

Ideal Es/N0 for quasi error-free packets (packet error ratio 1e-7, normal 64,800 bit frames, ideal channel) at code rate 3/4, from the DVB-S2 standard; Eb/N0 is derived from the spectral efficiency.

ETSI EN 302 307-1 V1.4.1 (2014-11), clause 6, Table 13. Eb/N0 = Es/N0 - 10 log10(efficiency), the standard's own note; author's calculation.

Rings have a second reason. A satellite's power amplifier is most efficient near its maximum output, and there it is not linear: it squeezes the peaks of the signal. A constellation whose points sit at very different amplitudes is distorted by that squeeze. Against square QAM of the same order, APSK puts its points on a few concentric rings, so it has fewer amplitude levels for the squeeze to distort; the DVB-S2 standard says its constellations are "optimized for operation over non-linear transponders". Its points sit on several rings, not on one ring as in PSK, so it needs more care in the amplifier; even PSK, once its pulses are shaped to save bandwidth, has an envelope that varies between symbols. The amplifier is then run below its maximum, an **output back-off**, and some modems pre-distort the signal to cancel part of the squeeze. The cost shows in the DVB-S2X tables: the 16APSK 2/3-L mode, in normal frames, needs an ideal Es/N0 of 8.43 dB in a linear channel; through a model hard-limiting amplifier at the best input back-off, the informative column of the same table gives 11.06 dB, counted against the amplifier's saturated power at a roll-off of 10 percent.

A different approach splits a wide channel into many narrow ones. **OFDM** (orthogonal frequency division multiplexing) sends hundreds or thousands of slow symbols side by side on closely spaced subcarriers, which makes it robust to echoes on the ground. Its sum of

many subcarriers has high peaks compared with its average, and a nonlinear amplifier in a satellite handles high peaks badly, so an OFDM link through such an amplifier needs more back-off.

The limit, and how close real codes come

In 1948 Claude Shannon showed that a channel of bandwidth B, disturbed by white noise, can carry at most $C = B \log_2(1 + S/N)$ bits per second with an error rate as small as one wishes, where S/N is the signal-to-noise ratio, and no more. Two consequences follow. Rate can be bought with bandwidth or with power, at an exchange rate that changes. At high signal-to-noise ratios capacity grows in step with bandwidth and only slowly with power. At low ones the opposite holds: capacity grows almost in step with power, and extra bandwidth gives less and less. And there is a floor. Written in energy per bit, the limit says Eb/N0 must be at least $(2^{\eta} - 1)/\eta$, where η is the spectral efficiency, bits per second per hertz (it equals the bits per symbol when the bandwidth is taken equal to the symbol rate, as in Figure 5.2); as η falls toward zero this tends to the natural logarithm of 2, which is -1.59 dB. Below that, no code at any rate and any bandwidth delivers reliable bits.

Real codes do not reach the limit, and no code has beaten it. Figure 5.2 sets the DVB-S2 modes against it. The standard states that its codes operate "at about 0,7 dB to 1 dB from the Shannon limit", and it names which limit: the one for the given constellation, in an ideal channel. Against Shannon's general limit, which allows any signal shape, the modes in Figure 5.2 sit about 1.1 to 2.9 dB away, generally more for the high-rate modes. Both statements are true; a supplier who quotes "within a decibel of Shannon" should say which limit, at which error rate, with which frame length, and before or after the losses of a real receiver.

FIGURE 5.2

Real codes sit 1.1 to 2.9 dB from Shannon's general limit for the modes shown, and closer to the limit of their own constellation

Mode	Information bits per symbol	DVB-S2 ideal Es/N0 (dB)	Shannon limit Es/N0 (dB)	Gap (dB)	Eb/N0: code, limit (dB)
QPSK 1/4	0.490	-2.35	-3.93	1.6	0.7, -0.8
QPSK 1/2	0.989	1.00	-0.07	1.1	1.0, 0.0
QPSK 3/4	1.487	4.03	2.56	1.5	2.3, 0.8
8PSK 3/4	2.228	7.91	5.66	2.3	4.4, 2.2
16APSK 3/4	2.967	10.21	8.34	1.9	5.5, 3.6
32APSK 9/10	4.453	16.05	13.20	2.9	9.6, 6.7
Any rate, as bits per symbol fall to zero	toward 0				limit -1.59

DVB-S2 ideal Es/N0 against the Es/N0 that Shannon's capacity formula requires at the same information bits per symbol, with the bandwidth taken equal to the symbol rate (no roll-off), white noise; the standard states 0.7 to 1 dB from the limit of each constellation.

ETSI EN 302 307-1 V1.4.1 (2014-11), Table 13 and clause 1; Shannon (1948): capacity = log2(1 + Es/N0) bits per symbol, so the limit is Es/N0 = 2^eta - 1 and Eb/N0 = (2^eta - 1)/eta. Author's calculation.

Codes as bought margin

An **error-correcting code** adds redundant bits so that the receiver can find and repair the bits the noise has flipped. The **code rate** is the share of the sent bits that carry information: a rate 1/2 code sends two bits for each bit of data. The code pays for itself because the receiver, using the redundancy, needs much less energy per useful bit.

The size of the gain is easiest to see at equal bits per symbol. Uncoded BPSK carries 1 bit per symbol and needs an Eb/N0 of 9.6 dB for one bit error in 100,000 (calculated from the standard formula, bit error rate = 0.5 erfc of the square root of Eb/N0). DVB-S2's QPSK with a rate 1/2 LDPC code carries 0.99 information bits per symbol, almost the same, and

needs an Eb/N0 of 1.0 dB for quasi error-free packets in the standard's ideal channel. About 8.5 dB less energy for each bit, at a stricter error target, for the same symbols on the air. In this ideal comparison that is a factor of about seven in power.

The space agencies' standard for telemetry coding, CCSDS 131.0-B-5 (September 2023), lists the families a mission can choose:

- **Convolutional:** rate 1/2, constraint length 7, punctured to 2/3, 3/4, 5/6 or 7/8.
- **Reed-Solomon:** block codes over bytes, (255,223) and (255,239), with interleaving depth 1 to 5 or 8 to spread a burst of errors over several codewords.
- **Concatenated:** Reed-Solomon outside, convolutional inside; at the receiver the convolutional decoder works first and the Reed-Solomon decoder cleans up what it leaves.
- **Turbo:** rates 1/2, 1/3, 1/4 and 1/6, for the weakest links.
- **LDPC** (low-density parity check): rate 223/255, and a family with rates 1/2, 2/3 and 4/5.

Coding has three costs. It spends rate: with the modulation fixed, a rate 1/2 code halves the data a given symbol rate carries. It spends delay: a DVB-S2 normal frame is 64,800 coded bits, and a block decoder needs the whole block before it can deliver its data. And it spends processing at the receiver: the standard's ideal figures assume 50 decoding iterations. A fade that wipes out a long run of symbols defeats a code built for scattered errors; it needs interleaving, a longer frame or a retransmission.

Adaptive coding and modulation

A link designed for the worst hour of the year wastes the margin of every other hour. **Adaptive coding and modulation** (ACM) changes the mode frame by frame to suit the signal quality the receiver reports. DVB-S2 specifies it for point-to-point use: each terminal reports its C/(N+I) through a return channel, and the transmitter picks for each frame the most efficient mode that terminal can still decode. By the time a frame sent in the chosen mode reaches the terminal, the report behind it is at least one round trip old, half a second through a geostationary satellite, so the loop can follow changes that are slow compared with that delay, not faster ones. The standard itself states that such systems "promise satellite capacity gains of up to 100 % to 200 %" over a fixed mode; that is the standard's claim, and the gain for a given system depends on how its signal quality varies.

FIGURE 5.3

Adaptive coding and modulation climbs a ladder: nine times the rate across 18 dB on its six DVB-S2 rungs



DVB-S2 modes at an illustrative 30 million symbols per second, no pilots, ideal Es/N0; highlighted, the mode walked through in Figure 5.4; the lowest rung is a DVB-S2X very-low-SNR mode.

ETSI EN 302 307-1 V1.4.1, Table 13; ETSI EN 302 307-2 V1.4.1 (2024-08), Table 20c. Rate = 30 Mbaud x spectral efficiency; author's calculation.

Figure 5.3 shows the ladder at an illustrative 30 million symbols per second. Across its six DVB-S2 rungs the rate runs from 14.7 Mbit/s with QPSK 1/4 at an Es/N0 of -2.35 dB to 133.6 Mbit/s with 32APSK 9/10 at 16.05 dB, a factor of nine across about 18 dB of signal quality. The extension standard, DVB-S2X (version of August 2024), adds finer steps and very-low-SNR modes; it states operation "down to -10 dB", and its spread BPSK mode BPSK-S 1/5 is listed at an ideal -9.9 dB. ACM does not create margin. It spends the margin the budget has at each moment, and it needs the return channel, the terminal's honest report and a scheduler that knows what to do with both.

Spreading: below the noise, and still usable

The GPS signal of the lead uses the opposite idea. Each 50 bit per second data bit is multiplied by a known code that changes sign 1,023,000 times a second (IS-GPS-200N). The code repeats every millisecond and is different for every satellite. The signal on the air is therefore about 2 MHz wide, and its power is spread thinly over that width. With the specified minimum power, the reference antenna and an assumed receiver noise

temperature of 290 K, the ratio of carrier to noise density is 45.5 dBHz; counting the signal's power against the noise in the 2.046 MHz main lobe of the spread spectrum, the signal is 17.6 dB below the noise.

The receiver knows the code. It multiplies the incoming signal by a local copy, aligned in time, and sums the products. Over one code period of 1 ms the signal adds up in amplitude while the noise adds only in power: the signal-to-noise ratio of that sum, the equivalent of a 1 kHz bandwidth, is 15.5 dB. Over one whole data bit of 20 ms it is the energy per bit, 28.5 dB above the noise density. The ratio of the chip rate to the data rate, 20,460 chips per bit, is 43.1 dB; measured from the 2.046 MHz main lobe, which is twice the chip rate wide, the step to one data bit is 3 dB more, 46.1 dB.

Two warnings keep the arithmetic honest. Spreading adds no energy: the correlator only gathers back what the code spread out, and what makes the bit strong is the low data rate, 50 bit per second, that gives each bit 20 ms of signal. And the three tasks of a receiver have three different thresholds. To **acquire** a satellite it must search over the 1,023-chip code and a range of Doppler shifts (Chapter 6); to **track** it must follow code and carrier as they drift; to **decode** the data it needs the Eb/N0 of a bit. The budget page that follows shows the data hop in open sky with 16.4 dB above its requirement. Add an assumed 20 dB obstruction loss and the same arithmetic leaves it 3.6 dB short of the data requirement: the data needs its own margin, separate from those of acquisition and tracking.

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: closes

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.

LINK LEDGER · LL-2000-02 · HOP BUDGET · HOP 1 OF 1

Hop 1 · Navigation data, open sky

GPS satellite to Any receiver · 1575.42 MHz (L1) · 25,247 km (5 degrees elevation) · reference plane: output of a 3 dBi linearly polarized receiving antenna (IS-GPS-200N clause 3.3.1.6)

Part	Line	Value	dB, and the level after	Evidence	Source and date
TRANSMIT POWER AND ANTENNA GAIN	EIRP implied by the specified minimum (model, 5 degrees)	solved	**+25.9** level 25.9 dBW	calculated	Solved so that the lines below give the IS-GPS-200N Table 3-Va minimum of -158.5 dBW at the reference antenna output; the satellite's power and antenna gain are not in the interface specification, 2026-11-23
LOSSES	Free space path loss	25,247 km at 1575.42 MHz	**-184.4** level -158.5 dBW	calculated	ITU-R P.525 free-space formula; slant range from about 20,200 km altitude (GPS.gov) at 5 degrees elevation, 2026-11-23
	Polarization: circular wave into a linear antenna	half the power	**-3.0** level -161.5 dBW	calculated	IS-GPS-200N (2022-08-01) clauses 3.3.1.9 (right-hand circular) and 3.3.1.6 (linearly polarized reference antenna), 2026-11-23
RECEIVE SENSITIVITY	Receive antenna gain (reference antenna)	3 dBi	**+3.0** level -158.5 dBW	standard	IS-GPS-200N (2022-08-01) clause 3.3.1.6, 2026-11-23
	System noise temperature	290 K	**-24.6** level -183.1 dBW/K	assumption	Value used by an L1 acquisition analysis (arXiv 2610.26353, preprint of an ION GNSS+ 2026 paper). To verify: the receiver's noise figure and antenna temperature, 2026-11-23
	Boltzmann's constant	-228.6 dBW/K/Hz	**+228.6** level 45.5 dBHz	standard	SI value of k (2019), 2026-11-23
BANDWIDTH	Data rate, 50 bit/s	50 bit/s	**-17.0** level 28.5 dB	standard	IS-GPS-200N (2022-08-01) clause 3.2.2 (LNAV data at 50 bps), 2026-11-23
CODING	Chip rate 1.023 Mchip/s; 20,460 chips per data bit	spreading adds no energy		standard	IS-GPS-200N (2022-08-01) clause 3.2.1.3 (C/A code: 1023 chips, 1 ms), 2026-11-23
	No forward error correction on the data; parity only	uncoded BPSK		standard	IS-GPS-200N (2022-08-01) clause 3.2.2 and Appendix II (LNAV), 2026-11-23
	Correlation, tracking and implementation loss	2.5 dB	**-2.5** level 26.0 dB	assumption	The same acquisition analysis (preprint) uses 2.51 dB for this signal. To verify: the receiver maker's data, 2026-11-23
REQUIRED SIGNAL QUALITY	Required Eb/N0, uncoded BPSK, bit error rate 1e-5	9.59 dB	**9.6**	calculated	Pb = 0.5 erfc(sqrt(Eb/N0)) solved for 1e-5, 2026-11-23
RESULT	**Achieved Eb/N0: the sum of the lines above**		**26.0**	calculated by this ledger	
	Required Eb/N0 for bit error rate 1e-5 on the 50 bit/s data before the parity check (a target chosen for this example; the specification sets none)		**9.6**	from the line above	
	Margin: achieved less required		**+16.4**	design minimum 3.0 dB	

Closes: margin +16.4 dB (design minimum 3.0 dB)

Operating point. 50 bit/s, satellite to receiver, 5 degrees elevation, open sky, minimum specified power, continuous broadcast, availability not assessed
Required Eb/N0, 9.6 dB: source. Pb = 0.5 erfc(sqrt(Eb/N0)) solved for 1e-5, 2026-11-23

Assumptions. Minimum specified received power from IS-GPS-200N (2022), a modern reference for the service dated to 2000; spherical Earth of radius 6,371 km; no interference or jamming (chapter 11); carrier and code already acquired and tracked; atmosphere inside the specification point, so the EIRP is model-implied; the 3 dB minimum margin is chosen for this example.

What the receiver must recover before any bit

A decoder works on symbols, and before it gets any the receiver has to find three things. The **carrier**: its exact frequency, which motion and oscillator errors move, and its phase, without which the points of the constellation spin. The **symbol timing**: when each symbol starts, so that each is sampled at its center. And the **frame**: where a block of coded bits begins. DVB-S2 helps with a header of 90 symbols at the start of every frame, sent in its most robust form so that it can be found before the payload is decoded, and, as an option, a block of 36 known pilot symbols after every 16 slots of 90 symbols, which lets the receiver keep its phase lock in weak signals. The receiver of a spread signal must also find the code phase. What sets how long this takes after a pass begins, the search over frequency and timing, is in Chapter 6; the symbols spent on headers and pilots are counted next.

From symbol rate to goodput

A supplier's headline rate is usually the rate of one layer, and the user receives another. Figure 5.4 walks one DVB-S2 carrier from symbols to data, using only the standard's own frame structure: 30 million symbols per second of QPSK, rate 3/4, normal frames, pilots on, a roll-off of 0.20. If every symbol carried payload, the radio would carry 60 Mbit/s of coded bits. The LDPC and BCH codes leave 44.82 Mbit/s; the 80-bit baseband header of each frame leaves 44.75; the physical layer header leaves 44.62; the pilots leave 43.56 Mbit/s, in a channel 36 MHz wide. That is 1.21 bits per second per hertz of occupied spectrum, before a single IP header.

FIGURE 5.4

A 30 Mbaud carrier delivers 43.6 Mbit/s of frames before a single IP header

Layer	What it spends	Rate after it
Symbols on the air	30 Mbaud of QPSK, 2 bits per symbol; 36 MHz occupied at roll-off 0.20 (nominal pulse-shaping width)	60.00 Mbit/s if every symbol carried payload
LDPC and BCH codes	48,408 of 64,800 bits carry data	44.82 Mbit/s
Baseband header	80 bits per frame	44.75 Mbit/s
Physical layer header	90 symbols per frame of 32,400	44.62 Mbit/s
Pilots	22 blocks of 36 symbols per frame	43.56 Mbit/s (1.21 bit/s per Hz)
Encapsulation of packets	GSE or transport stream headers	depends on packet sizes
Retransmission	frames lost and sent again	depends on the channel
Sharing	other users of the carrier; the busy hour	depends on the operator

One DVB-S2 carrier, QPSK 3/4, normal frames, pilots on, roll-off 0.20, layer by layer; the layers above the frames depend on the system and are not computed.

ETSI EN 302 307-1 V1.4.1 (2014-11): Table 5a (Kbch 48,408 for rate 3/4), clause 5.1.6 (80-bit BBHEADER), Table 11 and clause 5.5 (90-symbol PLHEADER, 36 pilot symbols every 16 slots), Annex A (roll-off). Author's calculation.

Above the physical layer the losses depend on the system, so this chapter does not put numbers on them: the encapsulation of IP packets into frames (Chapter 7), the retransmissions when a frame is lost, the share of the carrier given to other users, and the busy hour when everyone in a beam wants the same capacity. The rule is to ask, for any rate, at which layer it is counted and whether it is a peak or a sustained figure.

THE SYSTEM'S FAILURE

NASA's Galileo Jupiter spacecraft, 1991: coding buys decibels, not the antenna back. The spacecraft, launched toward Jupiter in October 1989, was to send its science through a high-gain antenna that unfurled like an umbrella. On 11 April 1991, JPL reported eight days later, the antenna "unfurled partially but did not completely unfold"; telemetry showed the motors had stalled with the ribs partly deployed, and it never deployed properly. The mission's own catalog in NASA's Planetary Data System records the consequence: without adaptations, the low-gain antenna could have returned only 8 to 16 bit per second from Jupiter, against the 134.4 kbit/s the high-gain antenna was designed for.

The same record lists what was done. Software changes on board, with hardware and software changes at the receiving stations on Earth, raised the rate from Jupiter by as much as ten times, to 160 bit per second. The ground arrayed antennas: 34 m dishes with the 70 m dish at each site, pairs of 70 m dishes, and the 64 m CSIRO antenna at Parkes, Australia. Lossy compression cut imaging and plasma wave data to as little as one eightieth of their volume. The mission flew its tour on the low-gain antenna.

The lesson, kept to that record: better processing at both ends and more collecting area on the ground recovered about ten times the rate, and compression made each bit carry more science. The gap to the design rate, a factor of about 840 in rate, stayed. Coding, compression and arraying buy decibels and useful bits; they do not give back an antenna.

SECURITY NOTE

Who can interfere or command. A modulation and a code are public standards. They make a link reliable and give no secrecy by themselves: anyone with the standard, a suitable receiver and the signal in view can demodulate and decode an unencrypted DVB-S2 carrier or CCSDS telemetry stream. A published spreading code can be generated by anyone, which is what makes a navigation signal both free to use and possible to imitate (Chapter 11). **How it is seen.** A jammer, and sometimes a spoofer, can show in the receiver's own measurements: a C/N0 that changes in ways the geometry does not explain, or an ACM terminal dropping to its lowest rung in clear sky. **How it is recovered.** Secrecy and proof of origin come from encryption and authentication in a separate security function, in the framing layer or above; a robust low rung of the ladder may keep a link alive against a weak interferer while the cause is found.

Monday rule: ask a supplier for the modulation and code at your margin, and for the rate at the worst signal quality in the contract, not the best.

CHAPTER SIX

Delay, Doppler and Acquisition



On 29 June 2001 NASA and the European Space Agency announced a new plan for the Cassini mission to Saturn. Engineers had found a design flaw: the receiver that was to pick up the Huygens probe's data during its descent to Titan could not compensate enough for the Doppler shift of the probe's signal. The probe's transmitter was not the problem; the shift between what it sent and what the orbiter would receive was. This chapter is about the three things that distance and motion do to a link before any margin matters: they delay it, they shift its frequency, and they make getting started a separate problem from staying connected.

Delay comes from geometry

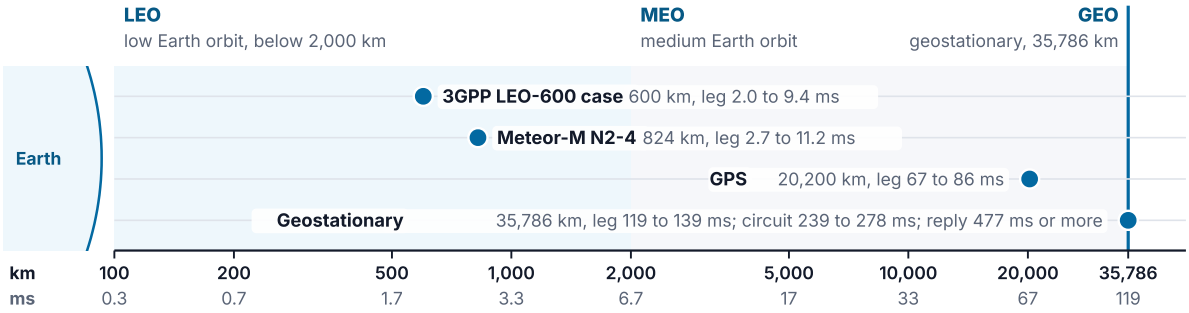
Radio travels at the speed of light, 299,792 km per second. Delay is distance divided by that speed, and the distance is the slant range: the straight line from the station to the satellite at the elevation where the satellite stands (Appendix B gives the formula). A satellite straight overhead is at its nearest. Near the horizon the same satellite is several times farther away.

A low orbit gives a few milliseconds per leg. At 600 km, the altitude the 3GPP study uses for its low orbit case, one leg takes 2.0 ms straight up, 6.4 ms at 10 degrees elevation and 9.4 ms at the horizon. The bench satellite of this book, Meteor-M N2-4, flies at a mean 824 km: 2.7 ms overhead, 11.2 ms at the horizon. GPS satellites, at about 20,200 km, are 67 to 86 ms away.

The geostationary orbit, at 35,786 km above the equator, needs three numbers, not one. One leg straight up takes 119.4 ms. A circuit through the satellite has two legs, ground to satellite to ground: 239 ms at the shortest, when both stations see the satellite overhead, and 278 ms when both stand at the edge of coverage, where the slant range is 41,673 km. A reply needs four legs: at least 477 ms before any processing, queueing or ground network. That is the source of the rule of thumb in this series: about a quarter second one way, half a second for a reply.

FIGURE 6.1

Distance sets the delay: milliseconds in low orbit, a quarter second through a geostationary satellite



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

One way propagation delay per leg for four orbits, straight up and at the horizon; a geostationary circuit has two legs and a reply has four.

Source: author's calculation, delay = range / c, slant range at the horizon with Earth radius 6,371 km (Appendix B). Altitudes: Meteor-M N2-4 from SatNOGS DB element set NORAD 59051, epoch 2026-11-23 07:06 UTC; GPS about 20,200 km (GPS.gov, read 2026-11-22); LEO-600 from 3GPP TR 38.821. Propagation only, before processing.

A low orbit link through a transparent satellite (chapter 4) also has two legs: the phone to the satellite, and the satellite to a gateway that must see it at the same time. Both legs vary with elevation, and the gateway is often not overhead either. The table compares the propagation time of the two kinds of circuit at a few geometries.

Propagation delay through one transparent satellite, two legs (calculated; Earth radius 6,371 km)

Circuit and geometry	One way, two legs	Reply, four legs
Low orbit, 600 km, both ends with the satellite overhead	4.0 ms	8.0 ms
Low orbit, 600 km, both ends at 30 degrees	7.2 ms	14.3 ms
Low orbit, 600 km, both ends at 10 degrees	12.9 ms	25.8 ms
Geostationary, both ends with the satellite overhead	239 ms	477 ms
Geostationary, both ends at the edge of coverage	278 ms	556 ms

The low orbit numbers are small but not zero, and they change during a pass by a factor of three. A protocol timer set from the best case fires early at the worst. The geostationary numbers are large but nearly constant, which is easier for a protocol to live with: the timer is set once.

These are propagation times. A real path adds the time a modem takes to frame and decode, the time a scheduler holds a packet for its turn, and the ground network behind the gateway. Chapter 10 follows the rest of the path; this chapter keeps to what the geometry sets.

What delay does to a conversation and to a protocol

A person notices delay at the turn of a conversation: one speaker stops, waits for an answer, and starts again before it arrives. Software notices it in its timers. Every protocol that waits for an acknowledgment has a timer that decides when to give up and send again. A timer fixed for a terrestrial network, and not adapted to the measured round trip, fires too early over a long path, and the link fills with copies of data that was never lost.

The 3GPP work on satellite access shows the problem in one number. Terrestrial 5G radio sends data in up to 16 parallel stop and wait processes for retransmission: each process waits for its acknowledgment before it can be used again. With the long round trips of a satellite, all 16 can be waiting at once and the link stalls. Release 17 raised the number to 32. The overview cited here states that 32 covers some air to ground scenarios but can be too few for low orbit configurations and for geostationary ones; how many processes a link needs depends on its round trip and its scheduling interval. The standard therefore lets the base station reuse a process before the round trip has passed, with the feedback for that process disabled, and leaves recovery to retransmission higher up the stack. Some timers of the medium access and radio link control layers were also extended (Lin and colleagues, an overview of the 3GPP work by Ericsson authors, arXiv 2103.09156, a preprint, not peer reviewed).

WHAT HASN'T CHANGED

Early Bird, Comsat's first satellite, offered up to 240 two-way telephone channels or one television channel, and commercial service began in June 1965 (NASA SP-4217, chapter 9). It flew in a geostationary orbit, so each of those calls already carried the delay computed above. The physics of a geostationary reply has not changed since: about half a second before anything else is added. What changed is what the delay is spent on. A voice in 1965 waited for a person; a protocol in 2026 waits for an acknowledgment.

Doppler: the frequency moves

When the distance between transmitter and receiver changes, the received frequency shifts. The shift is the carrier frequency times the rate at which the range changes, divided by the speed of light. It is positive, a higher frequency, while the satellite approaches, and negative while it recedes (Appendix B). As a fraction of the carrier it is the same at every frequency; in hertz it grows with the carrier.

A satellite at 600 km moves at 7.56 km/s. Seen from a fixed station on a non-rotating Earth, the largest shift occurs as the satellite rises or sets: 23.1 parts per million. At 2 GHz that is 46.1 kHz; at the 1.9 GHz of the model phone uplink in chapter 4 it is 43.8 kHz, the value in field 3 of that ledger. At closest approach the range stops shrinking and starts to grow, so the shift passes through zero.

The receiver has to follow not only the shift but how fast it changes. That rate is largest at closest approach. On a pass straight overhead at 600 km the frequency at 2 GHz falls by 581 Hz in every second around culmination, and by 552 Hz per second at 1.9 GHz. The bench satellite is gentler because its carrier is lower: at 137.9 MHz and 824 km the shift reaches 3.0 kHz (22 parts per million) near the horizon and changes by at most 27 Hz per second. Figure 6.2 gives both passes minute by minute.

FIGURE 6.2

The Doppler shift is largest near the horizon; it changes fastest overhead

Minutes to closest approach	824 km: elevation (deg)	137.9 MHz: shift (kHz)	137.9 MHz: rate (Hz/s)	600 km: elevation (deg)	2 GHz: shift (kHz)	2 GHz: rate (Hz/s)
-7	2.9	3.03	-0.2	below the horizon		
-6	7.2	3.01	-0.5	1.6	46.09	-1.5
-5	12.3	2.96	-1.1	6.0	45.85	-6.8
-4	18.8	2.87	-2.1	11.5	45.18	-16.9
-3	27.7	2.68	-4.3	19.1	43.57	-40.1
-2	40.8	2.29	-9.3	30.9	39.57	-105.3
-1	61.2	1.46	-19.3	52.2	28.24	-308.5
0	90.0	0.00	-27.4	90.0	0.00	-581.0

Calculated Doppler shift and its rate of change for an overhead pass, minute by minute before closest approach; after it the shift has the same size with the opposite sign.

Source: author's calculation (circular orbit, fixed user on a non-rotating Earth in the orbit plane, pass through the zenith; Earth radius 6,371 km, WGS 84 gravitational parameter). Shift = -f (dd/dt) / c, positive while the satellite approaches. Earth's rotation changes the values by a few percent.

The model behind these numbers is simple on purpose: a circular orbit, a station in the plane of the orbit and an Earth that does not turn. The Earth's rotation changes them by several percent, more for some orbits and sites (the ground at the equator moves at about 0.46 km/s, against the satellite's 7.56 km/s), and a pass that does not go overhead has a lower peak rate. For a design, the curve is computed from the real orbit and the real site; for a first assessment, the bounds above are enough to ask the right question of a receiver: over what range of frequency, and at what rate of change, does it stay locked?

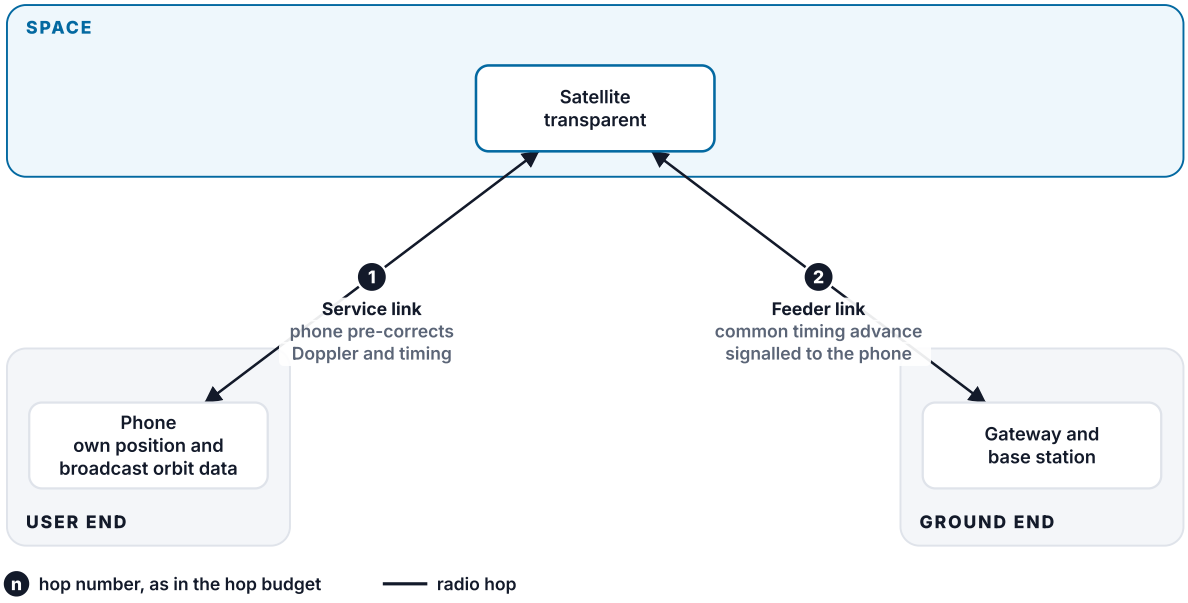
Who corrects the frequency and the timing

Three places can absorb Doppler and delay: the ground, the satellite and the user's terminal. A large ground station tracks the carrier with a loop that follows the frequency as it moves, and it can afford the processing. A geostationary satellite barely moves relative to the ground, so its users see little Doppler and the problem is only delay. A low orbit link to a small terminal has the hardest case: large shifts, fast rates, and a terminal with little processing to spare.

3GPP Release 17 chose to put most of the correction in the phone. A phone with satellite navigation computes, from its own position and the satellite's orbit data broadcast by the network, the relative speed and the round trip time to the satellite. From the relative speed it pre-compensates its uplink frequency, so that its signal arrives on the frequency the network expects. The base station, on the ground behind the gateway, broadcasts a common timing advance, which the overview describes as the round trip between the satellite and itself; the phone adds its own round trip to the satellite to get the full timing advance and sends early by that amount (arXiv 2103.09156). Release 17 assumes that every terminal using this satellite access has satellite navigation (3GPP overview of non-terrestrial networks, read 2026-11-23); other phones are outside this design.

FIGURE 6.3

In a Release 17 link the phone corrects its own Doppler and timing; the network tells it the feeder delay



Who corrects what in a 3GPP Release 17 link through a transparent satellite: the phone pre-compensates the service link, the base station broadcasts a common timing advance for the feeder link.

Author's diagram based on Lin, Rommer, Euler, Yavuz and Karlsson, "5G from Space: An Overview of 3GPP Non-Terrestrial Networks", arXiv 2103.09156 (read 2026-11-23).

The design choice has a consequence that a requirement should state. The phone's position and the orbit data are now inputs to the radio link. A phone without a usable position, or with stale orbit data, cannot pre-compensate correctly or time its transmission. The model ledger of chapter 4 assumes that this succeeds and that the remaining error sits inside its implementation line; this chapter is where that assumption is named.

Acquisition is not steady state

A hop budget describes a receiver that is already locked: it knows the carrier frequency, the symbol timing and where each frame starts. Before that, the receiver must find the signal. It searches across every frequency the carrier could have, the Doppler range plus the error of its own oscillator, and across every timing offset, until a known pattern lines up. The wider the uncertainty, the longer the search, and during the search no data moves.

Three numbers describe acquisition, and none of them is in the budget: the time to first lock from a cold start, the time to lock again after a short blockage, and the time to move to the next beam or satellite. A terminal that knows its position, the time and a current orbit can

predict the frequency and timing and search a narrow window. A terminal without them searches wide. The bench link shows the method: its receiver can be told the predicted Doppler curve in advance, so it only has to correct the residue.

A short blockage is the common case on the ground. A tree, a roof edge or a passing truck interrupts the signal for seconds. If the receiver loses lock, the outage is the blockage plus the time to reacquire, and that second term can be the longer one.

Handover between beams and satellites

A low orbit satellite is in view for minutes. At 600 km a pass straight overhead lasts 12.8 minutes from horizon to horizon, 5.8 minutes above 20 degrees and 4.1 minutes above 30 degrees, the elevation of the model ledger. The bench satellite at 824 km gives 15.6 minutes above the horizon and 7.7 minutes above 20 degrees. A service that must stay connected therefore moves between beams of one satellite and between satellites, many times an hour.

Each move is a small acquisition: a new frequency offset, a new delay, often a new Doppler slope in the opposite direction. Release 17 added a condition to the handover decision based on the phone's location and on when a satellite stops covering that location, so that a move can be prepared before the signal fades (arXiv 2103.09156). For a buyer the question is simple to write and hard to answer: how long is the gap at a handover, how often does one happen at my site, and what does my application see during it?

Timing as a service

A navigation satellite is, first of all, a clock that tells everyone in view what time it is and where it was when it said so. The GPS interface specification defines GPS time as a continuous time scale that starts at midnight between 5 and 6 January 1980, counts in weeks of 604,800 seconds, and is kept within one microsecond of Coordinated Universal Time, modulo one second; the navigation message relates GPS time to UTC as kept by the US Naval Observatory, UTC(USNO), to within 20 nanoseconds, one sigma (IS-GPS-200N, 2022-08-01, section 3.3.4). A receiver that solves for its position also solves for the time.

That is why timing appears in a chapter on links. Release 17 uses satellite navigation to time a phone's uplink. Cellular base stations, power grids and financial systems use it to keep their own clocks. A link that depends on received time inherits the weaknesses of the signal that delivers it, which chapter 11 takes up. How the navigation signal fits below the noise and is still decoded is in chapter 5.

THE SYSTEM'S FAILURE

Huygens, found in 2000. The Huygens probe was to send its data during its descent through Titan's atmosphere to the Cassini orbiter, which would relay it to Earth. In 2000 engineers identified a design flaw in the probe's communications system: the receiver would be unable to compensate enough for the Doppler shift in radio frequency between the probe's signal and the one received by the orbiter, which would have lost important data. The release does not say which part of the receiver fell short: Doppler moves the carrier and also stretches the timing of the bits, and a receiver must follow both. After six months of analysis by a joint ESA and NASA recovery task force, the agencies changed the mission instead of the hardware: Cassini's first two orbits around Saturn were shortened and an orbit added, so that during the descent Cassini would fly over Titan's cloud tops at about 65,000 km, which reduced the Doppler shift. The probe was to be released on 25 December 2004 for entry 22 days later (NASA JPL news release, 29 June 2001). The lesson the source supports: a receiver can have the power it needs and still fail if the frequency moves faster or farther than it was built to follow, and the receiver's tolerance to the real Doppler of the real geometry belongs in the link's checks, early enough that the geometry can still be changed.

SECURITY NOTE

Who can interfere or command. When the terminal corrects its own Doppler and timing, its position and its clock become inputs to the link. Anyone who can feed it a false position or a false time, by spoofing the navigation signal or by stale orbit data, can make it transmit on the wrong frequency or at the wrong moment, so that its signal is refused or lands on someone else's slot. **How it is seen.** The network sees uplinks that arrive off frequency or off time for the position the terminal reports; Release 18 added support for the network to verify the location a terminal reports; the 3GPP overview gives about 5 to 10 km for it (read 2026-11-23). It is a check, not a guarantee that spoofing is caught. The terminal can compare its navigation time with the network's time. **How it is recovered.** A fresh position fix from an independent source, current orbit data from the network, and a fallback that keeps a terminal silent rather than transmitting on a guess.

Bench step: what it requires

The bench link of this book has illustrative values for its Doppler curve, not design bounds: up to 3.0 kHz either side of 137.9 MHz, changing by at most 27 Hz per second, from the ideal overhead pass at the mean altitude of the satellite's public element set (NORAD 59051, epoch 2026-11-23 07:06 UTC). A prediction for a real pass needs that element set, the station's coordinates and a propagator. Checking it needs a recording of a real pass with its

start time, the station's coordinates, the element set used, and the carrier frequency measured against time from the recording. The prediction is then laid over the measurement on one plot. No recording exists yet, so nothing has been compared; the settings will be kept in the versioned companion repository when the experiment exists.

Monday rule: test your application at the real round-trip time, with the pass's Doppler curve and from a cold start, before you sign.

CHAPTER SEVEN

Framing



On 6 April 2019 the week counter in the legacy GPS navigation message ran out of digits for the second time. The field is 10 bits wide, so it counts weeks modulo 1,024, about 19.7 years, and starts again at zero. Every satellite kept working. Receivers built on the assumption that the counter would not wrap during their life could report dates and positions from the wrong epoch, as a maritime safety bulletin warned before the date. Nothing was wrong with the radio. A field in a frame was narrower than the time the system had to run. This chapter is about how a receiver turns a stream of symbols back into bits it can trust: where a frame starts, what it carries, how the receiver knows it is whole, and what each field does when it wraps.

The journey of one bit

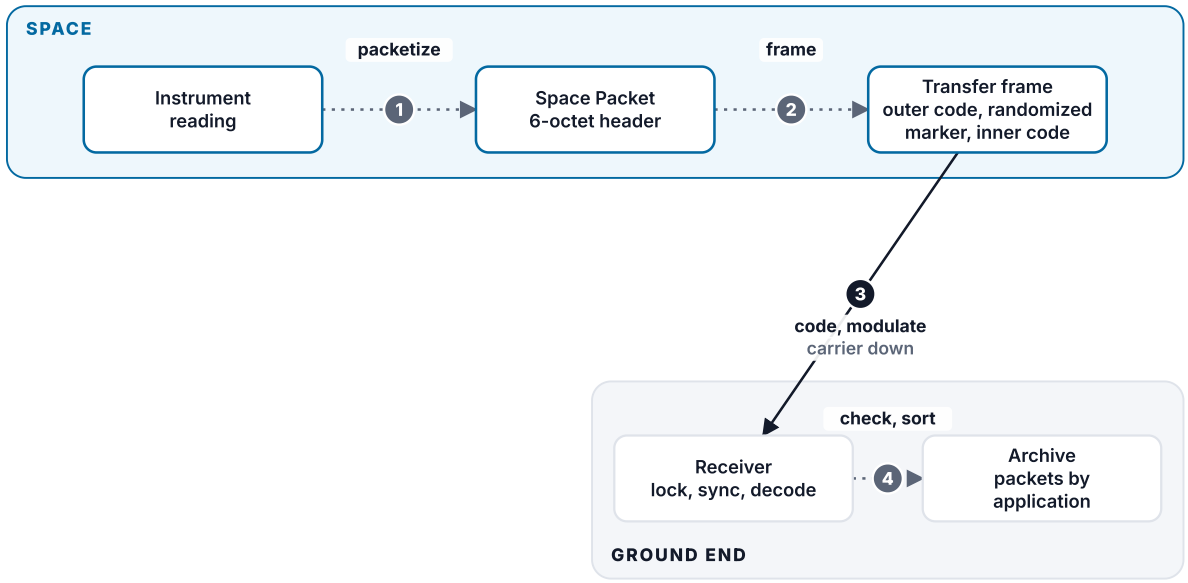
A reading from an instrument, a line of an image or a text message does not leave a satellite as it was written. It is wrapped several times, and each wrapping answers one question for the receiver.

- **The packet** says which application the data belongs to and in what order it was made.
- **The frame** carries packets over one radio link, in a telemetry chain usually in fixed-size units, with an error check and often a counter that helps the receiver notice a missing unit.
- **The code** adds redundancy so that the decoder can correct the errors the noise causes (chapter 5).
- **The sync marker and the randomizer** let the receiver find the start of each unit and keep its clock locked.
- **The carrier** is modulated with the coded symbols and sent (chapters 3 to 5).

The receiver undoes the wrappings, and the order depends on the code. With the concatenated CCSDS code (a convolutional inner code and a Reed-Solomon outer code) it locks to the carrier, recovers symbols, decodes the inner code, finds the sync marker, removes the randomizing pattern, decodes the outer code, checks the frame, and finally sorts the packets by application. A failure at any step looks the same from the outside: no data. The step that failed is visible only in the receiver's logs.

FIGURE 7.1

One bit is wrapped four times before it leaves the satellite, and unwrapped in reverse on the ground



The journey of one reading in a CCSDS telemetry link: packet, frame, sync marker and code, carrier; the ground undoes each step in reverse order.

Author's diagram based on CCSDS 133.0-B-2 (June 2020) and CCSDS 131.0-B-5 (September 2023), read 2026-11-23.

Finding the start: the sync marker and the randomizer

A demodulator produces a continuous stream of symbols with no boundaries in it. To find where a frame begins, the transmitter places a fixed pattern in front of each one, and the receiver searches for it. In the CCSDS telemetry standard for synchronization and channel coding this attached sync marker is 32 bits long, written in hexadecimal as 1ACFFC1D, for uncoded data and for convolutional, Reed-Solomon and concatenated coding; turbo and some LDPC codes use longer markers (CCSDS 131.0-B-5, September 2023, section 9). The receiver recognizes the regularly spaced markers and can confirm its lock with further checks.

The second problem is the content itself. A symbol synchronizer keeps its clock aligned by watching the transitions between ones and zeros. A long run of identical bits, such as an empty buffer filled with zeros, gives it nothing to follow, and it drifts. The same standard therefore applies a pseudo-randomizer: each bit of the frame is combined with a known pseudo-random sequence before transmission, and the receiver removes it after finding the marker. The standard notes that the recommended Reed-Solomon codes cannot by themselves guarantee enough bit transitions, and that "problems with telemetry links have been encountered because this Pseudo-Randomizer was not used" (CCSDS 131.0-B-5, sections 4.2.1 and 10.1). Whether randomizing is on is not signalled in the data; the receiver must know it in advance.

The marker sets the frame and code block boundaries for the stages that follow it; with a convolutional code, the inner decoding runs first. When a convolutional code is used, the marker itself is convolutionally encoded; with an outer Reed-Solomon code, the marker is encoded by the inner code but not by the outer one (section 9.2). The marker itself is not randomized: the pseudo-random sequence starts with the first bit after it (section 10.3). These details decide whether two implementations interoperate.

The CCSDS family: packets and frames

The Consultative Committee for Space Data Systems (CCSDS), a body of space agencies, publishes the recommendations this section follows. The application data travels in Space Packets. A Space Packet starts with a 6-octet primary header with four fields: a 3-bit version number, a 13-bit packet identification field, a 16-bit sequence control field and a 16-bit data length. Inside the identification field, one bit says whether the packet is telemetry or a telecommand, one bit says whether a secondary header follows, and 11 bits carry the application process identifier, which names the stream the packet belongs to. Inside the sequence control field, 2 bits mark segmentation and 14 bits carry the packet sequence count. The data field holds 1 to 65,536 octets, so a packet is 7 to 65,542 octets long (CCSDS 133.0-B-2, June 2020, sections 4.1.2 and 4.1.3).

In telemetry the 14-bit count is continuous modulo 16,384; the standard lets a telecommand packet carry a packet name in that field instead. It exists so that the ground can put packets of one application back in order and detect the missing ones. The standard adds a note that matters for any long mission: where a time code is used with the count to order packets over a long period, its resolution must be fine enough that it increments at least once between two recyclings of the count (section 4.1.3.4.3). Without that, two packets with the same count from different cycles look identical.

Packets ride in frames. The Space Packet standard of June 2020 cites the TM Space Data Link Protocol (CCSDS 132.0-B-2) for telemetry, the TC Space Data Link Protocol (CCSDS 232.0-B-3) for telecommand, the AOS Space Data Link Protocol (CCSDS 732.0-B-3) for higher rate links, and the Unified Space Data Link Protocol (CCSDS 732.1-B-1, October 2018), which covers both directions in one format. When no Reed-Solomon or LDPC code validates a frame, the frame's own error control field does (CCSDS 131.0-B-5, section 2.2.3). When no data is waiting, the TM, AOS and USLP protocols generate idle packets, identified by an application identifier of all ones, to keep the data transport synchronized (CCSDS 133.0-B-2, section 4.1.2).

FIGURE 7.2

Three framing families answer the same four questions in different ways

Family	Unit of data	How the receiver finds the start	How it checks the unit	Typical use
CCSDS	Telemetry transfer frame (TM, AOS or USLP; a telecommand uses its own synchronization , not read here), carrying Space Packets (6-octet header, 11-bit application identifier, 14-bit count)	32-bit attached sync marker 1ACFFC1D (longer for turbo and some LDPC codes); pseudo-randomizer	Reed-Solomon or LDPC decoding validates the frame; otherwise the frame's error control field	Science and agency spacecraft
DVB-S2	Base-band frame: 80-bit header and a data field, coded into 64,800 or 16,200 bits	Physical layer frame header (signals modulation and code)	BCH and LDPC codes; CRC-8 on the base-band header; CRC-8 per user packet for packetized streams	Broadcast and broadband links
Small satellites	AX.25 frames (with or without the G3RUH scrambler); CSP packets above	Depends on the framing listed per satellite	Depends on the framing; some use Reed-Solomon	CubeSat telemetry, amateur bands

How the CCSDS, DVB-S2 and small-satellite families carry data, mark the start of a unit and check it, as far as the documents read for this book state.

Source: CCSDS 133.0-B-2 (June 2020) sections 4.1.2 to 4.1.3; CCSDS 131.0-B-5 (September 2023) sections 2.2, 9 and 10; ETSI EN 302 307-1 V1.4.1 (2014-11) clauses 5.1 to 5.5; gr-satellites documentation, supported satellites; libcsp repository. Read 2026-11-23.

The commercial family: base-band frames

The DVB family was written for broadcasting and other broadband satellite applications, as the title of its second generation standard says. In DVB-S2, the input is a transport stream or a generic stream of user data. The mode adaptation stage cuts it into data fields and puts an 80-bit base-band header in front of each, whose last 8 bits are a CRC-8 over the first 9 bytes of the header; for packetized streams it also adds a CRC-8 check to each user packet. The base-band frame is then coded into a forward error correction frame of 64,800 or 16,200 bits, and a physical layer frame adds the signaling a receiver needs to find it and to know which modulation and code follow. When there is no data, the transmitter sends dummy physical layer frames (ETSI EN 302 307-1 V1.4.1, 2014-11, clauses 5.1 and 5.5).

The difference from the CCSDS family is in who the receiver is. A CCSDS telemetry link usually serves one mission's ground stations, which know the spacecraft. A DVB-S2 link serves receivers made by many vendors, which must discover the modulation and code frame by frame, because adaptive coding and modulation can change them for each frame (chapter 5).

The small-satellite family

Small satellites, and university and amateur missions, use a wider range of framings. The open decoder collection gr-satellites, a module for the GNU Radio software, lists the transmitters of the satellites it can decode with their modulation and framing. The framing names include AX.25, a link layer protocol taken from amateur packet radio, with or without the G3RUH scrambler; CCSDS concatenated and Reed-Solomon framing; and vendor framings such as one listed as "AX100 ASM+Golay" (gr-satellites documentation, supported satellites, read 2026-11-23).

One worked example from that list: the AALTO-1 CubeSat is listed with a 9,600 baud FSK downlink at 437.216 MHz using AX.25 framing with the G3RUH scrambler. Compared with the bench link, it differs in band (UHF instead of VHF), modulation (frequency shift keying instead of QPSK) and framing, and the receiver's tasks are similar: remove the scrambling, find where each frame starts and ends, check it, sort the contents. The order and the frame delimiters are AX.25's own, not a CCSDS marker. This book cites the listing and does not restate the AX.25 field widths, because the specification was not available to read.

Above the link layer, many CubeSats use the Cubesat Space Protocol (CSP), a small network protocol for distributed embedded systems, published as the open source libcsp library under the MIT license for FreeRTOS, Zephyr and Linux (libcsp repository). A study of the protocol lists its use in orbit, including on ESA's OPS-SAT in 2019 (Seidel and Beier, arXiv 2405.18135, a preprint, not peer reviewed).

The bench link's frames

The bench link of this book, the LRPT broadcast of Meteor-M N2-4, carries image data in frames that the open decoder SatDump processes with a Reed-Solomon check. Its documentation lists pipelines for Meteor-M LRPT at 72k and at 80k, a setting to discard data that fails the Reed-Solomon check (recommended on, with a note that a satellite may at times transmit bad Reed-Solomon codes), and an option that fills black lines caused by signal drop-outs or interference (SatDump documentation, pipelines, read 2026-11-23). Two expectations follow for the bench link, to be confirmed by a recording. With that setting on, a frame that fails its check is discarded, so a weak pass should show up mostly as missing image lines rather than a noisy picture. And the count of failed checks per frame, logged against elevation together with an estimate of the signal to noise ratio, indicates how close the pass came to the edge of its budget; the count alone does not measure the margin. That is field 8 of the bench link's ledger in chapter 12. The format's own specification, which would give its inner code, could not be read for this book, so no number about it is printed.

Links that are not there all the time

A low orbit satellite sees a given ground station for minutes per pass. Data made between passes must wait on board. The simplest answer is a recorder that is played back at the next contact. The general answer is a network that expects interruptions. The Bundle Protocol version 7 (RFC 9171, January 2022) forms a store-carry-forward overlay network: a node keeps a bundle until a next hop is available, can hand the responsibility for error control to that hop (custody transfer itself moved out of the base protocol into a separate bundle-in-bundle specification, RFC 9171 Appendix A), and can use scheduled, predicted or opportunistic contacts, including one-way ones. It runs over other protocols through convergence-layer adapters. The design accepts that the sender and the receiver may never be present in the network at the same time.

For an architect the important line is the one between the link and the store. A store and forward service has an availability per message, not per second: what matters is how long a message can wait, and how much storage there is for the messages that wait.

What "we lost a frame" looks like

A lost frame does not announce itself. The receiver sees one of four things, and each suggests where to look first:

- no sync marker where one should be: the carrier or the symbol timing may have been lost (acquisition, chapter 6), or the decoder is set up for the wrong code;
- a marker but a frame that fails its code check: often too little signal or too much interference (the budget, chapter 4), sometimes a configuration fault;

- a frame that passes but a gap in its frame count, where the format carries one: a frame was dropped earlier on the path, or the count was reset (a normal wrap, from the highest value back to zero, is not a gap);
- a packet whose sequence count jumps: a packet was lost or the source restarted (the Space Packet standard notes that after a reset of the count the completeness of a sequence cannot be determined, section 4.1.3.4.3).

A receiver that logs these four counts separately, per pass, can say which part of the link to investigate. A receiver that logs only "frames received" cannot.

THE SYSTEM'S FAILURE

The GPS week number. In the legacy navigation message the transmission week number is carried in ten bits, as a modulo 1,024 binary representation of the current GPS week; GPS time counts from midnight between 5 and 6 January 1980 (IS-GPS-200N, 2022-08-01, sections 20.3.3.3.1.1 and 3.3.4). The count therefore returns to zero every 1,024 weeks: at the start of the GPS week on the nights of 21 to 22 August 1999 and 6 to 7 April 2019 (calculated from the epoch). Before the second rollover the United Kingdom's Maritime and Coastguard Agency warned that it "could cause stand-alone GPS receivers and systems using GPS chips" to "produce data that is 19.7 years either in the past or future", with errors in both position and time (Safety Bulletin 13, 19 February 2019). The satellites did what the specification said. The receivers that failed were those that had not allowed for a field that wraps. The next rollover of the 10-bit count falls on the night of 20 to 21 November 2038 (calculated).

SECURITY NOTE

Who can interfere or command. Classic space framing gives no cryptographic proof of who sent a frame. A sync marker, a counter and a Reed-Solomon check show that a frame is whole, not that it is genuine. A peer-reviewed study of Earth observation downlinks lists earlier Meteor-M satellites' LRPT among the unencrypted broadcasts, and assesses spoofing of such downlinks by overshadowing the signal with commercially available radio equipment (Salkield and colleagues, "Firefly", Workshop on the Security of Space and Satellite Systems, 2023). Software that parses frames is also a target: a study of the Cubesat Space Protocol's C implementation identified and patched three security issues (Seidel and Beier, arXiv 2405.18135, a preprint). **How it is seen.** Signal level, frequency and timing that do not match the predicted pass; counters that jump or repeat; content that disagrees with other sources. **How it is recovered.** Authentication and encryption at a separate layer (chapter 11), parsers that reject malformed frames, and a decoder that logs what it discarded and why.

Bench step: what it requires

The framing step of the bench link is a comparison: the same published recording decoded twice, once by a reference decoder and once by the reader's own code, with the outputs compared byte for byte and every discarded frame logged with its reason. It needs a recording whose license allows reuse; SatNOGS states that its observation results are public under a Creative Commons Attribution-ShareAlike license (SatNOGS Network, read 2026-11-22). Nothing has been decoded. The settings, the recording's identifier and both outputs will be kept in the versioned companion repository when the experiment exists.

Monday rule: for every field in a frame, ask how wide it is, when it wraps, and what the receiver does then.

CHAPTER EIGHT

The Payload: Transparent, Regenerative, Crosslinked



On 1 November 1998 Iridium opened commercial service with 66 satellites that could pass a call from one satellite to the next across the sky. In early 2000 Globalstar opened a rival service whose satellites did nothing of the kind: they amplified what they heard and sent it straight back down to a gateway. Both were built for the same market, handheld satellite phones, in the same decade. This chapter asks one question of any link: what does the satellite do to the signal, and where is the switch?

The transparent payload

A **payload** is the part of a satellite that serves the mission; for a communications satellite it is the receivers, the frequency converters, the amplifiers and the antennas. The rest, power, attitude control and the command link, is the bus. The 3GPP, the body that writes the mobile standards, defines a **transparent payload** as an analog radio repeater with no on-board processing of the user's signal, meaning no demodulation or decoding: it receives a band, filters it, shifts it to another frequency, amplifies it and sends it down. The engineering name is a bent pipe.

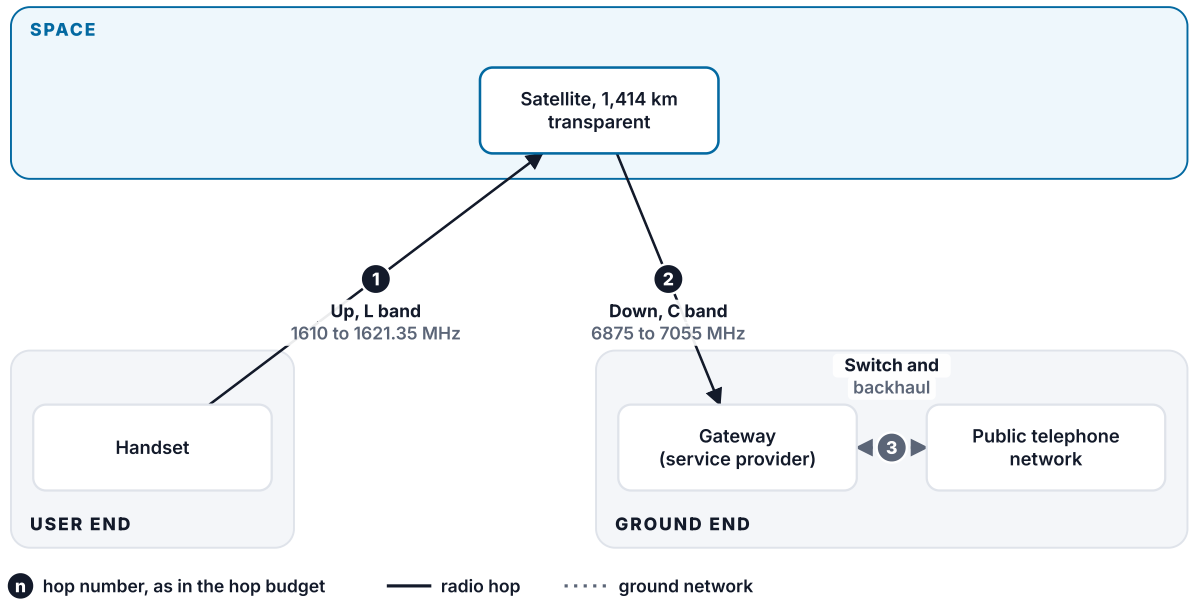
The pattern is old. Telstar in 1962 received near 6,390 MHz and sent near 4,170 MHz (Bell System Technical Journal, July 1963). One design consideration behind that pairing is that the satellite's power is scarce, so the hop the satellite powers used the lower frequency; allocations and interference also shape every band pair, and Globalstar's handset link below pairs L band up with S band down.

Globalstar's first generation is the case worked in this chapter. Its company filing for 2001 describes a 48-satellite constellation at 1,414 km whose satellites use a "bent pipe" design, "amplifying and reflecting received signals directly back to earth, with no intersatellite links." A handset sends to the satellite between 1610 and 1621.35 MHz; the satellite shifts the signal and sends it to a gateway between 6875 and 7055 MHz. The gateway, not the satellite, holds the switch: it decodes the call and connects it to the public telephone network (Figure

8.1). The other direction makes the mirror trip: the gateway sends up between 5091 and 5250 MHz, and the satellite shifts the signal to 2483.5 to 2500 MHz for the handset. Each direction is two hops through one repeater.

FIGURE 8.1

A transparent satellite: the call comes straight back down to a gateway in the same footprint



Globalstar's first generation: the handset and the gateway must see the same satellite at the same time; the satellite amplifies and shifts frequency, the switch is on the ground.

Author's diagram based on Globalstar's Form 10-K for 2001 (bands, bent pipe design, gateways).

What a transparent payload carries with it

A bent pipe adds no decisions of its own, and that has four consequences a buyer should know.

- **The uplink's noise comes down with the signal.** The satellite amplifies the noise it received together with the carrier. The circuit is therefore two hops plus their combination, derived in chapter 4 for Telstar.
- **There is a feeder link.** The hop between the satellite and the gateway is a second radio link with its own band, license and weather. In a phone service, it is a hop the user does not see.
- **A gateway must be in view.** The user and the gateway must see the same satellite at the same time. With no gateway, there is no service, whatever the satellites can do.

- **The repeater amplifies whatever arrives in its band.** That includes interference and any signal an outsider chooses to send. The security note returns to this.

The service ledger of the Globalstar call makes the third point concrete. It names one place inside a gateway's reach and one outside it, from the same filing: three gateways covered the United States and Canada "from Anchorage to Florida", while northwestern Alaska was excluded from the 2001 coverage list. The company gave coverage of about 67 percent of the world's land and 18 percent of its water at the end of 2001. Over the open ocean, out of reach of every gateway, a transparent satellite overhead could not complete a call. The question this ledger answers is where the service exists, which a hop budget cannot answer, so it has no page 2.

LINK LEDGER · LL-2000-01 · SERVICE LEDGER

2000 System: Globalstar call through a transparent satellite (first generation) Retired

Class: service only

1 Requirement	A voice or data call from a handset wherever a gateway sees the same satellite as the handset. Commercial service began in early 2000.
2 Ends and path	A handset and a gateway in the same satellite footprint; the gateway connects the call to the public telephone network. **Path:** Transparent: the satellite amplifies and returns signals to Earth, with no links between satellites.
3 Orbit and time	A constellation of 48 satellites at 1,414 km (52 launched). **Time:** 4.7 ms straight up; handset to gateway through the satellite at least 9.4 ms (calculated, propagation only, both ends directly below).
4 Band and permission	**Handset to satellite.** 1610 to 1621.35 MHz (L band) **Satellite to handset.** 2483.5 to 2500 MHz (S band) **Gateway to satellite and back.** 5091 to 5250 MHz up, 6875 to 7055 MHz down; a license in each gateway country
5 Capacity	**Up.** Code division access (Qualcomm); per-user rate not stated in the filing read. **Down.** As up; not stated. Inside a gateway's reach, for example a call in Florida: three gateways covered the United States and Canada from Anchorage to Florida. Outside it: northwestern Alaska, excluded from the 2001 coverage list.
6 Who owns each end	**Space segment.** Globalstar, L.P. **Ground segment.** Service providers: 38 gateways shipped, 26 installed, 25 in service (2001) **Customer relationship.** The service provider of each territory **The exit.** Not stated in the filing read
7 Trust	Two satellite and network control centers in California command the constellation. How commands are authenticated is not published in the filing.
8 How it fails, and how we would see it	No gateway in view, no call: coverage reached about 67 percent of the land and 18 percent of the water at the end of 2001. Satellite anomalies left 47 of 48 satellites in service in early 2002. **How we would see it:** Call success rates the company published: fixed phones averaged 92 percent, handsets lower; the filing ties a call's success to obstructions and to distance from the gateway.
9 Cost shape	Phone prices varied among local service providers; not stated as one number in the filing read.
10 Evidence	38 gateways shipped, 26 installed, 25 in service operator claim Globalstar Form 10-K for 2001 (SEC EDGAR), 2026-11-23 Coverage 67 percent of land, 18 percent of water operator claim Globalstar Form 10-K for 2001, 2026-11-23 48 satellites at 1,414 km; bent pipe operator claim Globalstar Form 10-K for 2001, 2026-11-23 9.4 ms through the satellite calculated Distance over the speed of light, 2026-11-23

Service only, no hop budget: the question here is where the service exists, which a hop budget cannot answer; the handset and gateway power figures were not read in a primary source.

A second generation of 48 satellites was ordered on 30 November 2006; later service is outside this ledger. Filed 15 February 2002 for Chapter 11.

The regenerative payload

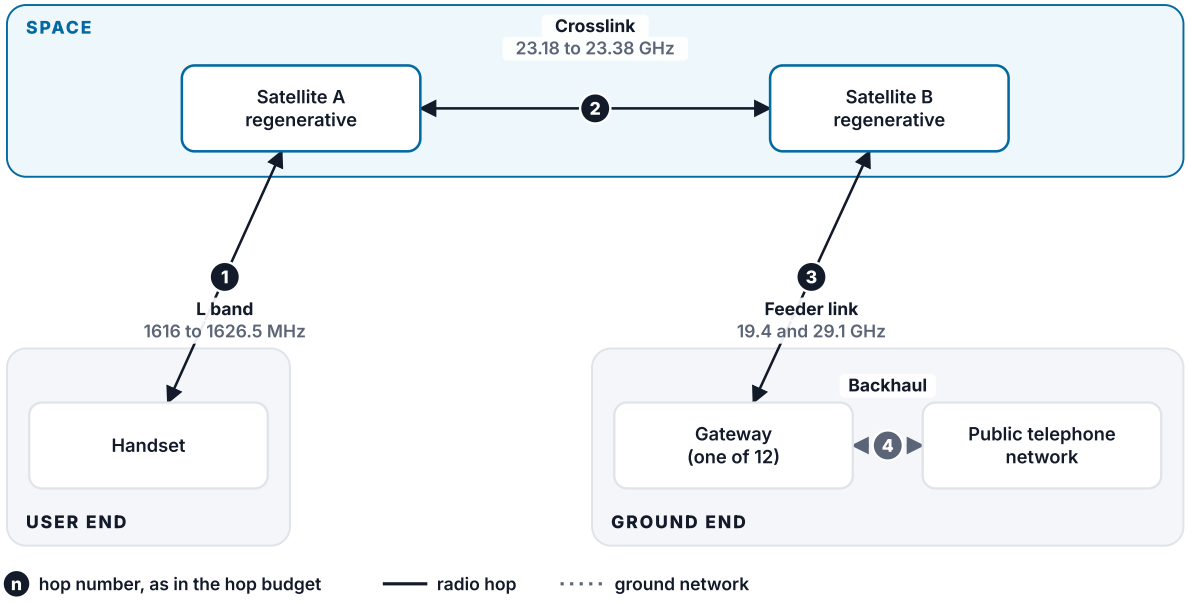
The 3GPP defines a **regenerative payload** as one that demodulates and decodes the signal on board, switches or routes it, then codes and modulates it again for the next hop. The bits are recovered in orbit, so the uplink's analog noise is not passed down: the downlink starts from recovered data, carrying whatever errors the on-board decoder left, and each hop has its own budget and its own verdict.

What moves on board is a modem, a switch and the software that runs them. That costs power, mass and heat, and it brings software that must be tested, updated and protected. It also buys three things: the satellite can route to another satellite, it can decide which traffic it serves, and it can discard a signal that is not in its own waveform after receiving it, although an interferer can still raise the noise or overload its receiver.

Iridium put the switch in orbit. Its 1998 filing describes satellites with three antenna systems: main mission antennas that talk to phones through 48 beams covering a circle about 4,340 km across, gateway link antennas, and cross-link antennas that talk to other Iridium satellites. Crosslinks used 23.18 to 23.38 GHz. A call could cross several satellites and come down at whichever of the 12 gateways served it; that is how the design reached oceans and poles without a gateway beneath them (Figure 8.2).

FIGURE 8.2

A regenerative, crosslinked satellite: the call can cross the sky before it comes down



Iridium's design: the satellite demodulates and routes, crosslinks carry the call between satellites, and 12 gateways served the design's global reach in 1998.

Author's diagram based on Iridium's Form 10-K405 for 1998 (bands, crosslinks, gateways).

The handset's hop, worked

The ledger below budgets the hop from an Iridium handset up to the satellite. Iridium's own filed link budget was not read. The numbers come instead from ITU-R Recommendation M.1184-3 (January 2018), whose table of representative mobile satellite systems lists a non-geostationary "system A" with 66 satellites at 780 km in six planes and 48 beams. That is the orbit and the beam count Iridium's own 1998 filing gives, but the recommendation does not name the system, and the ledger says so.

The operating point is the hardest one in the table: the edge of coverage, at the minimum elevation of 8.3 degrees, where the slant range is 2,456 km. At the top of the handset's peak EIRP range (6 dBW) and the bottom of the satellite's edge-of-coverage G/T range (-3 dB/K), a burst at 50 kbit/s arrives about 10 dB above the required Eb/N0 of 6.1 dB. That margin rests on three assumptions marked as such: 3 dB for body and hand, 0.1 dB for gases, and interference 6 dB below the noise. It also rests on one end of each range in the table, and the table does not say which ends occur together: with the handset at the bottom of its range (-4

dBW) as well, the margin is about 0 dB. The 10 dB is a constructed operating point, not a measured one. Straight overhead the free-space loss is 10 dB lower, so the edge is the case that matters.

The second page adds one line: the median loss of entering a building. ITU-R P.2109-2 gives a model for building entry loss with two classes of building. For the "thermally efficient" class (metallised glass, foil-backed panels) at 1.62 GHz, the median loss is 31.6 dB; for a traditional building it is 16.1 dB. Either one is larger than the 10 dB of margin. The filing said the same thing in words: in "densely packed urban areas or inside buildings with steel construction and metal coated glass … no meaningful satellite voice service is available."

LINK LEDGER · LL-1998-01 · SERVICE LEDGER

1998-11-01 System: Iridium handset voice call (first generation) (illustrative model) **Retired**

Class: full **Budget: closes (baseline); stress case A fails, as intended**

1 Requirement	A voice call from a handheld phone with open sky anywhere on Earth, oceans and poles included, to any telephone. Commercial service began on 1 November 1998.
2 Ends and path	A handset at one end; at the other, a gateway into the public telephone network (12 gateways in 1998) or a second handset. **Path:** Regenerative and crosslinked: the satellite carries the call to neighboring satellites over radio crosslinks and down to a gateway.
3 Orbit and time	66 satellites in six planes at about 780 km, one orbit about every 100 minutes; 48 beams per satellite cover a circle about 4,340 km across. **Time:** Handset to satellite 2.6 ms straight up and 8.2 ms at 8.3 degrees elevation (calculated, propagation only); crosslinks and the gateway add more, not budgeted here.
4 Band and permission	**Handset to satellite, both directions.** 1616 to 1626.5 MHz, time division; FCC authorization of 31 January 1995; phones licensed country by country **Satellite to gateway.** 19.4 to 19.6 GHz down, 29.1 to 29.3 GHz up; a license in each gateway country **Satellite to satellite.** 23.18 to 23.38 GHz crosslinks
5 Capacity	**Up.** One voice channel per handset: bursts at 50 kbit/s in a 90 ms time division frame. **Down.** The same frame and band, time division duplex. The voice coding rate and the number of calls per satellite were not verified in a primary source.
6 Who owns each end	**Space segment.** Iridium LLC **Ground segment.** 12 gateway companies; one gateway owned by the United States government **Customer relationship.** Gateway operators and their service providers **The exit.** Not stated in the parts of the filing read
7 Trust	The operator commands the constellation from its operations center in Virginia, with a backup in Italy and control stations in Canada and Hawaii. How commands are authenticated is not published in the filing.
8 How it fails, and how we would see it	Obstruction: the filing says that inside buildings of steel construction and metal coated glass no meaningful satellite voice service is available. Commercially, Iridium LLC operated under Chapter 11 from August 1999. **How we would see it:** Dropped calls and call completion rates, which the filing names among the factors of customer satisfaction. (The negative indoor margin on page 2 is calculated for one building class and geometry, not observed.)
9 Cost shape	Handset at least 3,000 dollars at retail, about 1,750 dollars wholesale (1998); call prices were not in the parts read.
10 Evidence	66 satellites, 780 km, 48 beams operator claim Iridium Form 10-K405, 1998, 2026-11-23 EIRP 6 dBW peak; G/T -3 dB/K; 50 kbit/s; Eb/N0 6.1 dB standard ITU-R M.1184-3, system A, 2026-11-23 Building entry loss 31.6 dB, median calculated ITU-R P.2109-2, 2026-11-23 Margin +10.0 dB open sky, -21.6 dB indoors calculated Page 2, 2026-11-23

Illustrative model: page 2 uses an ITU-R table of representative values whose system A matches Iridium's filed orbit and beam count; Iridium's own filed link budget, not read, would settle the mapping. The first generation was replaced from 2017 to 2019; later service is outside this ledger.

LINK LEDGER · LL-1998-01 · HOP BUDGET · THE BASELINE

Baseline · Handset to satellite, open sky

Handset to Iridium satellite, 780 km · 1621 MHz · 2,456 km slant range · reference plane: the handset's radiated EIRP; the satellite G/T as the recommendation gives it

Part	Line	Value	dB, and the level after	Evidence	Source and date
TRANSMIT POWER AND ANTENNA GAIN	Handset EIRP, peak (transmitter, feeder and antenna together)	6 dBW (range -4 to 6)	**+6.0** level 6.0 dBW	standard	ITU-R M.1184-3 (01/2018), Tables 4a and 4b, system A: user e.i.r.p. -4 to 6 dBW peak, top used, 2026-11-23
LOSSES	Free space path loss	2,456 km at 1621 MHz	**-164.4** level -158.4 dBW	calculated	ITU-R P.525; slant range at 8.3 degrees, Earth radius 6,371 km, 2026-11-23
	Atmospheric gases	0.1 dB	**-0.1** level -158.5 dBW	assumption	Assumption, to verify: ITU-R P.676 at 1.6 GHz, 8.3 degrees, 2026-11-23
	Polarization and pointing	0 dB	**+0.0** level -158.5 dBW	assumption	Assumption, to verify: handset axial ratio and pattern not published, 2026-11-23
	Body, hand and orientation	3 dB	**-3.0** level -161.5 dBW	assumption	Assumption, to verify: as LL-2026-01; handset patterns in the band, 2026-11-23
RECEIVE SENSITIVITY	Satellite G/T at the edge of coverage	-3 dB/K (range -3 to 10)	**-3.0** level -164.5 dBW/K	standard	ITU-R M.1184-3 (01/2018), Tables 4a and 4b, system A: edge of coverage -3 to 10 dB/K, low end used, 2026-11-23
	Boltzmann's constant	-228.6 dBW/K/Hz, subtracted	**+228.6** level 64.1 dBHz	standard	SI, 2019 redefinition: k = 1.380649e-23 J/K exactly, 2026-11-23
BANDWIDTH	Burst rate	50 kbit/s	**-47.0** level 17.1 dB	standard	ITU-R M.1184-3 (01/2018), Tables 4a and 4b, system A: 50 kbit/s burst, 90 ms frame, TDD, 2026-11-23
INTERFERENCE	Interference, C/N0 to C/(N0+I0)	I0/N0 = -6 dB	**-1.0** level 16.1 dB	assumption	Assumption, to verify: as LL-2026-01; operator's co-channel analysis, 2026-11-23
CODING	Modulation and code	QPSK with forward error correction; the code is not named		standard	ITU-R M.1184-3 (01/2018), Tables 4a and 4b, system A: QPSK with FEC, 2026-11-23
REQUIRED SIGNAL QUALITY	Required Eb/N0	6.1 dB	**6.1**	standard	ITU-R M.1184-3 (01/2018), Tables 4a and 4b, system A, Table 4a: 6.1 dB (error rate not stated), 2026-11-23
RESULT	**Achieved Eb/N0: the sum of the lines above**		**16.1**	calculated by this ledger	
	Required Eb/N0 for the required Eb/N0 of ITU-R M.1184-3 for system A (error rate not stated there)		**6.1**	from the line above	
	Margin: achieved less required		**+10.0**	design minimum 0.0 dB	

Closes: margin +10.0 dB

Operating point. one voice burst at 50 kbit/s, handset to satellite, 8.3 degrees elevation (edge of coverage), clear air, open sky; availability not assessed
Required Eb/N0, 6.1 dB: source. ITU-R M.1184-3 (01/2018), Tables 4a and 4b, system A, Table 4a: 6.1 dB (error rate not stated), 2026-11-23

Assumptions. Representative values from an ITU-R table, not Iridium's filed link budget, which was not read. Low end of the satellite G/T and top of the handset EIRP; the other ends of the two ranges move the margin by +13 dB and -10 dB. Not covered: fast fading, the downlink, the crosslinks, the gateway hop, availability. System A of ITU-R M.1184-3 is 780 km, 66 satellites, 6 planes, 48 beams; the recommendation does not name the system, and its use for first-generation Iridium is an assumption, to verify. The table does not say whether 50 kbit/s is the information or the channel rate, nor which the 6.1 dB refers to; the margin assumes both use the same rate (to verify).

LINK LEDGER · LL-1998-01 · HOP BUDGET · CASE A OF THE BASELINE

Case A: Same hop, inside a thermally efficient building

Handset to Iridium satellite, 780 km · 1621 MHz · 2,456 km slant range · reference plane: the handset's radiated EIRP; the satellite G/T as the recommendation gives it

Part	Line	Value	dB, and the level after	Evidence	Source and date
The other 11 lines are as in the baseline: not repeated here, and counted in the sums below.					
LOSSES	Building entry loss, thermally efficient, median	31.6 dB at P = 0.5	**-31.6** level -193.2 dBW	calculated	ITU-R P.2109-2 (08/2023), Annex 1, equations (1) to (10), Table 1: thermally efficient class, P = 0.5, 1.62 GHz, path elevation 8.3 degrees above the horizontal (traditional class: 16.1 dB), 2026-11-23
RESULT	**Achieved Eb/N0: the sum of the lines above**		**-15.5**	calculated by this ledger	
	Required Eb/N0 for the required Eb/N0 of ITU-R M.1184-3 for system A (error rate not stated there)		**6.1**	from the line above	
	Margin: achieved less required		**-21.6**	design minimum 0.0 dB	

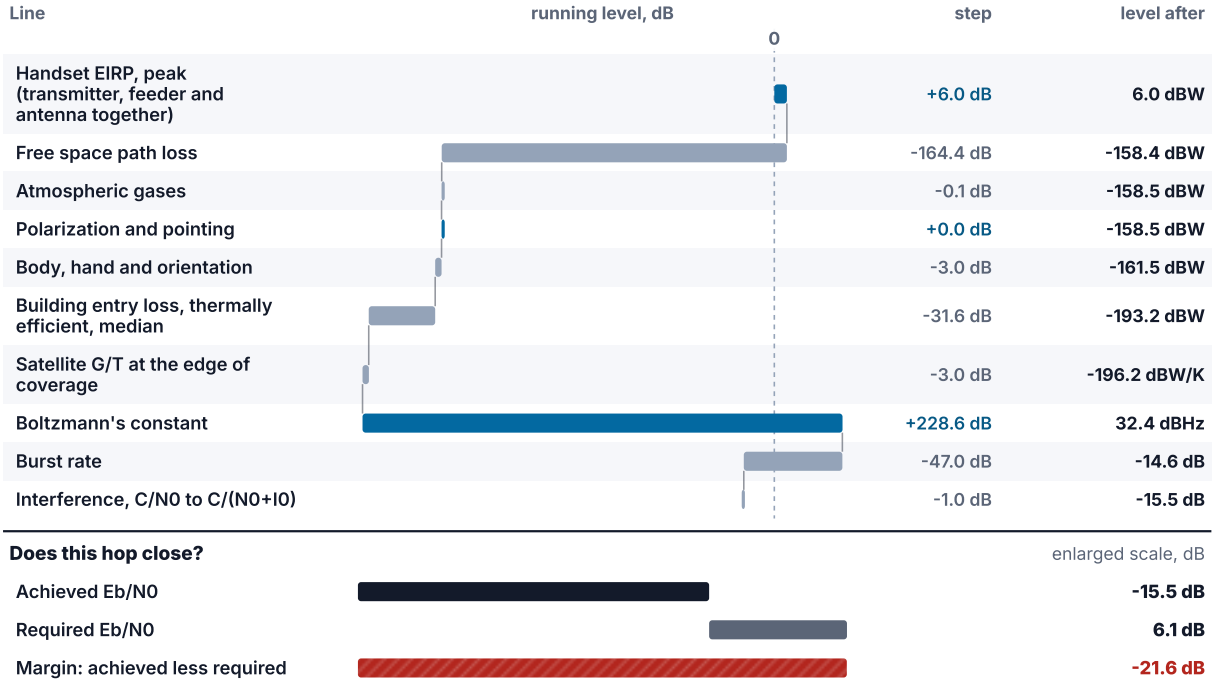
Does not close: short by 21.6 dB

Operating point. one voice burst at 50 kbit/s, handset to satellite, 8.3 degrees elevation (edge of coverage), clear air, inside a thermally efficient building, median loss; availability not assessed
Required Eb/N0, 6.1 dB: source. ITU-R M.1184-3 (01/2018), Tables 4a and 4b, system A, Table 4a: 6.1 dB (error rate not stated), 2026-11-23
Line that fails. Building entry loss, -31.6 dB: the hop misses its requirement by 21.6 dB

Assumptions. Representative values from an ITU-R table, not Iridium's filed link budget, which was not read. Low end of the satellite G/T and top of the handset EIRP; the other ends of the two ranges move the margin by +13 dB and -10 dB. Not covered: fast fading, the downlink, the crosslinks, the gateway hop, availability.

FIGURE 8.3

In this representative calculation the handset has about 10 dB in the open and misses by 21.6 dB indoors



Required for: the required Eb/N0 of ITU-R M.1184-3 for system A (error rate not stated there).
Operating point: one voice burst at 50 kbit/s, handset to satellite, 8.3 degrees elevation (edge of coverage), clear air, inside a thermally efficient building, median loss; availability not assessed.
Source of the required value: ITU-R M.1184-3 (01/2018), Tables 4a and 4b, system A, Table 4a: 6.1 dB (error rate not stated), 2026-11-23.

LL-1998-01, handset uplink, case A: the open-sky budget at 8.3 degrees elevation plus the median entry loss of a thermally efficient building; calculated, not observed.

Author's calculation from ITU-R M.1184-3 (system A) and ITU-R P.2109-2; see LL-1998-01.

The representative calculation is consistent with the filing's warning about buildings; it does not reproduce Iridium's own indoor performance. It also does not show why the company failed. Iridium LLC operated under Chapter 11 from August 1999, and the reasons the filings give are commercial: too few subscribers, too little revenue and a handset that cost at least 3,000 dollars at retail. Chapter 1 keeps that lesson to what the filings support.

RECONSTRUCTION · 1999 · THE REPORT FROM OUT OF REACH

The message	An adjuster's voice call from a flood zone.
The link	A first-wave handset
Note	A first-wave handset call; no 1999 price is printed without its source.

A reconstruction: the insurer is invented and illustrative. The link is the documented service of that year.

Crosslinks, then and now

A **crosslink** (or inter-satellite link) joins two satellites directly. In 1998 Iridium's crosslinks were radio. Its replacement constellation, completed on 5 February 2019 after 75 satellites were launched in eight launches, is again 66 crosslinked satellites, according to the company. Laser crosslinks, which Chapter 9 treats, are now offered as products (operator claims, dated there). A crosslink is a transport link; in Iridium's design, crosslinks together with routing on board moved the switch from a building to orbit, and with it the operator's dependence on gateways in other countries: fewer gateways were needed, and traffic could be landed where the operator chose.

The same choice in direct to device

The mobile standards made the same choice in two steps. 3GPP Release 17, whose protocol definitions were frozen in June 2022, supports transparent payloads only: the base station stays on the ground, behind the gateway, and the satellite repeats the phone's waveform. Release 19 adds regenerative payloads, with all or part of the base station on the satellite, and store and forward. A buyer who hears "5G from space" should ask which of the two a system uses, because it decides which ground must be in view and whose core network carries the call.

The same satellites can also change role. Iridium announced on 17 November 2026 that it had activated a standards-based narrowband service, Iridium NTN Direct, on its existing satellites (operator claim reported by trade press, Via Satellite; country, device and partner operators not checked). The air interface changed; the constellation did not.

Software-defined payloads, in one page

A separate question from where the bits are recovered is whether the payload can be changed after launch. A **software-defined payload** is one whose beams, frequencies and power can be changed from the ground; it may be transparent or regenerative. Eutelsat Quantum, launched on 30 July 2021, is described by the European Space Agency as a satellite that can be "completely repurposed while in space". SES describes O3b mPOWER

as a software-defined medium orbit system; its constellation reached 13 satellites when the last three were launched on 13 September 2026 (Boeing). What runs inside such a payload, and how it is qualified, is the subject of a later book in this series, on computing in orbit.

FIGURE 8.4

Iridium against Globalstar: where the switch lives

Line	Iridium (1998)	Globalstar (2001)
Orbit	66 satellites, about 780 km, six planes	48 satellites at 1,414 km (52 launched)
Payload	Regenerative: demodulates and routes	Transparent: amplifies and returns
Links between satellites	Yes, 23.18 to 23.38 GHz	None
Handset bands	1616 to 1626.5 MHz, both directions	Up 1610 to 1621.35 MHz, down 2483.5 to 2500 MHz
Gateways	12, one owned by the US government	25 in service, 38 shipped (26 installed), mainly owned by service providers
Where a call works	With open sky, oceans and poles included	Only where a gateway sees the same satellite
Commercial outcome	Chapter 11 from August 1999	Chapter 11 on 15 February 2002

Two designs of the same decade for the same handheld market, from the companies' own filings.

Iridium Form 10-K405 for 1998; Motorola Form 10-K for 1999; Globalstar Form 10-K for 2001 (SEC EDGAR).

THE SYSTEM'S FAILURE

Galaxy 15, 2010. On 5 April 2010 Intelsat lost control of its geostationary satellite Galaxy 15 (Via Satellite, trade press, 4 June 2010). The satellite stopped obeying commands, but its payload stayed on: it drifted along the geostationary arc "while continuing to broadcast on its C-band transponders" (SatNews, trade press, 13 January 2011). Intelsat moved the satellite's media traffic to its spare, Galaxy 12. As Galaxy 15 approached AMC-11, the neighboring operator SES moved that satellite to match the drift and used a tracking uplink at Intelsat's Clarksburg teleport to keep its own service separate (Via Satellite). On 23 December 2010 Intelsat reported that the satellite's battery had drained, which reset its command unit; after that it accepted commands from the ground again (SatNews).

The lesson is bounded. This was a loss of command with an active repeater. It shows what an uncommanded transparent repeater does to its neighbors: it keeps amplifying whatever it receives, wherever it drifts. It is not a defect of transparent designs, and the cause of the anomaly is not settled in the sources read.

SECURITY NOTE

Who can interfere or command. A transparent payload repeats any signal inside its band, so anyone in the footprint with enough power can try to occupy the receive beam and band; an ordinary bent pipe does not authenticate what it amplifies, although filtering, beam isolation and the operator's monitoring limit and expose such use. A regenerative payload discards signals that are not in its waveform, though recognizing a waveform is not authentication and jamming still raises its noise; it also runs software that can be attacked and must be updated through a command link. **How it is seen.** On a bent pipe, the operator's spectrum monitoring of the downlink shows unknown carriers; on a regenerative payload, on-board logs and failed authentication show them, if they are sent down. **How it is recovered.** Geolocate and remove the source on a bent pipe; on a regenerative payload, rely on authenticated commands, a safe mode and a way to load known-good software.

Monday rule: ask where demodulation happens and where the switch is; the answer tells you which ground must be in view and whose core network you depend on.

CHAPTER NINE

Optical Links



In 2023 a laser terminal the size of a tissue box, on a NASA CubeSat, delivered terabytes of error-free data to a ground station in California in a single pass, a record set out later in this chapter beside, not inside, the chapter's own model. Through a thick cloud the same kind of terminal can deliver nothing. This chapter asks what changes in the budget when the carrier is light, and what does not.

Why light

An optical link uses infrared light; the worked budget in this chapter uses 1550 nm. That wavelength is about ten thousand times shorter than a Ka band radio wave at 20 GHz (15 mm), and Chapter 3's rule applies unchanged: the gain of an aperture grows with the square of its diameter over the wavelength. An 80 mm telescope at 1550 nm has a receive gain of 104.2 dB (calculated, as (pi D / lambda) squared). A transmit beam with a full divergence of 15 microradians has a gain of 108.5 dB. Those two lines carry the budget.

The same short wavelength makes the beam narrow. At 15 microradians the beam is about 15 m wide after 1,000 km (calculated: the divergence times the distance). The beam is still far wider than an 80 mm telescope, so the receiver collects only a small fraction of the power; the narrow beam makes that fraction large enough. With 1 W at 10 Gbit/s, 40 degrees elevation and clear air, the generic model below leaves a positive margin; availability is not assessed. Light also brings a great deal of bandwidth, and it is not radio spectrum, so the laser hop needs no frequency assignment; the study used below describes the optical band as license-free. That is a statement about radio spectrum only: laser safety and coordination with aviation are separate questions, not researched for this book.

What light adds to the budget

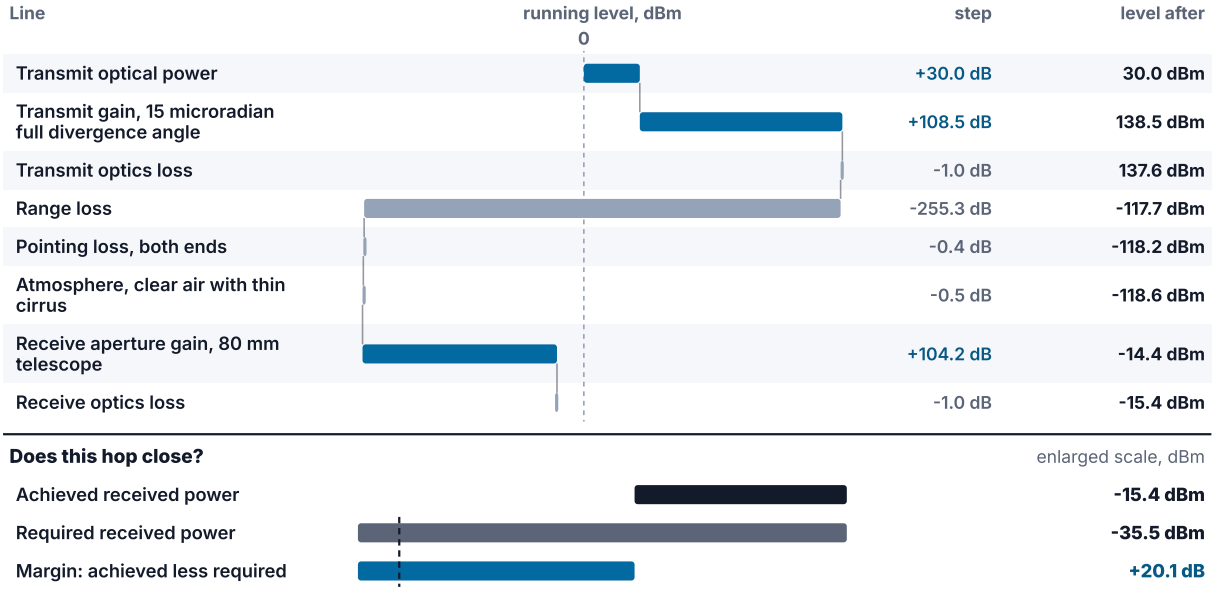
A narrow beam has to be aimed. Pointing, acquisition and tracking join the budget as lines, and they also take time before any bit moves. The budget page names two pointing lines, one for each end: a pointing error of one microradian against a 15 microradian beam costs about 0.3 dB at the transmitter. That is the residual error after point-ahead: in the time light takes to cross the hop the satellite moves, so the transmitter aims ahead of the direction from

which the receiver's light arrives, by about twice the cross speed over the speed of light, some 50 microradians at this altitude (calculated: the arriving light shows where the receiver was, and the outgoing light must meet it where it will be), several times the beam. Before that, the two terminals have to find each other. A 2025 study of pointing and acquisition delays models acquisition in low orbit at 30 to 60 seconds; citing the mission's own operations paper (Riesing and others, 2023), it reports that for TBIRD acquisition took up to 20 percent of the five-minute contact window, with the data rate tapering at the start and end (arXiv 2511.16063, a preprint, not peer reviewed).

The rest of the budget keeps the shape of Chapter 4, with different words for the lines. The optical page 2 runs from transmit power to the power at the detector, in dBm (decibels relative to one milliwatt; the same power reads 30 higher in dBm than in dBW, so 0 dBW is 30 dBm), and compares it with the receiver's **sensitivity**: the smallest power that gives the stated error rate at the stated rate. The receiver type must be named. A **direct detection** receiver responds to the light's intensity; on-off keying is one common format for it. A **coherent** receiver mixes the incoming light with a local laser and recovers its phase, as a radio receiver does; for comparable formats and coding it can need less received power, at the price of complexity. Background light, from the sunlit sky or Earth inside the receiver's field of view, is a separate line, largest by day.

FIGURE 9.1

The generic 10 Gbit/s laser downlink model in clear air: 20.1 dB above the receiver's need



Required for: 10 Gbit/s at bit error rate 1e-12. Dashed line: the design minimum margin, 3.0 dB.
Operating point: 10 Gbit/s, satellite to ground, 40 degrees elevation, clear air with thin cirrus, station 1 km above sea level; background light not assessed.
Source of the required value: Assumption, to verify: representative, Liang and others, IEEE WoWMoM 2022 (arXiv 2204.13177), Table 1, 2026-11-23.

The baseline of LL-2023-01, a generic model that is not any mission's budget: the gains are optical gains of a narrow beam and a small telescope, and the losses are range, pointing and air.

Author's calculation from the published budget of Liang and others (IEEE WoWMoM 2022, arXiv 2204.13177); see LL-2023-01.

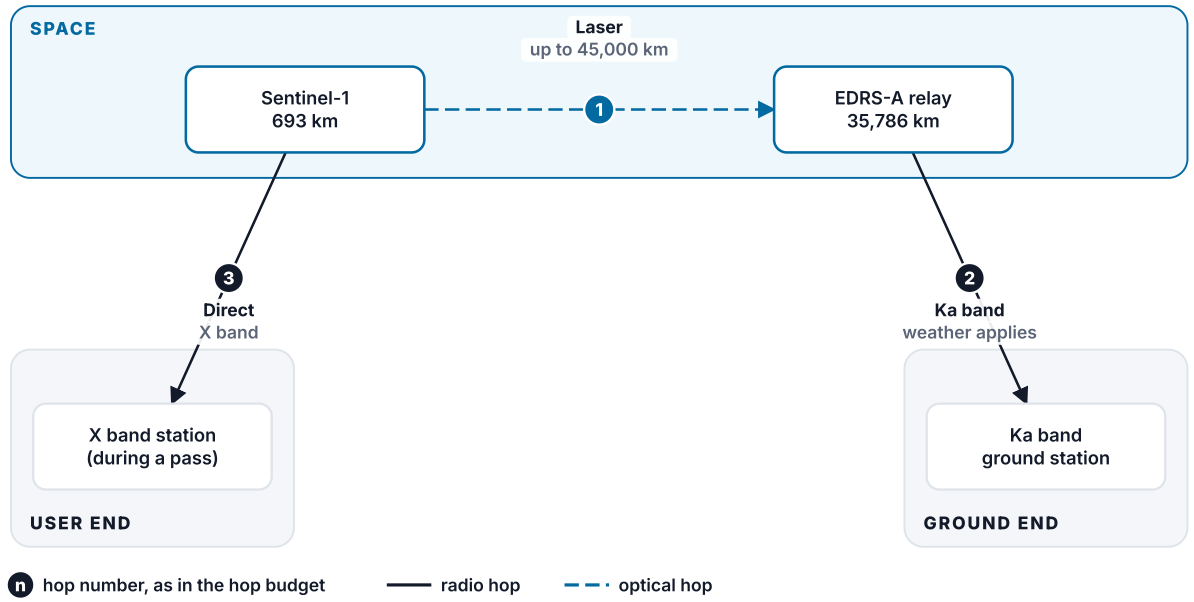
Space to space: relays and crosslinks

Between satellites there is no air, so the optical hop has no weather. Relays were an early operational use of space lasers. Europe's EDRS-A relay node in geostationary orbit takes data by laser from low orbit satellites and sends it to the ground in Ka band (arXiv 2410.23470, a preprint, not peer reviewed). One study reports the laser link at 1.8 Gbit/s over up to 45,000 km, with BPSK (Vieira, Pita and Mello, arXiv 2212.02030, a preprint, not peer reviewed, reporting the operator's nominal figure); the terminals use coherent detection. A paper with authors from the terminal's maker, Tesat-Spacecom, and the German Aerospace Center records laser terminals on Alphasat in geostationary orbit since 2013 and on Sentinel-1A since 2014 (arXiv 1510.04507, a preprint, not peer reviewed).

The relay changes the requirement more than the budget. A low orbit satellite sees a given ground station for minutes per pass; it sees a geostationary relay for much of each orbit. The price is distance: 150.1 ms for a laser hop of 45,000 km and 119.4 ms from the relay to a station directly below it, about 270 ms in all (calculated, propagation only); a station away from that point adds more. Figure 9.2 shows the two routes for Sentinel-1, which also stores 1,410 Gbit on board for the passes it cannot relay (Copernicus).

FIGURE 9.2

Relay through geostationary orbit against a direct downlink



Sentinel-1 can send to a ground station only during a pass, or by laser to a relay that sees it for much longer and passes the data down in Ka band.

Author's diagram based on the Copernicus SentiWiki S1 Mission page and Vieira, Pita and Mello (arXiv 2212.02030).

The service ledger of that relay path stays on one page. The laser terminal's transmit power, its apertures and its receiver sensitivity were not read in a primary source or a peer-reviewed paper on the book's date, so no budget is printed. The 520 Mbit/s that the Copernicus documentation gives for Sentinel-1 payload data is not attributed to either route here, because the source names both routes and does not settle which rate belongs to which.

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.

Laser crosslinks inside a constellation are now sold as products, and the dates are recent. Kepler announced on 24 August 2026 that its optical data relay constellation was in commercial service (Via Satellite, trade press). SpaceX sells its "mini laser" terminals to

other satellite builders, quoted at up to 25 Gbit/s over up to 4,000 km, with a first customer flight planned for the first quarter of 2027 (Via Satellite, trade press, 21 October 2025). Each is an operator claim until a measurement is published with who made it, how and when.

Space to ground: clear air, turbulence, cloud

The hop down to the ground is where weather returns. Clear air costs little: the study used for this chapter's budget computes 0.48 dB at 40 degrees elevation, from a station 1 km above sea level, with thin cirrus. Turbulence makes the received power flicker, which the budget does not show as a single line. Cloud is different in kind. A cloud of sufficient optical depth makes the link unavailable at any margin a terminal like this can carry.

The worked ledger below is a generic model with its own name, the **generic 10 Gbit/s laser downlink**. It is not the budget of any mission. Its terminal and receiver are those of a published link budget by Liang, Chaudhry, Erdogan and Yanikomeroglu (IEEE WoWMoM 2022, arXiv 2204.13177): 1550 nm, an 80 mm receive telescope, on-off keying at 10 Gbit/s and a sensitivity of -35.5 dBm for a bit error rate of 1e-12. The satellite flies at an assumed 483 km, and the transmit power of 1 W is marked as an assumption. In clear air at 40 degrees elevation the hop arrives 20.1 dB above the sensitivity. That leaves 17.1 dB above a 3 dB minimum, a design reserve chosen for this ledger, for anything the budget does not hold. The second page puts a 30 dB placeholder for a thick cloud in the path, and the hop fails its minimum by 12.9 dB. The placeholder is an assumption, chosen only to show the shape of the result.

LINK LEDGER · LL-2023-01 · OPTICAL HOP BUDGET · THE BASELINE

2026-11-23

System: The generic 10 Gbit/s laser downlink: a small satellite to one optical ground station (a model, not a mission)

Planned | Class: budget only | **Budget: closes (baseline); stress case A fails, as intended**

Baseline · Generic laser downlink, clear air

Small satellite, 483 km (assumed) to Optical ground station · 1550 nm · 717 km slant range · direct detection (on-off keying) · reference plane: the laser output; the detector input

Part	Line	Value	dB, and the level after	Evidence	Source and date
TRANSMIT OPTICAL POWER AND APERTURE	Transmit optical power	1 W	**+30.0** level 30.0 dBm	*assumption*	Assumption, to verify: 1 W, the limit the paper cites for one commercial terminal; no mission's own power is used, 2026-11-23
	Transmit gain, 15 microradian full divergence angle	16 / Theta squared	**+108.5** level 138.5 dBm	calculated	Liang and others, IEEE WoWMoM 2022 (arXiv 2204.13177): G = 16 / Theta^2, Theta the full divergence, 2026-11-23
	Transmit optics loss	efficiency 0.8	**-1.0** level 137.6 dBm	calculated	Liang and others, IEEE WoWMoM 2022 (arXiv 2204.13177), Table 1, 2026-11-23
LOSSES	Range loss	717 km at 1550 nm	**-255.3** level -117.7 dBm	calculated	20 log10(4 pi d / lambda); 483 km at 40 degrees, Earth radius 6,371 km, 2026-11-23
	Pointing loss, both ends	1 microradian each	**-0.4** level -118.2 dBm	calculated	Liang and others, IEEE WoWMoM 2022 (arXiv 2204.13177): exp(-G theta^2) at each end, Table 1, 2026-11-23
	Atmosphere, clear air with thin cirrus	40 degrees, station at 1 km	**-0.5** level -118.6 dBm	calculated	Liang and others, IEEE WoWMoM 2022 (arXiv 2204.13177), Table 5, 2026-11-23
RECEIVE APERTURE	Receive aperture gain, 80 mm telescope	(pi D / lambda) squared	**+104.2** level -14.4 dBm	calculated	(pi D / lambda)^2, D = 80 mm (representative, Liang and others, IEEE WoWMoM 2022 (arXiv 2204.13177)), 2026-11-23
	Receive optics loss	efficiency 0.8	**-1.0** level -15.4 dBm	calculated	Liang and others, IEEE WoWMoM 2022 (arXiv 2204.13177), Table 1, 2026-11-23
RECEIVER SENSITIVITY	Receiver sensitivity	-35.5 dBm at 10 Gbit/s	**-35.5**	*assumption*	Assumption, to verify: representative, Liang and others, IEEE WoWMoM 2022 (arXiv 2204.13177), Table 1, 2026-11-23
RESULT	**Achieved received power: the sum of the lines above**		**-15.4 dBm**	calculated by this ledger	
	Required received power for 10 Gbit/s at bit error rate 1e-12		**-35.5 dBm**	from the line above	
	Margin: achieved less required		**+20.1**	design minimum 3.0 dB	

Closes: margin +20.1 dB (design minimum 3.0 dB)

Operating point. 10 Gbit/s, satellite to ground, 40 degrees elevation, clear air with thin cirrus, station 1 km above sea level; background light not assessed
Required received power, -35.5 dBm: source. Assumption, to verify: representative, Liang and others, IEEE WoWMoM 2022 (arXiv 2204.13177), Table 1, 2026-11-23

Assumptions. Generic model: the terminal and receiver are those of a published budget; it is not any mission's budget. The 3 dB minimum is a design reserve chosen for this ledger (assumption). Not covered: turbulence fading, daytime background, acquisition time, availability over a year.

LINK LEDGER · LL-2023-01 · OPTICAL HOP BUDGET · CASE A OF THE BASELINE

Case A: Generic laser downlink, optically thick cloud (placeholder loss)

Small satellite, 483 km (assumed) to Optical ground station · 1550 nm · 717 km slant range · direct detection (on-off keying) · reference plane: the laser output; the detector input

Part	Line	Value	dB, and the level after	Evidence	Source and date
The other 9 lines are as in the baseline: not repeated here, and counted in the sums below.					
LOSSES	Optically thick cloud	30 dB placeholder	**-30.0** level -148.6 dBm	*assumption*	Assumption, to verify: a placeholder; settled by a cloud attenuation model or a site record, neither read, 2026-11-23
RESULT	**Achieved received power: the sum of the lines above**		**-45.4 dBm**	calculated by this ledger	
	Required received power for 10 Gbit/s at bit error rate 1e-12		**-35.5 dBm**	from the line above	
	Margin: achieved less required		**-9.9**	design minimum 3.0 dB	

Does not close: short by 9.9 dB, and by 12.9 dB against the design minimum of 3.0 dB

Operating point. 10 Gbit/s, satellite to ground, 40 degrees elevation, an optically thick cloud in the path, station 1 km above sea level; background light not assessed
Required received power, -35.5 dBm: source. Assumption, to verify: representative, Liang and others, IEEE WoWMoM 2022 (arXiv 2204.13177), Table 1, 2026-11-23
Line that fails. Optically thick cloud, -30 dB placeholder: the hop misses its 3 dB minimum by 12.9 dB

Assumptions. Generic model: the terminal and receiver are those of a published budget; it is not any mission's budget. The 3 dB minimum is a design reserve chosen for this ledger (assumption). Not covered: turbulence fading, daytime background, acquisition time, availability over a year.

A generic model: the terminal and receiver figures are those of a published link budget (Liang and others, IEEE WoWMoM 2022, arXiv 2204.13177) and the 483 km altitude is assumed. It is not the budget of any mission; TBIRD's own record is in a separate comparison table after this ledger.

For comparison, not part of the model: NASA's TBIRD mission, as its operators report it

Item	TBIRD's record	Source (operator claim; the last row second-hand)
Spacecraft and orbit	A tissue-box-sized laser terminal on a NASA CubeSat, about 300 miles up; launched May 2022; mission completed in 2024	NASA, 2024-09-25; MIT Lincoln Laboratory project page
Burst rate	200 Gbit/s (May 2023)	MIT Lincoln Laboratory; NASA
Contact and volume	4.8 terabytes of error-free data in a single pass of about five minutes, to a station at Table Mountain, California (June 2023)	NASA, 2024-09-25
Acquisition	Up to 20 percent of the five-minute contact, with the rate tapering at the start and end	Riesing and others, 2023, as reported in arXiv 2511.16063 (a preprint, not peer reviewed)
Link budget	Not read for this book; none of the model's lines is TBIRD's	

Three numbers that a buyer should keep apart are visible in that record. The **burst rate** was 200 Gbit/s. The **contact** was a pass of about five minutes. The **volume** delivered was 4.8 terabytes. At 200 Gbit/s for 300 seconds the volume would have been 7.5 terabytes (calculated); the difference can include acquisition, the rate taper at the start and end of the pass, and protocol overhead. A daily volume needs a fourth number the record does not give here: how many usable passes a day, at that station, in that season.

The mitigations for cloud are well known, and none of them is a guarantee. **Site diversity** places optical stations at sites chosen to reduce the correlation of their weather, which needs a joint availability assessment; studies of such networks, for example for Australia and New Zealand, estimate availability from cloud records (arXiv 2211.09248). **Storage on board** holds data until a clear pass. A **radio fallback** keeps a lower rate alive through cloud. Each of them costs money or capacity, and a buyer should see the numbers for each.

What is sold in 2026, and what is missing

In November 2026 a buyer can rent relay capacity from a commercial optical constellation and buy laser terminals for a new satellite, as the trade press reports above; renting is covered in depth later in this series. In the sources read for this book, public evidence of terminals of different makers working together was still thin; the dated finding below is one program's. A terminal from one company talking to a terminal from another is a stated goal of several programs, and the failure below shows how hard it was for one of them.

THE SYSTEM'S FAILURE

The first tranche of a military constellation, 2025. The United States Space Development Agency planned to demonstrate laser links in its first set of satellites, Tranche 0, built to its own optical terminal standard. A Government Accountability Office report of 26 February 2025 (GAO-25-106838) found that Tranche 0 "has not yet fully demonstrated laser communications technology in space" and that the agency "has yet to demonstrate a link between two OCT vendors in space as originally planned." It warned that "changing the SDA OCT Standard while each tranche is under development increases the risk that the OCTs may not be interoperable," and recommended that the agency demonstrate the minimum viable laser communications capability in space.

The lesson is bounded: demonstrating links between terminals from different makers took longer than the plan. The report says no more than that, and neither does this book.

SECURITY NOTE

Who can interfere or command. A beam 15 m wide at 1,000 km makes interception from the side difficult, since a listener needs a receiver inside the beam with enough aperture and alignment. It is not encryption. A receiver can also be dazzled or disturbed by light inside its own field of view, without anyone entering the beam. The ground station, its network and the relay's operator are ordinary targets, as Chapter 11 shows. **How it is seen.** Loss of lock, a falling received power without cloud, and failed decryption at the receiver; the station's logs of acquisition and power per pass. **How it is recovered.** Reacquire, switch to another station or to the radio fallback, and authenticate and encrypt the data end to end, independent of the light.

Monday rule: for an optical downlink, ask for availability by site and season, the number of sites, and the radio fallback rate.

CHAPTER TEN

From the Gateway to the Screen



Until May 2023, a user of one low orbit broadband service in the Philippines reached a server in the Philippines by way of a point of presence in Japan. A study of that service, published in 2024, found that this detour across submarine cables added 50 to 70 ms to each round trip; after a local point of presence opened in May 2023, latency to servers in the country fell by about 90 percent. The study attributes the change to the new point of presence, a piece of ground infrastructure. The decision this chapter changes is where you look for delay, cost and control: after the last radio hop the bit is on the ground, and on a low orbit path the ground can decide much of what the user feels.

The gateway and the feeder link

A gateway is the earth station where the satellite's traffic meets the ground network. The radio link between the satellite and the gateway is the feeder link; 3GPP, the body that writes the mobile standards, defines it as the link between the gateway and the payload, and calls the link between the payload and the user the service link. The two are separate hops with separate budgets, and they are often in separate bands.

The low orbit examples of this chapter come from one operator's public filings and one measurement study of the same network. They are illustrative, chosen because the regulator's orders and a peer-reviewed measurement could be read; they do not stand for the market, and the comparison at the end of this chapter says what was and was not read for other systems.

The feeder link often sits in a higher band than the service link. A gateway is a fixed site with a large dish and a professional installation, so it can use a narrow beam at a high frequency and carry the traffic of many users at once. One operator's United States grant of 2018 lists the user uplink at 14.0 to 14.5 GHz and lists further ranges in the Ka band, between 17.8 and 30 GHz, in the same authorization. What the higher band buys, and what rain costs it, is the subject of chapters 3 and 4. For this chapter the point is simpler: gateways are far fewer than users, each carries the traffic of many, and each has its own weather.

How many gateways, and where, is a design decision with three consequences.

- **Coverage.** With a transparent satellite (chapter 8), the user and a gateway must see the same satellite at the same time. A place with no gateway in reach has no service, however good the satellites are.
- **Altitude.** A lower orbit gives each satellite a smaller footprint, so the same coverage needs more gateways. When one operator asked in 2020 to move about 2,800 satellites from 1,100 to 1,300 km down to 540 to 570 km, a competitor argued to the regulator that this would "significantly increase the number of SpaceX gateway sites in the United States in order to provide the same level of service" (the FCC's summary of the argument, in its order of April 2021).
- **Weather and failure.** A heavy storm over one gateway can reduce or interrupt what that gateway carries, depending on its band, its margin and the availability it was designed for. Gateway diversity, a second site placed so that the two rarely fade at the same time, buys availability with a second building, a second antenna and a second backhaul.

Elevation also sets a limit. The same 2021 order authorizes that operator's user terminals and gateways at elevation angles as low as 25 degrees, and gateways in polar regions as low as 5 degrees. A gateway close to the horizon looks through more atmosphere; one that must stay above 25 degrees sees fewer satellites at any moment. Crosslinks between satellites change this picture: where terminal and gateway are not under the same satellite, laser links can carry the traffic through space to a distant gateway (chapter 9). A measurement study of one such network calls this an "extended bent-pipe", and notes that not all of that operator's satellites carry the laser links. In the 3GPP architecture for mobile networks the dividing line is stated plainly: the use of links between satellites requires a regenerative payload.

From the gateway to the network

The gateway is not where the internet begins. Behind it is backhaul, usually fiber, to a point of presence (PoP): the site where the operator's network hands traffic to other networks. In the study of 2024 the route was terminal, satellite, ground station, then "Starlink points-of-presence (PoPs), which route it to the destination server via terrestrial Internet". The gateway and the PoP need not be in the same city or the same country.

Three ground functions sit on this stretch, and each belongs to somebody.

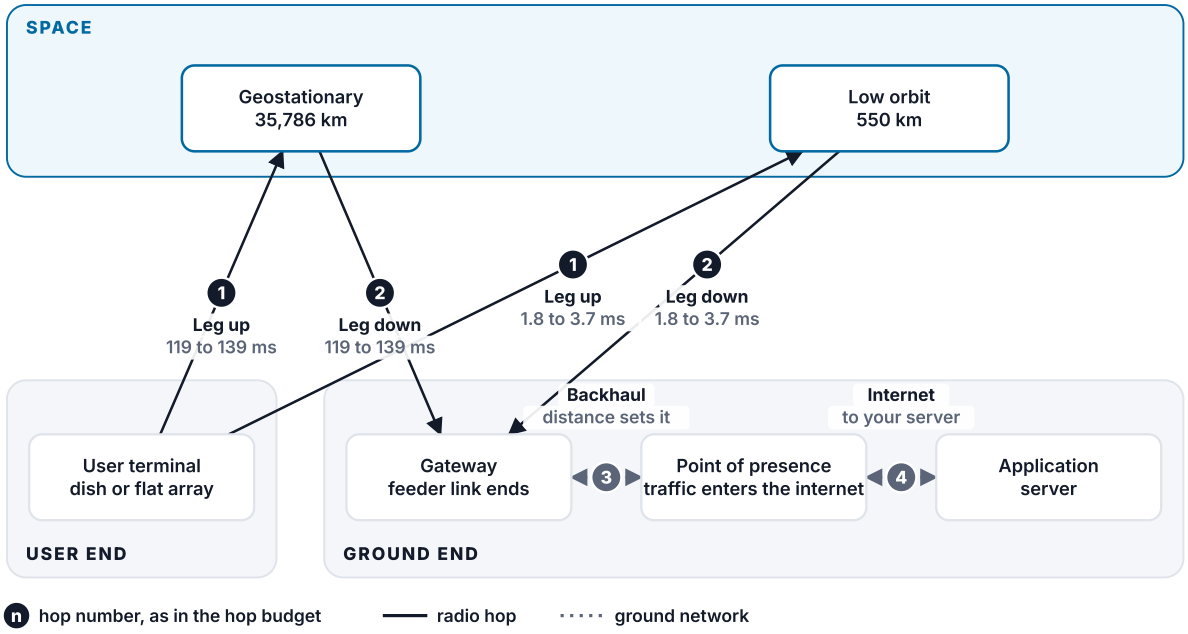
- **Address and routing.** The PoP decides which networks your traffic enters next, and where it appears to come from.

- **Policy.** Queues, traffic shaping, filtering and any lawful interception are usually applied in the operator's ground network, under the law of the country where it sits, among others.
- **Identity.** Who you are, what you may use and what you pay is usually decided by a ground system.

Direct to device makes the third function visible. In a mobile network, the core network authenticates the subscriber's SIM, applies roaming and charging, and routes emergency calls. With a transparent payload the base station stays on the ground, reached through the gateway at the end of the feeder link (the two may share a site), the satellite acting "just like a remote radio head relaying the signals". With a regenerative payload the base station flies, and the gateway can be a router to the core network. In the deployments described in this book the core is on the ground, and it is usually the partner mobile operator's. The United States framework for supplemental coverage from space, adopted by the FCC on 2024-03-14 and released the next day (FCC 24-28), lets the phones be licensed by rule and applies interim 911 call and text routing requirements. A satellite can reach a phone; whether the call reaches an emergency answering point is a ground question.

FIGURE 10.1

From the terminal to the server: the radio legs set the floor; routing, processing and queueing add the rest



Propagation per radio leg for a geostationary and a low orbit path (calculated), then the ground hops, whose delay depends on where the gateway, the point of presence and the server are.

Author's diagram. Leg times calculated from the altitude and the slant range: geostationary 35,786 km, from straight up to the horizon; low orbit 550 km (FCC 21-48, 2021), from straight up to the 25 degree minimum elevation in the same order. Propagation only, before processing, scheduling and queueing.

Transport over a long path

The time a reply takes depends on the orbit. The propagation time through one satellite follows from geometry alone: the slant range divided by the speed of light. The values in the table are calculated from the altitude, for a user and a gateway at the elevations named; they are propagation only, before any processing, scheduling, queueing or ground network.

Propagation through one satellite, by orbit (calculated)

Path	One leg	User to gateway, one way (two legs)	A reply (four legs)
Geostationary, 35,786 km, from straight up to the horizon	119 to 139 ms	239 to 278 ms	477 to 556 ms
Low orbit, 550 km, from straight up to 25 degrees	1.8 to 3.7 ms	3.7 to 7.5 ms	7.3 to 15.0 ms

The geostationary figures agree closely with the ones the Internet Engineering Task Force used in 1999. Its best current practice for TCP over satellite, RFC 2488, gives a one way delay of 279.0 ms for ground stations at the edge of the satellite's view and says the round trip "could be at least 558 ms". So a geostationary path is about a quarter second one way and half a second for a reply, before the ground adds anything.

TCP, the transport most applications used for decades, learns the path by sending and waiting for acknowledgments. Two of its mechanisms pay for a long round trip.

- **Slow start.** A new connection starts with a small amount of data in flight and grows it as acknowledgments return, round trip by round trip. RFC 2488 puts the consequence in one line: "slow start takes more real time over GSO satellites than on typical terrestrial channels". A short transfer can finish before slow start does, so it never reaches the rate the link could carry.
- **The window.** A sender may have no more data unacknowledged than the receiver's advertised window allows, and no more than its own congestion window. The TCP header carries the receive window in a 16 bit field, so without an extension "the largest window that can be used is 2^16 = 64 KiB" (RFC 7323). At a geostationary reply time of 477 ms that caps one connection at about 1.1 Mbit/s, whatever the radio can carry (calculated: 65,535 bytes in one round trip). To fill a 50 Mbit/s link over the same round trip, about 3.0 million bytes must be in flight, unacknowledged. That product of rate and round trip is the bandwidth delay product, and the sender and receiver must both allow a window that large.

RFC 2488 recommends the standard remedies: window scaling, selective acknowledgments, path MTU discovery so that each packet is as large as the path allows, and forward error correction on the satellite link so that a radio error does not look like congestion. Window scaling and selective acknowledgments work only when both TCP endpoints support them; forward error correction belongs to the radio link itself. Many operators did not wait for every endpoint.

The other answer is a performance enhancing proxy, described in RFC 3135 (June 2001). A common form splits the connection: a box near the user and a box at the gateway each terminate TCP, acknowledge locally, and carry the data across the satellite with their own protocol. The user's sender sees a short round trip and opens its window quickly. The cost is in the same document: a split proxy breaks the end to end meaning of TCP, and "a user or network administrator must choose between using PEPs and using IPsec".

Encryption changes the picture in different ways. TLS carried over TCP leaves the TCP headers and acknowledgments visible, so a split proxy can still work on it; IPsec and QUIC do not. QUIC, standardized in RFC 9000 (May 2021), runs over UDP and integrates the TLS handshake; in the RFC's words it "authenticates the entirety of each packet and encrypts as much of each packet as is practical". A proxy in the middle can neither read QUIC's acknowledgments nor generate valid ones for the sender. For that traffic the cost of delay returns to the endpoints: to the congestion control in the sender's software, to the flow control limits it sets (QUIC has its own, without TCP's 16 bit field), and to how many round trips the application needs before the user sees anything.

Low orbit shrinks the problem without removing it. At the measured round trip of about 40 ms to the PoP, described in the next section, a 50 Mbit/s flow needs about 250 kB in flight, and a connection without window scaling is capped near 13 Mbit/s (both calculated). The rule is the same at every orbit: delay times rate is the data in flight, and something must allow it.

Where the time goes

The propagation table gives the floor. The measured numbers are higher, and the difference is where the engineering is. The study of 2024, by Mohan and colleagues at the Technical University of Munich and the University of Edinburgh, used probes on users' own connections to isolate the stretch from the terminal to the PoP. They found that this round trip fell between 36 and 48 ms, with the median around 40 ms for almost all countries. The radio legs through one satellite account for 7.3 to 15.0 ms of that round trip at the authorized altitude and elevations. The rest is the ground distance from the station to the PoP, any crosslinks, and processing, scheduling and queueing, in shares that the table cannot separate. The study points to three things it could observe: the placement of ground stations and PoPs, which explains much of the difference between countries; a globally synchronized reconfiguration of the satellite links every 15 seconds, which causes regular swings in delay and rate; and queueing under load. It does not publish a breakdown of the idle round trip, and neither does the operator.

The ground part of the path can be the longer part. The Philippines case in this chapter's opening is one example: the radio stretch was unchanged, and a PoP in another country added 50 to 70 ms. The same study found a large terrestrial share in the latency from Mexico and from most African countries it measured, which the authors attribute to "non-optimal PoP assignments". For an application, the delay that matters is to its own server, and the server's location relative to the PoP can matter as much as the orbit.

Load is the second effect. In public speed tests, the study measured round trips during active downloads about 2 to 4 times the same tests' lowest values, with some reaching almost 400 to 500 ms. That is consistent with queueing, which software can manage, though the tests alone cannot say where the queues were; either way it is a reason to measure under load rather than idle.

On a geostationary path the order is reversed: the two radio legs dominate. At 239 to 278 ms one way through the satellite, a ground network of a few tens of milliseconds is a small addition, and a reply is at least about half a second however good the ground is.

RECONSTRUCTION · 2012 · THE REPORT FROM OUT OF REACH

The message	Claim photos from a hurricane zone.
The link	A dish on a truck, Ku band
Note	Half a second for every reply.

The insurer is invented and illustrative. This scene is a design example on the class of service authorized by the FCC's 2009 rules for vehicle-mounted earth stations, not a dated service.

The 2012 scene runs on that second kind of path. A vehicle-mounted earth station that reaches geostationary satellites in the Ku band became a licensed application in the United States in 2009, when the FCC adopted rules for it and named emergency preparedness among its uses. Every reply to a photo upload from such a dish waits about half a second for propagation alone (0.48 to 0.56 s, calculated); a protocol that needs ten round trips before the first byte of data spends about five seconds waiting.

The low orbit path of this chapter, as one service ledger:

LINK LEDGER · LL-2026-04 · SERVICE LEDGER

2021 to 2023 (historical)

System: Low orbit broadband: terminal, satellite, ground station, PoP (one operator, many users' sites)

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

1 Requirement	Illustrative: a field office needs 25 Mbit/s down, 3 Mbit/s up and a reply under 100 ms in the busy hour, 99 percent of each month.
2 Ends and path	A flat phased array terminal at the site; the internet beyond the operator's point of presence (PoP). **Path:** Terminal, satellite, ground station, PoP; laser crosslinks where one satellite does not see both ends.
3 Orbit and time	Shells at 540 to 570 km; terminals and gateways at 25 degrees elevation or more, polar gateways down to 5 degrees (filed and authorized, 2021). **Time:** 3.7 to 7.5 ms one way over two legs through one satellite at 550 km (calculated); 36 to 48 ms round trip to the PoP, median about 40 ms (measured); the rest (ground, crosslinks, processing, queueing) is not separated in the source.
4 Band and permission	**User link.** 14.0 to 14.5 GHz up, within 10.7 to 12.7 GHz down; FCC 18-38 (2018), United States **Ground station links.** Ka band ranges in the same grant, not tied to a hop in the text read
5 Capacity	**Up.** About 4 to 12 Mbit/s (75th percentile of public speed tests, 2021 on; published 2024). **Down.** About 50 to 100 Mbit/s (same). Shared: a test is one user at one moment; under load, round trips grew 2 to 4 times.
6 Who owns each end	**Space segment.** SpaceX, the licensee **Ground segment.** Its ground stations and PoPs; sites not checked **Customer relationship.** The operator or a reseller **The exit.** Not checked: a contract question
7 Trust	The operator commands the satellites and updates the terminal; no customer keys are described. Traffic comes down at a ground station and leaves at the PoP, each under its country's law. Link encryption not stated: encrypt end to end.
8 How it fails, and how we would see it	Obstruction, load, a distant PoP and the 15 second swings the authors attribute to satellite link reconfiguration move delay and rate. **How we would see it:** From your server: probes every few seconds summed each minute, and short throughput tests both ways; a minute fails when any field 1 limit fails.
9 Cost shape	Monthly fee and terminal; prices not printed. Leaves out installation, power and a second path.
10 Evidence	Field 1 figures *assumption* To verify: the buyer sets them, 2026-11-23 540 to 570 km; 25 degrees, 5 for polar gateways **standard** FCC 21-48 (2021), regulatory document, 2026-11-23 3.7 to 7.5 ms one way (two legs) **calculated** 550 km, 25 to 90 degrees, 2026-11-23 36 to 48 ms to the PoP; 50 to 100 Mbit/s down, 4 to 12 up; 2 to 4 times under load; 15 s swings **measured** Mohan and others, 2024, 2026-11-23

Service only, no hop budget: the documents read publish no waveform, transmit power or antenna figure for either radio hop, so no hop is given a verdict.

Historical: a 2021 to 2023 profile, not today's fleet. Measured numbers are the researchers'.

Up and down are different services

Broadband satellite services are commonly asymmetric, and the reasons are structural. The forward direction, from the gateway to the user, starts at a large ground antenna and uses the power the satellite allocates to that beam. The return direction starts at the user's terminal, which is small, low powered and one of many sharing the satellite's receive capacity. The study of 2024, using public speed tests from 2021 onward, reports that "most Starlink clients achieve" about 50 to 100 Mbit/s download and about 4 to 12 Mbit/s upload "at the 75th percentile".

Suppliers state the asymmetry in their own numbers. Amazon described its Leo Ultra enterprise terminal, at the start of an enterprise preview on 2025-12-01, as "delivering up to 1 Gbps downlink and 400 Mbps uplink" (an operator claim, as reported by the GSMA). A rate in a data sheet is a peak for one terminal; a speed test is one user at one moment; neither is the rate your site gets at the busy hour with its neighbors on the same beam.

For many enterprise uses the upload is the service. A claims adjuster sends photos; a sensor sends readings; a camera sends video. Write the requirement for each direction separately, and ask for the return rate at the worst signal quality in the contract.

The last step

Beyond the server, the bit enters the user's device, its operating system and its screen; that part of the path belongs to the series *Every Pixel Matters*. How the application is built to survive a slow or broken path (retries, timeouts, queues and local copies) belongs to *Every Boundary Holds*.

For comparison: other broadband and direct to device systems, and what this book read for them

System	What the book uses	Why no more
OneWeb	Named only	The operator's pages could not be read on 23 November 2026; the research papers found give its altitude only second-hand
Telesat Lightspeed	Named only	The operator's pages could not be read; the schedule found was second-hand, not a primary source
Today's Inmarsat fleet	History only: the maritime service of 1976, Marisat, in chapter 3	The current fleet page could not be read
O3b mPOWER (medium orbit)	Fleet size, chapter 8 and Appendix D	Read: Boeing, 2026-09-13 (operator claim)
Amazon Leo (low orbit)	Name, V band grant and an enterprise preview terminal, chapters 3 and 10	Read: Amazon, FCC DA 26-553, GSMA news item
Direct to device outside the United States	Apple's satellite messaging in Canada, Mexico and Japan, and its emergency service in 21 countries and regions (chapter 12)	Read: Apple Support, pages published 2026-05-15 and 2026-10-05 (operator claim); no other country's operator page was read

THE SYSTEM'S FAILURE

Globalstar's satellites were built as a "bent pipe", in the words of the company's annual report for 2001: they amplify received signals and send them straight back to earth, and "Globalstar satellites relay calls to earth through Globalstar gateways". Those gateways were "currently owned and operated primarily by the Globalstar service providers". The report counts them: QUALCOMM had "manufactured and shipped 38 gateways, 26 of which have been installed", and the service ran "through 25 gateways", which at the end of 2001 covered about 67 percent of the world's land mass and about 18 percent of its waters. A call needed a working gateway in view of the same satellite; where none had been built and run, the satellites overhead had nowhere to deliver it. The report lists regions, among them India, Malaysia, Indonesia and the Philippines, for which no suitable service provider had been found, and says this reduced demand for the service. On 15 February 2002 Globalstar and some of its subsidiaries filed for Chapter 11. The filing gives several causes for the company's position, and this box claims no single one. What it shows is narrower: in a transparent design, the gateway and the partner who runs it are part of the coverage, not an accessory to it.

SECURITY NOTE

Who can interfere or command. The operator commands its network; the law of each country where a gateway or PoP sits reaches the traffic that lands there, which is readable there unless it is encrypted end to end. An operator's management network can send commands to large numbers of terminals at once (chapter 11).
How it is seen. Trace the route from your site to your own server: it often shows the PoP's network, though tunnels and address records can mislead, so confirm the PoP's location with the operator. A change of PoP often shows as a step in delay.
How it is recovered. Encrypt from your device to your server, so that the ground in between carries data it cannot read; keep a second path through another operator or the terrestrial network.

Monday rule: measure the service from your application's server, up and down, idle and under load, not from the terminal's status page.

CHAPTER ELEVEN

The Security of a Link



On 24 February 2022, consumer modems of a European satellite broadband service stopped working in large numbers. In the operator's account, the satellite was not the way in: the attacker came in through the ground, reached the network that manages the modems, and sent them "legitimate, targeted management commands": valid commands of the network's own kind, sent without authority. The decision this chapter changes is where a security review of a satellite link starts: not at the antenna, but at every place where someone can listen, transmit, or send a command, and the ground is most of those places.

Seven attacks, in two groups

This chapter sorts the attacks on a satellite link into seven kinds. The kinds overlap (an entry through the ground can lead to taking command), and the list is a working checklist, not a complete theory. Four act on the radio signal itself:

- **Listening:** receiving a signal that was not meant for you.
- **Jamming:** transmitting energy that drowns the wanted signal in noise.
- **Spoofing:** transmitting a false signal that a receiver accepts as the real one.
- **Replay:** recording a valid signal or message and sending it again later.

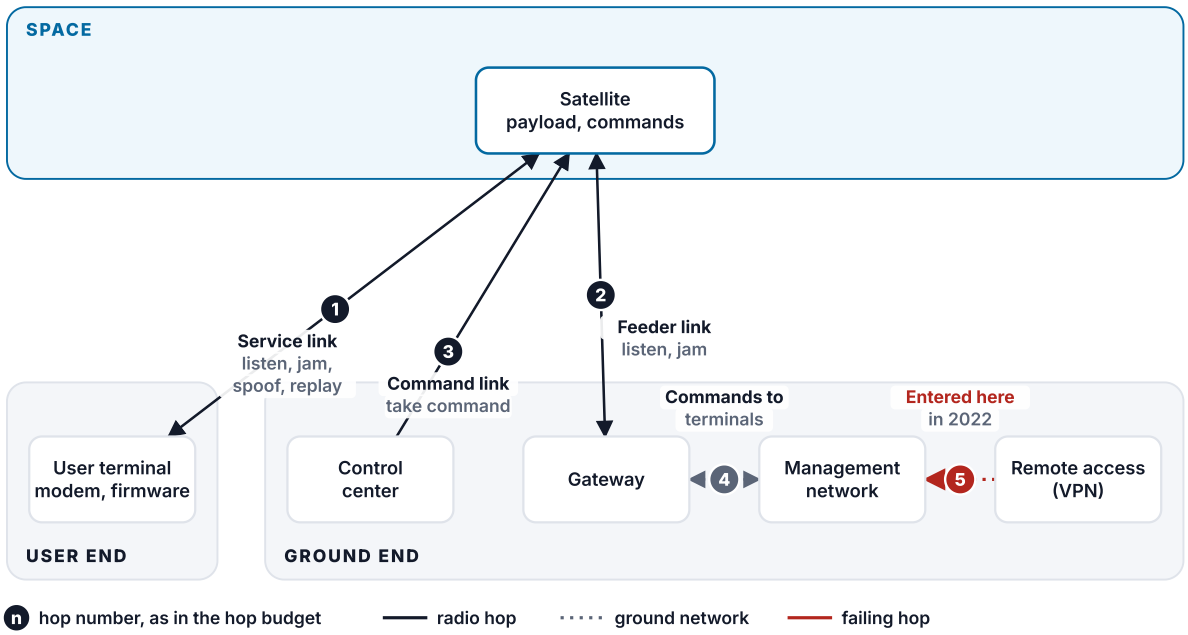
Three act on the system around the signal:

- **Taking command:** sending commands to the satellite, or to the terminals, that the operator did not send.
- **Entering through the ground:** reaching the operator's management, control or customer networks, and acting from inside them.
- **The supply chain:** changing a component, a firmware image or an update before it reaches the link.

Each attack needs a different capability and leaves a different trace. Listening needs a suitable antenna and receiver in the footprint and leaves no trace on the link. Jamming needs a transmitter in the right place and can usually be seen by someone who watches the spectrum and the receiver's quality in the right place and band. Taking command needs keys or a way around them. The three system attacks are ordinary network and software attacks, aimed at a network that happens to include a satellite. Figure 11.1 puts the seven on one path.

FIGURE 11.1

Seven attacks, five places: the radio is only part of the surface



Where each attack acts on one broadband path; the red hop is the route of the 2022 attack in the operator's account: a misconfigured remote access device into the management network, not the radio.

Author's diagram. The 2022 route follows the operator's incident overview of 2022-03-30 (Viasat), as quoted in trade press; the physical placement of the devices is schematic. The supply chain (the seventh kind of attack) acts on every box and is not drawn as a hop.

Listening: the downlink is a broadcast

A satellite's downlink beam covers a region, not a user. A geostationary transponder beam can cover a diameter of thousands of kilometers. Any receiver inside the footprint with enough antenna gain can receive the signal, and a receiver that only listens transmits nothing, so the link gives no sign of it.

The question is therefore not whether a downlink can be received, but what is in it. A peer reviewed study presented at the ACM Conference on Computer and Communications Security in October 2025, by Zhang and colleagues at the University of California San Diego and the University of Maryland, scanned 39 geostationary satellites across 25 longitudes and 411 transponders "using consumer-grade equipment". In their sample, the authors report that "50% of GEO links contained cleartext IP traffic", and that "while link-layer encryption has been standard practice in satellite TV for decades, IP links typically lacked encryption at both the link and network layers". Among what they observed: cellular backhaul with the contents of calls and texts, industrial control traffic for utilities, and in-flight Wi-Fi.

The lesson the study supports is specific, and its title states it: these were internal links, and they were in the clear. On the links the authors observed, encryption was not in use; the paper does not establish whose decision that was in each case, and the sample is not a census of all geostationary traffic. For the reader's own traffic the rule is simple: treat every satellite hop as a public broadcast, and encrypt from your device to your server. Whether the operator also encrypts the radio link is then a second layer, not the only one.

Interference and jamming as a budget

Chapter 4 treats interference as a line in the hop budget: the step from C/N0, the carrier to noise density ratio, to C/(N0+I0), with I0 the interference density in the receiver's band. A jammer is interference with intent, and it is assessed with the same line. The table gives the loss for five ratios of interference to noise (calculated from the formula in chapter 4).

What interference costs, by its ratio to the receiver's own noise (calculated)

I0/N0	Loss of C/(N0+I0) against C/N0
minus 10 dB	0.41 dB
minus 6 dB	0.97 dB
0 dB (equal to the noise)	3.01 dB
plus 6 dB	6.97 dB
plus 10 dB	10.41 dB

Two things follow. Interference well below the noise costs little: at minus 10 dB it takes under half a decibel of margin. Interference above the noise costs roughly its own excess, decibel for decibel. A fixed margin is a tolerance for a stated level of interference, not protection against a source that can raise its level. The formula also assumes interference that adds to the noise like noise; a strong source can overload a receiver or a payload amplifier in ways this one line does not capture.

What decides the interference density at the victim is geometry, and that is where a review should start:

- **Where the source is,** against the victim antenna's beam. A narrow beam receives a source off its axis through its sidelobes, many decibels down; a wide beam, low gain antenna, such as a phone's, receives over a wide range of directions and rejects little by angle (chapter 3).
- **Which hop it hits.** A source on the ground near a user hits that user's downlink. A source that reaches the satellite's receiver on the uplink can raise the noise for the carriers that share that receiver's band, and a transparent payload repeats it down to the users of those carriers (chapter 8).
- **Bandwidth and waveform.** A source spread over a wide band puts less density into each carrier; a narrow source on one carrier mainly hurts that carrier.

This book stops at the level of the assessment: who could be in the beam, which hop, how much margin there is. It gives no powers, methods or settings for a source.

Interference and rain look alike on a signal quality meter, and an operator must tell them apart before acting. Rain typically follows the weather, fades the carriers on the affected path and the satellite's beacon together, and moves with the storm. Interference typically appears at times unrelated to the weather, often on some carriers and not others, and a spectrum analyzer may show energy where no assigned carrier should be. No single sign settles it; weather data, the beacon, other beams, other sites and the operator's logs, taken together, usually do.

Spoofing a one way signal: navigation

A navigation signal is a broadcast that the receiver uses to compute its position and time. The receiver transmits nothing, which is what makes it simple and cheap, and it also means the receiver cannot ask the satellite whether a signal is genuine. A spoofer is a transmitter near the victim that produces signals the receiver accepts as the real ones. Unlike a jammer it need not stop the receiver: the receiver stays locked and reports a wrong position or a wrong time.

The defense that the civil systems have moved toward is to authenticate the navigation message cryptographically, so that a receiver can check that the data came from the system operator. Galileo declared an initial service of its Open Service Navigation Message Authentication (OSNMA) in July 2025; it lets receivers verify that the broadcast ephemeris and clock data come from Galileo satellites (Inside GNSS, trade press, 2026-01-21). It covers Galileo's message, not the GPS civil signal. A paper of 2022 by Motallebighomi and colleagues at Northeastern University and the CISPA Helmholtz Center (a preprint, not peer

reviewed), written while "Galileo and GPS are currently evaluating broadcast authentication techniques", shows the limit of that defense. The receiver measures the signal's time of arrival, and a signature on the message does not prove when the signal arrived. The attack is a form of relay, as the paper's title says: the authors built a real-time spoofer that receives the authentic signals near the victim and generates, from them, signals for another place, without modifying the message contents, and report that in their evaluation a receiver could be moved "to locations as far as 4000 km away from the actual location" without breaking any cryptographic operation. Their conclusion is about broadcast positioning in general: it has "fundamental limitations ... even if all communications are cryptographically protected".

Replay is the same problem in the time dimension: a valid message, recorded and sent again, still passes any check that does not include freshness. A signature says who wrote a message, not when it was sent.

So the practical defense is layered: cross-checks against sources the spoofer is less likely to control at the same time, such as a second constellation, an inertial sensor, a network clock, or the expected motion of the vehicle. Each has its own limits and its own assumptions about the attacker. A survey of interference management for aviation receivers (Morales-Ferre and colleagues, IEEE Communications Surveys and Tutorials, 2020) describes a common front end check: a jammer forces the automatic gain control to reduce gain, and "this change of the AGC level can be used to detect an interferer". A spoofer that stays close to the real signal level is harder to see, which is why the cross-check matters.

The command link

The command link is how the operator tells the satellite what to do: point here, switch that, load this software. Whoever can send a command that the satellite accepts controls the satellite. Two separate protections apply:

- **Authentication:** the satellite accepts only commands that prove they come from a holder of the right key. It defends against forged commands, and, with a counter or a time in the protected part, against replayed ones.
- **Encryption:** nobody else can read the commands or the telemetry. It defends against listening.

Classic space framing provides neither by itself. The CCSDS standard for the Space Packet, 133.0-B-2 (June 2020), says so in its security annex: "The SPP does not provide any security function". It points to where security can be added: at the data link layer with the Space Data Link Security protocols (CCSDS 355.0-B-1 and 355.1-B), or at the network layer with the Bundle Security Protocol; for Bundle Protocol version 7 the IETF security protocol is BPSec (RFC 9172, January 2022). NASA publishes an open source library, CryptoLib, that provides

"a software-only solution using the CCSDS Space Data Link Security Protocol - Extended Procedures (SDLS-EP) to secure communications between a spacecraft running the core Flight System (cFS) and a ground station".

Cryptography moves the problem to the keys. Where are they made, who holds them, how are they loaded before launch, how are they changed in orbit, and what happens if a ground copy is stolen? A satellite that cannot change its keys after launch keeps whatever weakness its ground copy develops for the life of the mission. The same questions apply to the terminals: in the 2022 case the commands were valid ones, sent from inside the network that was allowed to send them.

The ground is the soft part

A satellite operator's ground segment is a set of ordinary networks: the control center that commands the satellites, the gateways, the network that manages and updates the user terminals, the customer and billing systems, and the remote access that engineers use to reach all of them. Each is built from servers, routers, firewalls and software that are attacked every day on the ground. The radio is hard to reach; a misconfigured remote access device is not.

The two studies in this chapter point the same way. The 2022 attack used the management network, not the radio. The listening study found sensitive traffic in the clear on internal links, not a weakness in the satellites. In both cases the satellite did what it was designed to do. How to design those ground networks so that one breach does not reach every terminal (segmentation, least privilege, verified updates, assuming a breach) is the subject of the series *Every Boundary Holds*.

The supply chain belongs here too. A terminal's firmware, a modem's update server, a payload's software load and a ground station's management software each come from somebody. A signed image shows where an image came from, not that it is safe; a known list of components and a protected path back to a known good version are what let an operator recover from a bad one.

What to ask, attack by attack

A buyer can rarely test a satellite operator's security directly, but can ask questions whose answers can be checked later. A supplier may decline some of them; a declined answer is itself something to record.

Questions for the supplier, one per attack

Attack	The question	A useful answer names
Listening	Is traffic encrypted on the service link and the feeder link, and between the gateway and the point of presence?	The layer, the algorithm family and who holds the keys
Jamming	How do you detect and locate interference, and what happens to my service while you do?	The monitoring, the response time and the fallback
Spoofing	Does the terminal depend on satellite navigation for time or position, and what does it do if those are wrong?	The dependency and the cross-check
Replay	Are commands and updates to the terminal protected against being sent twice?	A counter or a time in the protected message
Taking command	Who can command the satellite and the terminal, with whose keys, and how are keys changed?	Roles, key custody and the change procedure
Entering through the ground	Can one person or one compromised system reach every terminal at once?	Segmentation and approval steps
Supply chain	Are firmware and updates signed, can a bad update be rolled back on my site, and what stops a rollback to an older, signed but vulnerable version?	Signing, the rollback path and its time, version enforcement

The answers are not proof. They are statements the supplier can be held to, and they show which questions nobody on the supplier's side had considered. Chapter 12 turns them into the lines a quote or data sheet should contain.

Fields 7 and 8, filled for two links

Field 7 of the service sheet asks who can command or interfere; field 8 asks how the link fails and how anyone would see it. Here they are filled for two links of this book: the Ka band consumer forward link of chapter 4 and the GPS civil signal of chapter 5.

Fields 7 and 8 for two links

Field	Ka band consumer forward link (chapter 4)	GPS L1 C/A, civil (chapter 5)
7. Trust	The satellite operator commands the satellite; the service operator manages and updates every modem over its own management network. The customer holds no satellite command or modem management keys. If the satellite is transparent, it repeats any signal in its band.	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 signal gives it no way to prove that a signal is genuine.
8. How it fails	Rain lowers signal quality and the rate steps down; beyond the design availability the link drops. Interference looks like rain. A breach of the management network can disable many modems at once.	Jamming raises the noise until the receiver loses lock. Spoofing makes it report a wrong position or time while locked. Both act locally, with no access to the satellites.
8. How we would see it	Each modem's logged signal quality and modulation, against rain at the site and other modems in the beam. Many modems failing together in clear sky is a lead toward the ground, not proof.	Jamming: gain control and C/N0 often fall on many satellites at once. Spoofing: position or time disagrees with an independent source. A receiver that logs neither, and has no integrity alarm, has little to go on.

FIGURE 11.2

Each attack has a different attacker, a different sign and a different repair

Attack	Who can do it	How it is seen	How service is recovered
Listening	Anyone inside the downlink footprint with a dish and a receiver	It leaves no sign on the link	Not recoverable after the fact; end to end encryption keeps the content unreadable, not the traffic pattern
Jamming	A transmitter in the victim antenna's beam or sidelobes, on the ground or in orbit	Signal quality falls on some carriers, at times unrelated to weather; a carrier appears where none should be	Locate and stop the source with the regulator; narrow beams, other bands, other satellites
Spoofing	A transmitter close to the victim receiver that imitates a public signal	The receiver stays locked but its position or time disagrees with an independent source	Cross-checks against independent sources; authenticated messages help against forged data, not against relays
Replay	Anyone who recorded a valid frame or signal	A valid message arrives twice, or late	Sequence counters and freshness checks at the receiver
Taking command	Whoever holds, or steals, the command keys and a way to the command uplink	Commands in the log that no operator sent; unexpected state on board	Authenticated and encrypted commands; key change; a protected recovery mode
Entering through the ground	Anyone who reaches the management network: in 2022, through a misconfigured remote access device	Many terminals change state at once; logins and commands nobody planned (a lead, not proof)	Investigate and remove the access; segment the network; reflash or replace terminals from known good images

Attack	Who can do it	How it is seen	How service is recovered
Supply chain	Whoever builds, ships or updates a component	Hard to see; behavior that the specification does not explain	Signed firmware (shows origin, not safety), a known bill of materials, a protected path back to a known good version

Who can do each attack, how it shows up, and how service comes back, kept at the level of the operator's and the user's decisions.

Author's table based on this chapter's sources: Zhang and others (ACM CCS 2025) for listening; Motallebighomi and others (arXiv 2204.11641, 2022, a preprint, not peer reviewed) for spoofing; CCSDS 133.0-B-2 for the command link; the operator's incident overview of 2022-03-30 for entry through the ground.

THE SYSTEM'S FAILURE

KA-SAT, 24 February 2022. In its overview of 30 March 2022, as reported in trade press on the day it was published, the operator Viasat described a ground based intrusion: the attacker exploited a misconfiguration in a VPN appliance, reached the trusted management segment of the KA-SAT network, and moved to the part used to manage and operate it. From there it issued valid commands without authority, "legitimate, targeted management commands on a large number of residential modems simultaneously". In the operator's words, as quoted, the commands "overwrote key data in flash memory on the modems", "rendering the modems unable to access the network", "but not permanently unusable". The operator reported that the satellite itself was not directly hit and that the attack stayed within one consumer part of the network; modems that could be reached were restored with firmware updates, and replacement modems were shipped for the rest. The overview does not name the attacker or the tool, and this book adds nothing to it. The lesson it supports, on the operator's account: the radio link and the satellite were not the way in, and a management network that can command large numbers of terminals at once is part of the link.

SECURITY NOTE

Who can interfere or command. This chapter is the note; Figure 11.2 gives, for each of the seven attacks, who can do it. **How it is seen.** Listening leaves no sign on the link; the other six are seen only by someone who logs signal quality, spectrum, commands and terminal state, and compares them with an independent source. **How it is recovered.** Encryption does not stop anyone receiving the signal; it keeps the content unreadable, though not the traffic's size and timing, and it cannot undo a disclosure. After an intrusion: investigation, removal of the attacker's access, key change, segmentation, and restored or replaced terminals.

Monday rule: ask who can send a command or an update to the terminal on your site, over which network, and how you would know if someone else did.

CHAPTER TWELVE

Reading a Link End to End



In its business update of 9 November 2026, AST SpaceMobile listed twelve BlueBird satellites unfolded and in operation, numbered 1 to 6 and 8 to 13, and a target of about 45 in orbit by the middle of 2027. Number 7 was missing: the company's financial notes record its write-off in the second quarter. A reader who had planned a service on the fleet as it was announced in early 2026 was planning on an operator claim. This chapter turns the tools of the book into a method for reading any link or any supplier's offer: ask the six questions, sort every number by how it is known, fill both pages, and write down what is missing.

The six questions on one path

The bench link of this book is small enough to follow end to end. Meteor-M N2-4 broadcasts weather images at 137.9 MHz to anyone in view; a station with a horizontal dipole and a low-cost receive-only radio could record and decode them. The six questions of the Reader's Brief, asked of that path:

- **What must be delivered, and by when?** One pass of the broadcast, listed at 80 kbit/s, decoded, at 20 degrees elevation and above, in clear sky, with 3 dB of margin. Images minutes after the pass, not in real time.
- **How is the work divided?** The satellite supplies the power and the antenna pattern; the station supplies a simple antenna and a quiet site. There is no gateway and no network.
- **Does each hop close?** There is one hop. Its page 2, later in this chapter, solves for the required satellite EIRP, because no document read gives the satellite's transmit power or antenna pattern.
- **Who owns each end, and who gave permission?** A state weather program owns and operates the satellite (a peer-reviewed survey lists Roscosmos and Roshydromet). Nobody owns the spectrum: the right to transmit on these frequencies is a frequency assignment that a national administration records under the ITU Radio Regulations, and that assignment was not read for this book. The station transmits nothing.

- **How does it fail, and who can interfere?** Noise at the site, a stale orbit prediction, or a stronger signal on the same frequency. No source read documents any authentication on it, and earlier satellites of the series are listed as unencrypted (chapter 7).
- **What can I use or rent before I build?** Published recordings and open decoders exist; a reader can test a decoder on someone else's recording before building a station.

The same six answers, written for a commercial service, become the first page of a review. Where an answer is "not published", that is the finding.

How a number is known

Every number in this book carries an evidence class: measured, calculated, simulated, operator claim, standard, assumption, or published history. For a service, four further stages describe how far a claim has come, and they are different facts with different sources:

- **Announced:** the operator says it will exist. A target such as "about 45 satellites by the middle of 2027" is an announcement.
- **Authorized:** a regulator has granted the right to operate in a band, in a country.
- **Demonstrated:** a test has worked, under conditions the operator chose.
- **In commercial service:** a customer can buy it today, in a named country, from a named operator, on a named device.

The dated examples in this book show the stages apart. Apple's Emergency SOS via satellite became available on 15 November 2022 in the United States and Canada for the iPhone 14 line (Apple Newsroom, 2022-11-15). Skylo announced on 19 March 2025 that Verizon customers with select Galaxy S25 and Pixel 9 phones could text any device by satellite when out of reach of terrestrial networks, with coverage that "is not complete, uniform, or comprehensive worldwide" (Skylo newsroom, read 2026-11-23). Trade press reported that T-Mobile's satellite texting with Starlink launched commercially on 23 July 2025 (Broadband Breakfast). Apple's support page for Messages via satellite (published 15 May 2026, read 24 November 2026) lists it as available in the United States, Canada, Mexico and Japan on an iPhone 14 or later, with iOS 18 or later in the United States, and its Emergency SOS page (published 5 October 2026) lists 21 countries and regions. Each of these is a statement about one country, one operator, one set of devices and one date. None of them says anything about another country or another phone.

What a quote or a data sheet should contain

A supplier's data sheet usually gives a peak rate, a coverage map and a price. The two pages of the Link Ledger ask for more. Figure 12.1 turns them into twelve lines to send to a supplier before a contract. A supplier may decline some of them; a declined line is itself a

finding, and it belongs in field 10 of the service ledger as "not published". How such lines become enforceable terms of a contract is a separate subject and is not taken up here.

FIGURE 12.1

Twelve lines to ask a supplier for, taken from the two pages of the Link Ledger

#	Line	What to ask for	Ledger field
1	The requirement the service is sold against	Rate up and down, availability, where, at the busy hour	1, 5
2	The path	Transparent, regenerative or crosslinked; my gateway; where traffic exits	2
3	Time in view	Contact minutes per day at my site; handover gaps	3
4	Band and permission	Band of each hop; who holds it in my country; terminal approval	4
5	The terminal	EIRP, G/T, antenna, pointing, minimum elevation	2, page 2
6	The satellite toward my site	EIRP and G/T toward my site, or the budget that solves for them	page 2
7	The waveform	Modulation and code at my margin; required Eb/N0, Es/N0 (with its symbol rate) or C/N0, and its source	page 2
8	The budget	Both directions: reference plane, operating point, margin	page 2
9	Delay	Round trip from my application's server, over a pass and a day	3
10	Sharing	Capacity per beam and how it is shared at the busy hour	5
11	Trust and failure	Who commands, whose keys, how the terminal is updated, which logs I get	7, 8

#	Line	What to ask for	Ledger field
12	Cost shape and exit	What is fixed, what scales, what happens if the operator stops	6, 9

Each line maps to a field of the service ledger or to the hop budget; a line the supplier declines is recorded as not published.

Author's table based on the Link Ledger of this book (Appendix A).

What to measure, and how to keep the log

A ledger is a prediction. A measurement log checks it. The log needs few columns, all dated and timed: throughput up and down at the application, round trip delay from the application's own server (chapter 10), outages with their start and end, and the conditions at the time, such as weather and elevation where they are known. Each row names who measured it and with what. A measurement the supplier reports, without a record the buyer can check, is an operator claim; a measurement made by the buyer on the buyer's equipment, or by a named party whose record can be checked, is measured, by that party. Keeping such a log so that it can be trusted later is a records problem that this book does not take further.

The log is compared with the ledger at the same operating point. A service that meets its rate at noon in clear sky and fails at the busy hour points first to sharing (chapter 1), though interference or a changed operating point can also explain it. A service whose delay is half a second through a low orbit path is spending the time somewhere other than the radio legs: in processing, in routing between satellites, or on the ground (chapter 10). The comparison does not prove a cause; it tells the buyer which line of the ledger to question first.

The bench link as an exercise

The bench link is the method at its smallest, set as an exercise for the reader: prediction first, then the recording, then the comparison on one page. The author has not run it, and the book's conclusions do not depend on it. Its ledger, LL-2026-03, is complete as a prediction. Page 1, printed in chapter 2, states the requirement, the orbit (a mean altitude of 824 km, 98.7 degrees inclination and a 101.2 minute period, calculated from the public element set for NORAD 59051, epoch 23 November 2026, 07:06 UTC), the passes, the band and the owners. Page 2 is a sensitivity range, because the operator's transmit power and antenna pattern were not found in any document read. Instead of claiming that the link closes, page 2 asks what the satellite must radiate toward the station for the hop to close with 3 dB of margin.

At 20 degrees elevation, with the listed 80 kbit/s taken as the information rate (the cautious reading until the format document says which rate it is) and a required Eb/N0 of 4.5 dB taken as a stand-in from the DVB-S table for its rate 1/2, constraint length 7 convolutional code, the answer depends mostly on the site:

The satellite EIRP the bench link needs for 3 dB of margin (calculated, LL-2026-03)

Site and geometry	System noise temperature	EIRP needed
Quiet site (galactic noise), 20 degrees	1,416 K	5.3 dBW
Rural site (median man-made noise plus galactic), 20 degrees	3,218 K	8.8 dBW
Residential site (median man-made noise plus galactic), 20 degrees	7,523 K	12.5 dBW
Quiet site, 10 degrees	1,416 K	7.8 dBW
Quiet site, 60 degrees	1,416 K	-0.5 dBW
Quiet site, overhead	1,416 K	-1.6 dBW

Two things stand out. The site costs more than the geometry: moving the same dipole from a quiet site to a residential one raises the EIRP the satellite would need by 7.3 dB, more than going from 20 degrees down to 10. And with the satellite EIRP frozen at the quiet-site value, the residential case does not close: it is 4.3 dB below zero margin, 7.3 dB short of its 3 dB design minimum, and the line that fails is the system noise temperature. The noise values come from the median man-made noise of ITU-R P.372 (the 2001 edition was read), with the galactic noise added, since a noisy site does not remove the sky; they are medians for categories of site, not a measurement of any site. The reader's next step is a measurement: a noise survey of 137 to 138 MHz at the real site, then a recorded pass. Until a reader makes one, the line that matters most on the ledger reads "measured: none yet".

LINK LEDGER · LL-2026-03 · HOP BUDGET · THE BASELINE

Baseline · Downlink, quiet site

Meteor-M N2-4 (LRPT) to Horizontal dipole and receive-only radio · 137.9 MHz · 1,812 km slant range · reference plane: the dipole's terminals; the radio is connected at the antenna

Part	Line	Value	dB, and the level after	Evidence	Source and date
TRANSMIT POWER AND ANTENNA GAIN	Satellite EIRP (solved)	5.3 dBW	**+5.3** level 5.3 dBW	calculated	Solved here; not published, 2026-11-23
LOSSES	Free space path loss	1,812 km at 137.9 MHz	**-140.4** level -135.1 dBW	calculated	Appendix B formula, 2026-11-23
	Polarization, circular to linear	3.0 dB	**-3.0** level -138.1 dBW	calculated	10 log10(2); RHCP per WMO OSCAR, 2026-11-23
	Ionospheric scintillation	1 dB	**-1.0** level -139.1 dBW	assumption	To verify: ITU-R P.531, 2026-11-23
RECEIVE SENSITIVITY	Dipole gain toward the satellite	0 dBi	**+0.0** level -139.1 dBW	assumption	To verify: antenna model, 2026-11-23
	System noise temperature	1,416 K	**-31.5** level -170.7 dBW/K	calculated	551 K (ITU-R P.372-7, galactic) + 290 (F - 1), NF 6 dB to verify, 2026-11-23
	Boltzmann's constant, subtracted	-228.6 dBW/K/Hz	**+228.6** level 57.9 dBHz	standard	SI 2019, 2026-11-23
BANDWIDTH	Rate, taken as information rate	80 kbit/s	**-49.0** level 8.9 dB	operator claim	WMO OSCAR, 2026-11-22
INTERFERENCE	Interference, C/N0 to C/(N0+I0)	I0/N0 = -10 dB	**-0.4** level 8.5 dB	assumption	To verify: site survey, 2026-11-23
CODING	Modulation and code	QPSK, coded		assumption	To verify: CGMS LRPT specification, 2026-11-23
	Implementation loss	1.0 dB	**-1.0** level 7.5 dB	assumption	To verify: test recordings, 2026-11-23
REQUIRED SIGNAL QUALITY	Required Eb/N0	4.5 dB	**4.5**	standard	EN 300 421, Table 3 (stand-in), 2026-11-23
RESULT	**Achieved Eb/(N0+I0): the sum of the lines above**		**7.5**	calculated by this ledger	
	Required Eb/(N0+I0) for bit error ratio 2e-4 after Viterbi decoding (quasi error free after Reed-Solomon, in the stand-in standard)		**4.5**	from the line above	
	Margin: achieved less required		**+3.0**	design minimum 3.0 dB	

Closes: margin +3.0 dB (design minimum 3.0 dB)

Operating point. 80 kbit/s, satellite to a receive-only station, 20 degrees elevation, clear sky, quiet site (galactic noise only); one pass; availability not assessed
Required Eb/(N0+I0), 4.5 dB: source. EN 300 421, Table 3 (stand-in), 2026-11-23

Assumptions. A prediction; measured: none yet. EIRP solved, not known; code chain and required Eb/N0 are stand-ins to verify.

LINK LEDGER · LL-2026-03 · HOP BUDGET · CASE A OF THE BASELINE

Case A: Same downlink, residential site (median man-made noise)

Meteor-M N2-4 (LRPT) to Horizontal dipole and receive-only radio · 137.9 MHz · 1,812 km slant range · reference plane: the dipole's terminals; the radio is connected at the antenna

Part	Line	Value	dB, and the level after	Evidence	Source and date
The other 10 lines are as in the baseline: not repeated here, and counted in the sums below.					
TRANSMIT POWER AND ANTENNA GAIN	Satellite EIRP (frozen)	5.3 dBW	**+5.3** level 5.3 dBW	calculated	Solved here; not published, 2026-11-23
RECEIVE SENSITIVITY	System noise temperature	7,523 K	**-38.8** level -177.9 dBW/K	calculated	6,107 K residential + 551 K galactic (ITU-R P.372-7) + 290 (F - 1), NF 6 dB to verify, 2026-11-23
RESULT	**Achieved Eb/(N0+I0): the sum of the lines above**		**0.2**	calculated by this ledger	
	Required Eb/(N0+I0) for bit error ratio 2e-4 after Viterbi decoding (quasi error free after Reed-Solomon, in the stand-in standard)		**4.5**	from the line above	
	Margin: achieved less required		**-4.3**	design minimum 3.0 dB	

Does not close: short by 4.3 dB, and by 7.3 dB against the design minimum of 3.0 dB

Operating point. 80 kbit/s, satellite to a receive-only station, 20 degrees elevation, clear sky, residential site (median man-made noise); one pass; availability not assessed
Required Eb/(N0+I0), 4.5 dB: source. EN 300 421, Table 3 (stand-in), 2026-11-23
Line that fails. System noise temperature: median residential man-made noise raises it from 1,416 K to 7,523 K, 7.3 dB worse, with the satellite EIRP frozen at the quiet-site value

Assumptions. A prediction; measured: none yet. EIRP solved, not known; code chain and required Eb/N0 are stand-ins to verify.

The 2026 message

The prologue asked whether an adjuster in 2026, with her own phone and no tower in reach, could send a message by satellite. The answer depends on four facts that must all be true on the same date: the country, the operator, the device and the service. The scene follows one path that could be confirmed on the book's date, Apple's Messages via satellite in the United States, and Figure 12.2 draws it hop by hop with the evidence class of each step. Apple's page names the satellite network's provider, Globalstar or third-party providers, but not the orbit; the orbit decides the delay of every message (chapter 6), so it is the first question to the supplier.

RECONSTRUCTION · 2026 · THE REPORT FROM OUT OF REACH

The message	The adjuster's own phone, no tower in reach.
The link	Direct to device
Note	Only a service commercially launched in that country before the book's date; Appendix D dates the newest record of each status.

A reconstruction: the insurer is invented and illustrative. The link is the documented service of that year.

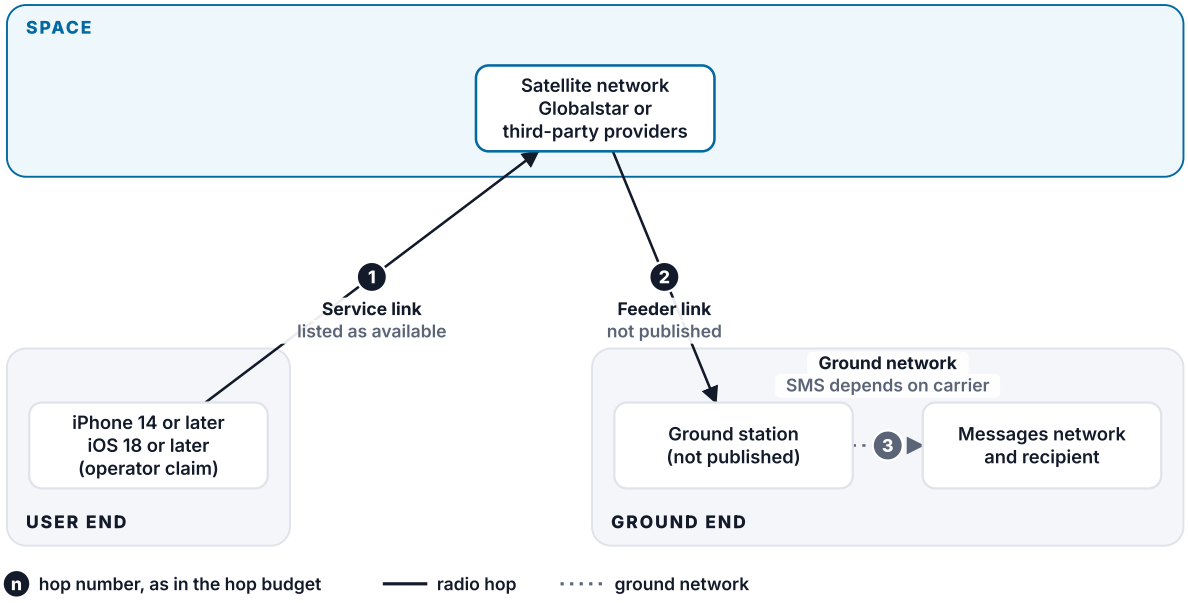
The 2026 message: what could be confirmed on 24 November 2026

Item	What was read	Class
Country	The United States (the page also lists Canada, Mexico and Japan)	operator claim
Operator and service	Apple, Messages via satellite; satellite network provided by Globalstar or third-party network providers, as the page's footnote says	operator claim
Device	An iPhone 14 or later, iOS 18 or later in the United States	operator claim
Conditions and limits	Outside, with a clear view of the sky; a message might take 30 seconds in ideal conditions and over a minute under light foliage; no photos, videos or group messages; SMS depends on the carrier; not for emergencies	operator claim
Date	Apple Support, About Messages via satellite, page published 15 May 2026, read 24 November 2026	operator claim

So the scene ends this way on 24 November 2026. If the adjuster's own phone is an iPhone 14 or later on a current system, she steps outside, finds open sky, and sends her text by satellite; in ideal conditions, Apple says, a message might take 30 seconds to send. Her photos do not: the service carries no pictures, so the claim waits for a tower or a terminal. For a genuine emergency the same phone has Apple's separate Emergency SOS via satellite.

FIGURE 12.2

The 2026 message: Apple's Messages via satellite in the United States, and how each step is known



A text from an iPhone 14 or later in the United States up to a satellite of the network Apple names, down to a ground station and on to the recipient, with the evidence class of each step as read on 24 November 2026.

Author's diagram based on Apple Support, About Messages via satellite, published 2026-05-15, read 2026-11-24. The page names the satellite network's provider but not the orbit, the ground stations or the link figures.

Other direct to device paths had been announced or launched in the United States before the book's date; they are kept apart from the scene because their status on that date could not be confirmed the same way. Each row is one operator, one set of devices and one date, and says nothing about the others.

For comparison: other direct to device paths, as read from 22 to 24 November 2026

Path	What was read	Class	Status on the book's date
Verizon with Skylo	Texting to any device on select Galaxy S25 and Pixel 9 phones from 19 March 2025 (Skylo newsroom); coverage "not complete, uniform, or comprehensive worldwide"; Skylo uses licensed mobile satellite spectrum (Verizon News, 2024-08-28)	operator claim	Not confirmed: the carrier's own page could not be read
T-Mobile with Starlink	Satellite texting launched commercially on 23 July 2025 (Broadband Breakfast)	operator claim (trade press)	Not confirmed from the carrier's own page
Apple Emergency SOS via satellite	iPhone 14 or later, 21 countries and regions; emergencies only, with no cellular or Wi-Fi coverage (Apple Support, page published 5 October 2026)	operator claim	Listed as available; not a routine message path

THE SYSTEM'S FAILURE

BlueBird 7, April 2026. AST SpaceMobile's update to investors of 9 November 2026 lists BlueBirds 1 to 6 and 8 to 13 as unfolded and in operation, and its reconciliation notes a decrease in gross property "due to BB7 write off" in the second quarter of 2026 (SEC, Form 8-K exhibit 99.2). Trade press reported that the satellite was lost after a New Glenn upper stage left it too low in April 2026 (Spaceflight Now). The same filing targets about 45 BlueBirds in orbit by the middle of 2027. The lesson the sources support is about evidence, not about this company: a constellation schedule is an operator claim until the satellites are operating, and a plan that depends on a number of satellites should carry that number with its date and its class.

SECURITY NOTE

Who can interfere or command. Field 7 of the service ledger asks who can command the satellite, whose keys protect the traffic, and how the terminal is updated. For a broadcast like the bench link the answers are "the operator" and "none documented"; the station still runs a radio driver, a decoder and an operating system whose updates must be trusted, and a decoder parses whatever arrives. For a commercial service they are the supplier's answers, and they are contract terms, not brochure lines. **How it is seen.** The buyer's own log: unexpected terminal updates, changes in where traffic exits, signal behavior that does not match the prediction. **How it is recovered.** What the contract says about notification, key changes and the right to audit; if it says nothing, that is the finding to record.

Bench step: what it requires

Two exercises would test this chapter's method, and both are written here as what they require. The first measures a service in use against its ledger: a terminal or a messaging plan, and a dated log of throughput up and down, delay and outages, kept as described above. Its evidence would be that log, set against the ledger's operating point. The second predicts and measures the bench link: a station (a dipole, a receive-only radio, a computer), a noise survey of the site, a pass prediction from a current element set, a recording with its time, place and settings, and a decode. Its evidence would be the received signal and the frame error counts against elevation, and the recorded carrier frequency laid over the Doppler prediction of chapter 6, on one page with the hop budget. Neither has been run for this book; both are left to the reader, and nothing in the book waits on them. When one is run, each ledger line it settles changes class, and not before.

Monday rule: fill both pages for the service you already use; the empty fields are your questions for the supplier.

CLOSING

Epilogue: Who Supplies the Margin Next



In 1962 the ground supplied almost all of the margin: a horn-reflector antenna with 3,600 square feet of aperture, a maser receiver, a transmitter of 2 kW (Hoth, O'Neill and Welber, The Telstar Satellite System, Bell System Technical Journal, July 1963). In 2026 a phone in a pocket can send a message to a satellite, because the satellite and the operator's ground now carry the work the user's end cannot. Every chapter of this book has read the same two pages, and the same few lines on them keep moving. This epilogue names four of them, with the dated evidence that they are moving, and keeps the forecast in a labeled box.

Array area in orbit

The line that moves most visibly is the satellite's receive gain, which is antenna area. A phone cannot grow, so the satellite does. In its business update of 9 November 2026, AST SpaceMobile described the array of its second-generation BlueBird satellites as about 2,400 square feet, against about 700 for the first generation (SEC filing, exhibit 99.2). That is one operator's design, not a requirement of direct to device service: Chapter 4's model ledger shows that the area a satellite needs depends on the rate, the phone's power, the losses on the path and the noise, and other operators make other choices.

Larger arrays bring their own lines. A large array needs power and processing to form its beams, it must be unfolded in orbit, and every satellite lost costs more. The same filing records that one satellite of the fleet, BlueBird 7, was written off; Chapter 12 tells that case.

Processing on board

The second line is the place of the switch. Chapter 8 followed it from the ground (Globalstar, 2000) to orbit (Iridium, 1998), and the mobile standards are making the same move: 3GPP Release 17 supports transparent payloads only, and Release 19 adds regenerative payloads with the base station, or part of it, on the satellite. Old satellites can take on new work when their payload is programmable: Iridium announced on 17 November 2026 that it had activated a standards-based narrowband service on its existing constellation (operator

claim, Via Satellite, trade press). Processing on board recovers the bits in orbit; it is crosslinks or storage on board, not processing alone, that remove the need for a gateway in view. All three cost power, heat and software that must be protected and updated.

Light between satellites

The third line is the crosslink. Chapter 9 showed relays and constellation crosslinks moving from demonstration to sale: a commercial optical relay service announced on 24 August 2026, and laser terminals sold to other satellite builders (both trade press). When satellites can pass traffic among themselves, the ground segment shrinks to the places where the operator chooses to land the traffic, and those places become concentrated points of law and inspection, alongside the spectrum rules of each user's country and the authority over the spacecraft. What is still thin is the link between terminals of different makers, which the failure of Chapter 9 records.

Permission on the ground

The fourth line is not physics. Field 4 of every service ledger, band and permission, decides whether a hop that closes may be used. In the United States the Federal Communications Commission adopted a new framework for space licensing, Part 100, on 22 July 2026; its effective date was not set when this book checked. Until it takes effect, Part 25 applies. For direct to device, the Commission's supplemental coverage framework lets a satellite operator use a mobile carrier's terrestrial spectrum, with phones licensed by rule. How permission works, country by country, is covered in depth later in this series.

WHAT HASN'T CHANGED

Every hop in this book, from Telstar's 6,390 MHz uplink in 1962 to a laser downlink in 2023, was added up the same way: power, gains and losses in decibels, against what the receiver needs at a stated operating point. The arithmetic did not change. What changed is who could afford each line. A ground station could afford a maser and a horn in 1962; a phone cannot afford a dish in 2026, so the satellite carries the area. Cloud can still make a laser downlink unavailable, and building entry loss can still defeat a handset, as the first filings warned. A reader who checks which line a new system has moved, and who supplies it, has asked the right question of it.

OUR VIEW, AS OF NOVEMBER 2026

The margin is moving off the user's end and onto the satellite and the operator's ground, and we expect that to continue, within the limits of power, mass and cost in orbit, while users expect an ordinary phone to work. The consequence for a buyer is that more of every ledger becomes operator claim: the satellite's G/T, the array's scan loss, the processing on board and the crosslinks are all on the operator's side, and few of them are published. The two pages of this book do not get easier to fill. They get more important, because the empty fields are the questions a supplier has to answer.

Where the series goes next

- **Book 2** follows the history: how each system from Telstar to the phone in a pocket divided the power, antenna area and processing between the user's end, the satellite and the ground, and what limits drove that split.
- **Book 3** reads today's constellations and direct to device services as networks a buyer can choose between.
- **Book 4** covers spectrum, permission and debris: who must agree before a hop may be used.
- **Book 5** covers what can be rented before anything is built: ground access, relay and capacity.
- **Book 6** covers satellite data and positioning, the one way links a buyer receives as a product.
- **Book 7** covers computing in orbit, the processor behind every regenerative payload.
- **Book 8** covers flight software, code that runs where nobody can reach it.

Each of them uses the same two pages. The reader who can fill them for one link can read the rest.

APPENDICES

APPENDIX A

The Link Ledger: Blank, Field Guide and Index

This appendix holds the form itself: page 1 blank with its field guide, page 2 blank for a radio hop and for an optical hop, a short guide to filling each part, and the index of every worked example in this book. Copy the blank pages, or use the workbook that comes with the book, which carries the same fields and live formulas for page 2.

How to fill page 1, the service

Page 1 describes the service before any budget is drawn. Fill it in the order of the fields, and write a date on it: most of what it holds changes.

- **1 Requirement.** The six numbers of chapter 1: message size, deadline, rate up and down, coverage, availability, and the terminal's limits. A requirement without a date and a place is a wish.
- **2 Ends and path.** Who talks to whom, and the path as it really is: transparent, regenerative, crosslinked, or store and forward. The path decides how many hop budgets page 2 needs.
- **3 Orbit and time.** The altitude, whether contact is continuous or by passes, the delay one way and for a reply, and the Doppler a terminal must follow.
- **4 Band and permission.** The frequencies of each hop, who holds the right to use them, under which rule and in which country. "Not assessed" is an honest entry; a blank is not.
- **5 Capacity.** Up and down separately, peak against sustained, and how many users share it.
- **6 Who owns each end.** The space segment, the ground segment, the customer relationship, and the exit: how the user leaves.
- **7 Trust.** Who can command the satellite and the terminal, whose keys protect the traffic, how updates arrive, and how jamming or spoofing would be noticed.
- **8 How it fails, and how it would be seen.** Name the silent failure, the one that produces no alarm, and the record that would show it.
- **9 Cost shape.** Per minute, per megabyte, per month or per terminal. A price only with its date and what it leaves out.
- **10 Evidence.** The few numbers that carry the argument, each with its class, its source and the date it was read.

How to fill page 2, one hop

One block for each radio or optical hop. Name the reference plane first. Then fill the parts in order, each line with a signed number in decibels, a class, a source and a date: transmit, losses, receive, bandwidth or rate, interference, coding, and the required value. Choose the rate line by the required value: subtract the information rate to compare with a required Eb/N0, the symbol rate to compare with a required Es/N0 (as the DVB-S2 tables give it, and as chapter 4's Ka band example does at 100 Mbaud), or the noise bandwidth to compare with a required C/N. A required C/N0 needs no rate line at all. The sum of every line except the required value is the achieved value; the margin is achieved less required. Write the operating point (rate, direction, elevation, weather, designed availability) before the margin, so the margin cannot pick its own conditions. A transparent satellite needs two hop pages and the combined line of Appendix B, section B.5. An optical hop names its receiver, direct detection or coherent, and replaces the noise lines with the receiver's sensitivity and the background light.

Where a supplier does not publish a line, do not invent it. Solve for it, as chapter 4 does for a satellite's G/T, and write what the solved value means: what the system must have, not what it has. Where a hop does not close, print it anyway and name the line that fails and by how many decibels.

The classes of a number

Class	Use it when
measured	Read from an instrument or a log, by a named party, on a date
calculated	It follows from stated inputs by a formula the text gives
simulated	A model produced it; the model and its settings are named
operator claim	The operator or supplier stated it and nobody independent checked it
standard	A published standard or regulation gives it; the clause or table is named
assumption	No primary source has been read yet; printed as "assumption, to verify", with what would settle it
published history	An official agency history or audit report, such as NASA's history of satellite communications, or labeled scholarship reports it; name the work and the page. Use it for what the history reports, not for an engineering value it quotes from a source you can read yourself

Only these seven classes are used. A regulator's order or authorization is a standard, labeled a regulatory document; trade press reporting an operator's announcement is an operator claim. An operator's figure is never promoted to measured. A study's evaluation value, such as those of 3GPP TR 38.821, is a standard document's number but not a requirement; say so on the line.

Index of the worked examples

Every worked example in this book, with its class and what its page 2 shows. The model phone uplink is printed once, in chapter 4, and is not repeated here.

The worked Link Ledgers in this book

Id	Date	System	Class	Status	Budget	Requirement	PDF page
LL-1962-01	1962-07-10	Telstar 1: one television channel across the Atlantic through a transparent satellite	full	Retired	closes	Carry one television channel with sound, or the equivalent of 600 one way telephone channels, between Andover, Maine and stations in France and Britain while the satellite is in view of both. An experiment: commercial grade quality was the aim, not a contract.	12, 58 to 59
LL-1976-01	1976	Marisat, ship to shore (telephone and telex)	service only	Retired	service only	Telephone and telex between merchant ships at sea and the shore network: Atlantic and Pacific regions from summer 1976, Indian Ocean from November 1978. A ship pays for a terminal; the Navy pays for UHF channels on the same satellites.	38
LL-1998-01	1998-11-01	Iridium handset voice call (first generation) (illustrative model)	full	Retired	closes (baseline); stress case A fails, as intended	A voice call from a handheld phone with open sky anywhere on Earth, oceans and poles included, to any telephone. Commercial service began on 1 November 1998.	97 to 99
LL-2000-01	2000	Globalstar call through a transparent satellite (first generation)	service only	Retired	service only	A voice or data call from a handset wherever a gateway sees the same satellite as the handset. Commercial service began in early 2000.	93

Id	Date	System	Class	Status	Budget	Requirement	PDF page
LL-2000-02	2000-05-02	GPS L1 C/A, satellite to any receiver (civil signal after Selective Availability)	full	In service	closes	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.	67 to 68
LL-2011-01	2026-11-23	A Ka band spot beam, representative: geostationary forward link to a consumer dish	budget only	Planned	closes (baseline); stress case B fails, as intended; case A closes	Budget only: see page 2.	166 to 168
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.	108
LL-2022-01	2022-11-15	Emergency SOS via satellite on the iPhone 14 lineup (Apple; Globalstar as satellite operator)	service only	In service	service only	From outside cellular and Wi-Fi coverage, get a short emergency message, the answers to a short questionnaire and the user's location to emergency services: directly where they accept text, otherwise through a relay center. Open sky; the phone shows where to point it.	20
LL-2023-01	2026-11-23	The generic 10 Gbit/s laser downlink: a small satellite to one optical ground station (a model, not a mission)	budget only	Planned	closes (baseline); stress case A fails, as intended	Budget only: see page 2.	110 to 111

Id	Date	System	Class	Status	Budget	Requirement	PDF page
LL-2026-01	2026-11-23	A phone uplink to a low orbit satellite near 1.9 GHz (hypothetical model ledger)	full	Planned	closes (baseline); stress cases A and B fail, as intended	Hypothetical, labeled so. One phone sends 64 kbit/s of information up to a low orbit satellite in open sky at 30 degrees elevation, with 3 dB of design margin. Stress cases: 10 Mbit/s (case A) and a stated 10 dB obstruction (case B).	55 to 57
LL-2026-03	2026-11-23	Meteor-M N2-4 LRPT at 137.9 MHz to a dipole and a receive-only radio (the bench link)	full	Planned	closes (baseline); stress case A fails, as intended	Decode one pass of the 80 kbit/s LRPT weather broadcast on a dipole and a receive-only radio, with 3 dB of margin at 20 degrees elevation in clear sky. Measured: none yet.	30, 141 to 142
LL-2026-04	2021 to 2023 (historical)	Low orbit broadband: terminal, satellite, ground station, PoP (one operator, many users' sites)	service only	Not checked	service only	Illustrative: a field office needs 25 Mbit/s down, 3 Mbit/s up and a reply under 100 ms in the busy hour, 99 percent of each month.	121

A full ledger has page 1 and one budget block per hop; a service-only ledger stops at page 1 and says why there is no budget; a budget-only ledger is page 2 alone, used where the service around the hop is not the point.

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

LINK LEDGER · BLANK · OPTICAL HOP BUDGET

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

From ____ to ____ · wavelength · range · direct detection or coherent · stated rate

Part	Line	Value, in its own unit	dB, signed	Evidence	Source and date
TRANSMIT OPTICAL POWER AND APERTURE	Transmit optical power (dBm)				
	Transmit gain, from aperture and beam divergence				
LOSSES	Range loss				
	Pointing loss				
	Atmospheric and cloud loss				
RECEIVE APERTURE	Receive aperture gain				
	Receive optics loss				
RECEIVER SENSITIVITY	Sensitivity in dBm at the stated rate, in the dark (convert photons per bit to dBm first)				
	Background light: the rise in the sensitivity it causes (dB, positive)				
RESULT	**Achieved received power (dBm): the sum of every line above the required one**			calculated	
	Required: the sensitivity plus the background light, in dBm at the stated 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:

How to add it up. Write every line in decibels with its sign: gains positive, losses negative. Start from the transmit power in dBm and keep every line in dB, so the sum is a power in dBm. The received power is the sum of every line above the sensitivity. Background light does not lower the received power: it raises the power the receiver needs, so it is added to the sensitivity. The margin is the received power less the required power. Cloud is a line, not a footnote: write the budget for clear air and again for the cloud you must survive.

APPENDIX B

The Decibel and the Budget Sheet

A hop budget is one long addition. This appendix gives its unit, the formula of each line, the way two hops combine, the constants and one worked example. Every value was computed from the stated inputs and rounded once, at the end; repeating the arithmetic gives the same digits.

B.1 The decibel

A decibel is ten times the base-10 logarithm of a power ratio. A ratio of 1,000 is 30.0 dB; a ratio of 2 is about 3 dB (3 dB is a ratio of 2.00 to three significant figures). Because the logarithm of a product is the sum of the logarithms, a chain of gains and losses that multiply in watts adds in decibels.

A decibel is a ratio, so a power needs a reference. Two are used in this book:

Unit	Reference	Example
dBW	1 watt	0.2 W is -7.0 dBW
dBm	1 milliwatt	0.2 W is 23.0 dBm

The two differ by exactly 30 dB. A phone of power class 3 has a nominal maximum output of 23 dBm, about 200 mW; its standard allows a tolerance of plus or minus 2 dB around it, and allows the phone to reduce its maximum for some waveforms and allocations. Other units in a budget: dBi is antenna gain against an ideal antenna that radiates equally in all directions; dBK is a temperature in kelvin, in decibels; dB/K is a gain-to-noise-temperature ratio; dBHz is a bandwidth in decibels relative to 1 Hz; a rate is written the same way relative to 1 bit/s, so 64 kbit/s is 48.1 dB and 10 Mbit/s is 70.0 dB, and subtracting it from C/N0 gives Eb/N0.

Rule for the page: gains carry a plus sign, losses a minus sign, and every line says its unit. A number without a sign and a unit is not a budget line.

B.2 Constants

Constant	Value	Source
Speed of light, c	299,792,458 m/s (exact)	SI definition
Boltzmann's constant, k	1.380649e-23 J/K (exact); in decibels -228.6 dBW/K/Hz	SI, 2019
Mean Earth radius	6,371 km	the value used for every slant range in this book
Earth's gravitational parameter	3.986004418e14 m^3/s^2	WGS 84

B.3 The lines of one hop, in order

The budget runs from the transmitter to the decoder. Each line below names its formula and its unit.

1. **Transmit power**, in dBW, at a named point: the amplifier output, or the antenna connector. That point is the **reference plane**. A feeder loss counts only if it sits between the reference plane and the antenna.
2. **EIRP**, the equivalent isotropically radiated power: EIRP = P - L(feeder) + G(transmit), in dBW. It is the power an ideal isotropic antenna would need to give the same signal in the direction of the receiver.
3. **Free-space path loss**: L(fs) = 20 log10(4 pi d / lambda), in dB, with d and lambda in the same unit (ITU-R P.525-5, November 2024, equation 5). With the frequency f in hertz, lambda = c / f. The recommendation's equation 6 gives the same loss as 32.4 + 20 log10(f) + 20 log10(d) with f in megahertz and d in kilometers; the constant is 32.45 before rounding, and with f in gigahertz it becomes 92.45. The exact form gives 153.3 dB at 2 GHz over 550 km; equation 6 as printed gives 153.2 dB, the rounding of its constant. Over 5 km at the same frequency the free-space loss is 112.4 dB, so the gap between a low orbit satellite and a nearby cell is 40.8 dB in free space (20 log10 of the distance ratio, 110). A real cell usually loses more than free space, so the gap is a reference, not a comparison of two real links.
4. **Slant range**: a satellite at altitude h seen at elevation e is at d = sqrt(R^2 sin^2(e) + 2Rh + h^2) - R sin(e), with R, h and d in the same unit. At 600 km altitude the range is 600 km straight up, 1,075 km at 30 degrees and 1,932 km at 10 degrees. Low elevation costs range, and range costs decibels: 30 degrees instead of straight up costs 5.1 dB at any frequency.
5. **Named losses**, each on its own line, each with its source: atmospheric gases, rain, ionospheric scintillation, a shadowing margin, polarization mismatch, the user's body, an obstruction. A loss without a source is an assumption and is marked so.

6. **Receive G/T**, in dB/K: G/T = G(receive) - 10 log10(T(sys)), with the gain and the noise temperature referred to the **same plane**. At the antenna terminal, the gain is the antenna's and a feeder before the receiver is inside the temperature, T(sys) = T(antenna) + (L - 1) T(p) + L T(r), with L the feeder loss as a ratio, T(p) its physical temperature and T(r) the receiver's noise temperature. At the receiver input, the gain is reduced by the feeder loss and the temperature is referred there. Do not do both. With the receiver connected directly to the antenna, T(sys) = T(antenna) + 290 (F - 1), F being the noise figure as a ratio. A handheld receiver with an antenna temperature of 290 K and a noise figure of 7 dB has T(sys) = 1,453 K. A satellite antenna of 30 dBi with a system noise temperature of 776 K has G/T = 1.1 dB/K.
7. **Carrier to noise density**: C/N0 = EIRP - L(fs) - (sum of losses) + G/T - k, in dBHz. Subtracting k, a negative number, adds 228.6 dB.
8. **Interference** is a line, not a remark. If the interference density is I0 and r = I0/N0 in decibels, the step from C/N0 to C/(N0+I0) is -10 log10(1 + 10^(r/10)), treating the interference as noise-like. Interference 6 dB below the noise (a ratio of 10^(-0.6), about 0.25) costs 1.0 dB; interference equal to the noise costs 3.0 dB. Interference with structure (a strong narrow carrier, a pulsed source) needs a waveform-level analysis instead.
9. **Rate**: Eb/(N0+I0) = C/(N0+I0) - 10 log10(R), with R the information rate in bit/s (not the symbol rate); 10 log10(R) is a rate written in decibels, not a bandwidth. Or, in a bandwidth B, C/(N+I) = C/(N0+I0) - 10 log10(B). Say which. Without interference these are Eb/N0 and C/N.
10. **Required value**: the Eb/N0, Es/N0 or C/N0 (or a C/N with its noise bandwidth) that the stated modulation and code need for a stated error rate, with its source; an Es/N0 also names the symbol rate it is counted at, plus an implementation loss for everything the ideal curve leaves out.
11. **Margin** = achieved less required, in dB. The hop closes at its operating point when the margin is at or above the design minimum written down before the budget was filled in.

    From a standard's Es/N0 to Eb/N0. A coding standard often gives the energy per transmitted symbol, Es/N0, and the spectral efficiency, the information bits carried per symbol. Then Eb/N0 = Es/N0 - 10 log10(efficiency). For QPSK with a rate 1/4 LDPC code, the DVB-S2 standard (ETSI EN 302 307-1 V1.4.1, Table 13: quasi error free, long frames, ideal synchronization) gives an ideal Es/N0 of -2.35 dB at 0.490243 bit per symbol: Eb/N0 = 0.7 dB. For QPSK 1/2 it gives 1.00 dB at 0.988858 bit per symbol: Eb/N0 = 1.0 dB. The standard itself says that a link budget must take the satellite channel's impairments into account; that is the implementation line. A curve from one standard used for a system built to another (DVB-S2 for a cellular uplink, say) is a stand-in: it gives a starting number, not that system's threshold, and the gap is not known to be small or large until a link-level result for the real waveform exists.

Rounding. Each line is rounded for print, but totals are computed before rounding. A column can therefore differ by 0.1 dB from the sum of its printed lines. The sheet says so instead of adjusting a line.

B.4 Antennas: gain and aperture

A circular aperture of diameter D has a linear gain g = eta (pi D / lambda)^2, where eta is the aperture efficiency and lambda = c / f; in decibels G = 10 log10(g). A 1 m dish at 2 GHz with an efficiency of 0.6 has 24.2 dBi. The inverse is the effective aperture, again with the linear gain: Ae = g lambda^2 / (4 pi), with g = 10^(G/10). An antenna of 30 dBi at 2 GHz has an effective aperture of 1.79 square meters. At 1.9 GHz the wavelength is 0.158 m.

Two warnings. A G/T does not give an area without three more numbers: the noise temperature; the directional reduction toward the user (the loss when an array steers its beam away from straight ahead, the edge of the beam, pointing error) together with any dissipative loss before the receiver; and the efficiency. So a conversion from G/T to area is a range with those three named. And an effective aperture is not a deployed area; whether many beams can each use the whole surface of an array depends on its architecture and processing.

B.5 Two hops through a transparent satellite

A transparent satellite repeats what it hears, noise included. The noise of the uplink and the noise of the downlink both reach the ground receiver, so the inverse carrier to noise ratios add, in linear terms:

```
1 / (C/N0)total = 1 / (C/N0)up + 1 / (C/N0)down
```

Convert each hop's C/N0 from dBHz to a linear value in hertz (70 dBHz is 10^7 Hz), add the inverses, invert the sum and convert back. Two hops of 70 and 73 dBHz give 68.2 dBHz; two equal hops of 70 dBHz give 67.0 dBHz, 3 dB below either. The total is below the weaker hop. The rule holds when the satellite is linear, the two noises are independent and both C/N0 values are referred to the same final carrier; amplifier distortion, intermodulation and interference each add a further term of the same form. Chapter 4 derives the rule and works Telstar 1 this way: hops of 90.6 and 88.6 dBHz combine to 86.5 dBHz. A regenerative satellite decodes and re-sends, so its two hops are budgeted separately and their error rates, not their noise, combine.

B.6 Delay and Doppler (check values)

Quantity	Formula	Value
Delay straight up, 600 km	d / c	2.0 ms
Delay straight up, 35,786 km (geostationary)	d / c	119.4 ms
Slant range to a geostationary satellite on the horizon	B.3 line 4, Earth radius 6,371 km	41,673 km
Delay at that range	d / c	139.0 ms
Orbital speed at 600 km	sqrt(mu / (R + h))	7.56 km/s
Largest Doppler shift as a fraction of the carrier, 600 km, satellite on the horizon	abs(delta f) / f = v R cos(e) / ((R + h) c)	23.1 parts per million; 46.1 kHz at 2 GHz

The shift itself is delta f = -f (dd/dt) / c, with dd/dt the rate of change of the range: positive (a higher frequency) while the satellite approaches, negative while it recedes. The figure assumes a circular orbit, a fixed user on a non-rotating Earth, in the plane of the orbit; the Earth's rotation changes it by a few percent. The delays are propagation only, before processing, scheduling and retransmission. A geostationary circuit through one satellite has two legs, up and down, so it takes about a quarter second one way, and a reply takes about half a second.

B.7 Worked example: one phone to one satellite

The inputs are a phone at its nominal 23 dBm with a 0 dBi reference antenna, a satellite at 600 km whose G/T toward the phone is 1.1 dB/K (an evaluation assumption that a 3GPP study uses for its first set of low orbit satellite parameters at 2 GHz, not a real satellite), a carrier at 2 GHz, an information rate of 64 kbit/s, and QPSK with a rate 1/4 LDPC code. The required Eb/N0 of 0.7 dB is the DVB-S2 ideal value used as a stand-in, and the implementation loss of 2.5 dB is an assumption to verify.

Step 1: straight up, free space only

Line	Value
EIRP: 23 dBm is -7.0 dBW, plus 0 dBi	-7.0 dBW
Free-space loss, 600 km at 2 GHz	-154.0 dB
Satellite G/T	+1.1 dB/K
Boltzmann's constant, subtracted	+228.6 dB
C/N0	**68.7 dBHz**
Information rate, 64 kbit/s	-48.1 dBHz
Eb/N0 achieved	**20.6 dB**
Required C/N0 (Eb/N0 0.7 dB + implementation loss 2.5 dB + rate 48.1 dBHz)	51.3 dBHz
Margin	**+17.4 dB**

Seventeen decibels looks comfortable, but nothing real has been added yet.

Step 2: 30 degrees, the named losses and the interference line

Line	Value
EIRP, as in step 1	-7.0 dBW
Free-space loss at the 1,075 km slant range	-159.1 dB
Atmospheric gases (assumption, to verify)	-0.1 dB
Ionospheric scintillation (3GPP study value)	-2.2 dB
Shadowing margin (3GPP study value)	-3.0 dB
Polarization mismatch, linear phone into circular reception (3GPP study value)	-3.0 dB
Body, hand, orientation and antenna efficiency (assumption, to verify)	-3.0 dB
Subtotal of the five named losses above (not a further line)	-11.3 dB
Satellite G/T, as in step 1	+1.1 dB/K
Boltzmann's constant, subtracted	+228.6 dB

Line	Value
C/N0	**52.3 dBHz**
Interference, I0/N0 = -6 dB (assumption, to verify)	-1.0 dB
C/(N0+I0)	**51.3 dBHz**
Eb/(N0+I0) achieved	**3.3 dB**
Required C/(N0+I0), as in step 1	51.3 dBHz
Margin	**0.0 dB**

The geometry, the losses and the interference cost 17.3 dB (the margins print as 17.4 and 0.0 because each is rounded once from 17.36 and 0.02). Under these assumptions the hypothetical hop reaches the decoding threshold with essentially no margin, and it does not meet a 3 dB design minimum; it says nothing about service or availability. Chapter 4 asks the question the other way round, at 1.9 GHz and a 3 dB design margin: the satellite needs 3.6 dB/K, 2.5 dB more than the study's value.

B.8 What a budget does not tell you

A budget gives the margin at one operating point: one rate, one direction, one elevation, one weather, one user. It does not give the availability over a year, the rate when many users share the beam, the time to acquire the signal, or the cost. Where an operator does not publish a power or a G/T, the budget solves for it and says so: the number describes what the satellite must have, not what any satellite has.

B.9 The Ka band forward link of chapter 4, in clear sky and in rain

The hop pages of chapter 4's third example, moved here so that the chapter keeps its argument and the appendix keeps the tables. The baseline solves the satellite EIRP for a 1 dB margin in clear sky; cases A and B add a stated 6 and 14 dB of rain. The rain values are a sensitivity study with no availability attached (chapter 4).

LINK LEDGER · LL-2011-01 · HOP BUDGET · THE BASELINE

2026-11-23 System: A Ka band spot beam, representative: geostationary forward link to a consumer dish

Planned | Class: budget only | Budget: closes (baseline); stress case B fails, as intended; case A closes

Baseline · Downlink, clear sky (16APSK 3/4)

Geostationary satellite, one spot beam to Consumer dish, 0.75 m · 19.7 GHz · 37,778 km slant range · reference plane: the satellite's radiated EIRP toward the site; the dish's noise referred to the input of its low noise block

Part	Line	Value	dB, and the level after	Evidence	Source and date
TRANSMIT POWER AND ANTENNA GAIN	Satellite EIRP toward the site (solved at clear sky)	56.8 dBW	**+56.8** level 56.8 dBW	calculated	Solved for 1 dB in clear sky, 2026-11-23
LOSSES	Free space path loss	37,778 km at 19.7 GHz	**-209.9** level -153.0 dBW	calculated	ITU-R P.525-5; Appendix B, 2026-11-23
	Atmospheric gases	0.6 dB	**-0.6** level -153.6 dBW	assumption	Assumption: ITU-R P.676, to verify, 2026-11-23
	Polarization and pointing	0.5 dB	**-0.5** level -154.1 dBW	assumption	Assumption: terminal data, to verify, 2026-11-23
RECEIVE SENSITIVITY	Dish gain, 0.75 m	41.9 dBi	**+41.9** level -112.2 dBW	calculated	Calculated: 0.75 m, efficiency 0.65 (both assumed), 2026-11-23
	System noise temperature (antenna 60 K, noise figure 1.2 dB)	152 K	**-21.8** level -134.0 dBW/K	calculated	Calculated: 60 K clear sky, rain radiating at 275 K, noise figure 1.2 dB (assumed; ITU-R P.618 to verify), 2026-11-23
	Boltzmann's constant	-228.6 dBW/K/Hz, subtracted	**+228.6** level 94.6 dBHz	standard	SI 2019, exact, 2026-11-23
BANDWIDTH	Symbol rate	100 Mbaud	**-80.0** level 14.6 dB	assumption	Assumption: one 100 Mbaud carrier, 2026-11-23
INTERFERENCE	Interference from other beams, Es/N0 to Es/(N0+I0)	C/I 16 dB in the 100 MHz symbol rate	**-2.3** level 12.2 dB	assumption	Assumption: operator reuse analysis; held fixed in rain, 2026-11-23
CODING	Modulation and code	16APSK, LDPC rate 3/4, 2.966728 bit per symbol		standard	EN 302 307-1, Table 13, 2026-11-23
	Implementation loss	1 dB	**-1.0** level 11.2 dB	assumption	Assumption: modem result, to verify, 2026-11-23
REQUIRED SIGNAL QUALITY	Required Es/N0	10.21 dB	**10.2**	standard	ETSI EN 302 307-1 V1.4.1, Table 13, 2026-11-23
RESULT	**Achieved Es/N0: the sum of the lines above**		**11.2**	calculated by this ledger	
	Required Es/N0 for quasi error free (packet error ratio 1e-7) on the standard's ideal curve; the implementation loss is subtracted above		**10.2**	from the line above	
	Margin: achieved less required		**+1.0**	design minimum 1.0 dB	

Closes: margin +1.0 dB (design minimum 1.0 dB)

Operating point. 297 Mbit/s, satellite to dish, 40 degrees elevation, clear sky, design margin 1 dB
Required Es/N0, 10.2 dB: source. ETSI EN 302 307-1 V1.4.1, Table 13, 2026-11-23

Assumptions. Representative, not one operator's system. The satellite EIRP is solved; dish, noise, gases, pointing, interference and implementation are assumptions to verify. Rain lowers carrier and same-satellite interference together, so C/I is held fixed.

LINK LEDGER · LL-2011-01 · HOP BUDGET · CASE A OF THE BASELINE

Case A: Downlink, a stated 6 dB of rain (QPSK 3/5)

Geostationary satellite, one spot beam to Consumer dish, 0.75 m · 19.7 GHz · 37,778 km slant range · reference plane: the satellite's radiated EIRP toward the site; the dish's noise referred to the input of its low noise block

Part	Line	Value	dB, and the level after	Evidence	Source and date
The other 8 lines are as in the baseline: not repeated here, and counted in the sums below.					
LOSSES	Rain	6 dB	**-6.0** level -160.1 dBW	*assumption*	Assumption: a stated value, no site or percentile, 2026-11-23
RECEIVE SENSITIVITY	System noise temperature (antenna 221 K, noise figure 1.2 dB)	313 K	**-25.0** level -143.2 dBW/K	calculated	Calculated: 60 K clear sky, rain radiating at 275 K, noise figure 1.2 dB (assumed; ITU-R P.618 to verify), 2026-11-23
INTERFERENCE	Interference from other beams, Es/N0 to Es/(N0+I0)	C/I 16 dB in the 100 MHz symbol rate	**-0.4** level 5.1 dB	*assumption*	Assumption: operator reuse analysis; held fixed in rain, 2026-11-23
CODING	Modulation and code	QPSK, LDPC rate 3/5, 1.188304 bit per symbol		standard	EN 302 307-1, Table 13, 2026-11-23
REQUIRED SIGNAL QUALITY	Required Es/N0	2.23 dB	**2.2**	standard	ETSI EN 302 307-1 V1.4.1, Table 13, 2026-11-23
RESULT	**Achieved Es/N0: the sum of the lines above**		**4.1**	calculated by this ledger	
	Required Es/N0 for quasi error free (packet error ratio 1e-7) on the standard's ideal curve; the implementation loss is subtracted above		**2.2**	from the line above	
	Margin: achieved less required		**+1.8**	design minimum 1.0 dB	

Closes: margin +1.8 dB (design minimum 1.0 dB)

Operating point. 119 Mbit/s, satellite to dish, 40 degrees, a stated 6 dB of rain (a sensitivity value; no availability attached), design margin 1 dB
Required Es/N0, 2.2 dB: source. ETSI EN 302 307-1 V1.4.1, Table 13, 2026-11-23

LINK LEDGER · LL-2011-01 · HOP BUDGET · CASE B OF THE BASELINE

Case B: Downlink, a stated 14 dB of rain (QPSK 1/4)

Geostationary satellite, one spot beam to Consumer dish, 0.75 m · 19.7 GHz · 37,778 km slant range · reference plane: the satellite's radiated EIRP toward the site; the dish's noise referred to the input of its low noise block

Part	Line	Value	dB, and the level after	Evidence	Source and date
The other 8 lines are as in the baseline: not repeated here, and counted in the sums below.					
LOSSES	Rain	14 dB	**-14.0** level -168.1 dBW	assumption	Assumption: a stated value, no site or percentile, 2026-11-23
RECEIVE SENSITIVITY	System noise temperature (antenna 266 K, noise figure 1.2 dB)	359 K	**-25.5** level -151.8 dBW/K	calculated	Calculated: 60 K clear sky, rain radiating at 275 K, noise figure 1.2 dB (assumed; ITU-R P.618 to verify), 2026-11-23
INTERFERENCE	Interference from other beams, Es/N0 to Es/(N0+I0)	C/I 16 dB in the 100 MHz symbol rate	**-0.1** level -3.2 dB	assumption	Assumption: operator reuse analysis; held fixed in rain, 2026-11-23
CODING	Modulation and code	QPSK, LDPC rate 1/4, 0.490243 bit per symbol, the lowest mode of the table		standard	EN 302 307-1, Table 13, 2026-11-23
REQUIRED SIGNAL QUALITY	Required Es/N0	-2.35 dB	**-2.4**	standard	ETSI EN 302 307-1 V1.4.1, Table 13, 2026-11-23
RESULT	**Achieved Es/N0: the sum of the lines above**		**-4.2**	calculated by this ledger	
	Required Es/N0 for quasi error free (packet error ratio 1e-7) on the standard's ideal curve; the implementation loss is subtracted above		**-2.4**	from the line above	
	Margin: achieved less required		**-1.9**	design minimum 1.0 dB	

Does not close: short by 1.9 dB, and by 2.9 dB against the design minimum of 1.0 dB

Operating point. 49 Mbit/s attempted, satellite to dish, 40 degrees, a stated 14 dB of rain (a sensitivity value; how often it occurs needs a named site's statistics)
Required Es/N0, -2.4 dB: source. ETSI EN 302 307-1 V1.4.1, Table 13, 2026-11-23
Line that fails. Rain: 14 dB of rain and the noise it adds leave the lowest mode 1.9 dB short of zero margin and 2.9 dB short of the design minimum; no mode in the table closes

Representative and hypothetical: no number on these pages is any operator's. The rain values are a sensitivity study with no availability attached; an availability needs ITU-R P.618 at a named site. Fields 7 and 8 for this link are filled in chapter 11.

Sources for this appendix (read 2026-11-23): ITU-R P.525-5 (11/2024), equations 5 and 6; ETSI EN 302 307-1 V1.4.1 (2014-11), clause 6, Table 13; 3GPP TS 38.101-5 V17.8.0 (2024-08), clauses 6.1 and 6.2.1; 3GPP TR 38.821 V16.2.0 (2023-03), Tables 6.1.1.1-1, 6.1.1.1-3 and 6.1.3.2-1 and clause 6.1.1.1; the SI Brochure, 9th edition.

Glossary

The terms the chapters define, 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. The 3GPP terms used for direct to device are marked (3GPP).

Term	Meaning
Acquisition	Finding a satellite's signal and locking to its frequency and timing before any data flows; for a laser, finding the other terminal's beam [6, 9]
Adaptive coding and modulation	Changing the modulation and code as the signal quality changes, so the rate can fall during a fade instead of the link failing, while the lowest mode still has margin [5]
Availability	The share of time a link meets its requirement, over a stated period and place; a statistic, not a margin [1, 4]
Background light	Sunlight scattered by the sky into an optical receiver; a separate line in an optical budget by day [9]
Band	A named range of frequencies (L, S, C, X, Ku, Ka and others); using one needs permission [3]
Beam divergence	The full angle by which a laser beam spreads; it sets the beam's width at a distance and its transmit gain [9]
Bent pipe	Another name for a transparent payload [8]
Building entry loss	The extra loss of a signal entering a building; ITU-R P.2109 models it for two classes of building [8]
Burst rate	The rate while a terminal transmits; a time division system sends in bursts, so its average rate is lower [8, 9]

Term	Meaning
Bus	The parts of a satellite that keep it alive (power, attitude, thermal, command), as distinct from the payload [8]
C/N0	Carrier to noise density ratio, in dBHz: the received power over the noise in one hertz [4]
C/(N0+I0)	The same ratio after interference is added to the noise; interference is a budget line [4]
Coherent receiver	An optical receiver that mixes the incoming light with a local laser and recovers its phase [9]
Combined line	For a transparent circuit, the noise combination of the hops: for independent noise, the inverse carrier to noise ratios add in linear terms [4, 8]
Crosslink	A direct link between two satellites, by radio or laser; also called an inter-satellite link [8, 9]
Decibel (dB)	Ten times the logarithm of a power ratio: 3 dB is a factor of 2, 10 dB a factor of 10; dBW, dBm, dBi and dB/K name the reference [R, B]
Direct detection	An optical receiver that measures the light's power, usually with on-off keying [9]
Direct to device	Satellite service to an ordinary or slightly modified handheld device; "in service" needs country, operator, device and date [1, 3, 12]
Doppler shift	The change in received frequency caused by the satellite's motion toward or away from the receiver [6]
Downlink, uplink	Satellite to ground, and ground to satellite, for any hop; not the same as forward and return [4]
Eb/N0	Energy per bit over noise density, in dB: the signal quality per bit that a code needs [4, 5]
EIRP	Equivalent isotropically radiated power: transmitter output less feeder loss plus antenna gain toward a stated direction, in dBW [4]

Term	Meaning
Elevation angle	The angle of the satellite above the horizon as seen from the ground; low elevation means a longer path [2]
Evidence class	The kind of support behind a number: measured, calculated, simulated, operator claim, standard, assumption, or published history [R, 12]
Feeder link	The link between a gateway and the satellite (3GPP: gateway to payload) [8, 10]
Footprint	The area on the ground a satellite or one of its beams covers [2, 8]
Forward, return	The direction of traffic: forward from the network to the user, return from the user to the network; each crosses an uplink and a downlink [4]
Free-space path loss	The spreading loss between two isotropic antennas, 20 log10(4 pi d f / c) [4, B]
G/T	A receiver's figure of merit: antenna gain over system noise temperature, in dB/K [4]
Gateway	The ground station that joins a satellite system to the terrestrial network; in 3GPP terms, the station that terminates the feeder link [8, 10]
Geostationary orbit	A circular orbit about 35,786 km above the equator in which a satellite keeps its place in the sky [2]
Hop	One radio or optical link between two ends, with its own budget page [R, 4]
Hop budget	Page 2 of the Link Ledger: the signed decibel lines from transmitter to receiver, against what the receiver needs [4]
Implementation loss	The gap between a real receiver and the ideal curve of its modulation and code [4, 5]

Term	Meaning
Link Ledger	The two pages this book fills for a link: page 1 the service (ten fields), page 2 the hop budget; classes full, service and budget [R, A]
Low Earth orbit	Orbits below about 2,000 km, a convention rather than a physical boundary; short delay, short passes, many satellites for continuous coverage [2]
Margin	The achieved signal quality less the required one, at a stated operating point [4]
Medium Earth orbit	Orbits between low Earth orbit and geostationary orbit, such as navigation systems near 20,000 km [2]
Modulation	How bits are put on a carrier: BPSK, QPSK, APSK, on-off keying and others [5]
Operating point	The conditions a verdict holds for: rate, direction, elevation, weather and the availability designed for; "closes" is never said without one [4]
Optical link	A link whose carrier is light, usually infrared; between satellites, or between a satellite and a ground telescope [9]
Pass	One period during which a low orbit satellite is above a station's horizon: rise, culmination, set [2]
Payload	The part of a satellite that serves the mission; for a communications satellite, its receivers, converters, amplifiers and antennas [8]
Pointing loss	The loss when an antenna or a laser beam is not aimed exactly at the other end [4, 9]
Reference plane	The point in a chain to which a budget line is referred, for example the antenna connector or the detector input [4]
Regenerative payload	A payload that demodulates, decodes, switches or routes, and modulates again on board (3GPP) [8]

Term	Meaning
Relay satellite	A satellite, usually geostationary, that receives data from other satellites and passes it to the ground [9]
Release 17, Release 19	3GPP releases: Release 17 added satellite access with transparent payloads only; Release 19 adds regenerative payloads (3GPP) [8]
Receiver sensitivity	The smallest received power that gives the stated error rate at the stated rate; the required line of an optical budget [9]
Service link	The link between the satellite and the user's device (3GPP: payload to UE) [8]
Site diversity	Ground stations at sites chosen to reduce the correlation of their weather, so that one is more likely to be clear; judged by joint availability [9]
Slant range	The straight distance from a ground station to a satellite at a given elevation [2, 4]
Software-defined payload	A payload whose beams, frequencies and power can be changed from the ground after launch [8]
Store and forward	Holding data on board until a station is in view, then sending it [1, 7]
System noise temperature	The noise of a receiving chain, expressed as the temperature of an equivalent resistor, in kelvin [4]
Time division duplex	Sending and receiving on the same frequency at different times, as Iridium's handsets do [8]
Transparent payload	A payload that receives, filters, shifts frequency and amplifies, without demodulating or decoding the user's signal (3GPP: an analog radio repeater) [8]
UE	User equipment: the phone or device (3GPP) [6, 8]

APPENDIX D

Dated Register of Volatile Facts, as of the book's date

Some facts in this book will be out of date soon after it is read: which services are in commercial service, how many satellites a fleet has, who owns whom, what a regulator has decided, and what a measurement found on the network as it was. 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. Before relying on any row, read its source again. Nothing in this register is a price: no current or volatile price is used in the book, and historical prices are dated where they appear.

How to read a row

- **As of** is the date the fact describes: a launch, an announcement, a filing, the end of a measurement campaign.
- **Read** is the date the source was read for this book. A row is refreshed by reading the source again: if the fact still stands, only the read date changes, and a status row (in service, operational) needs a source that speaks for the new date, not only an old announcement; if the source reports a new state, the row is rewritten with the new as of date; if the source can no longer be read, the row is struck.
- **Kind** is one of the seven evidence classes of the Reader's Brief, and no other. A label in brackets says what kind of document carried the fact: trade press, a regulatory document (a regulator's order or authorization, classed as standard), a peer-reviewed paper, a community database or a tool's documentation. An operator claim is what a company or agency says about itself, including what trade press reports it said; a measurement names who measured.
- **Ch** is where the book uses the fact. R is the Reader's Brief, EP the Epilogue.

Services and their status

Fact	As of	Source	Read	Kind	Ch
Meteor-M N2-4 listed as operational; LRPT near 137.1 and 137.9 MHz at 80 kbit/s; launched 2024-02-29	2026-01-23 (page date)	WMO OSCAR, Satellite: Meteor-M N2-4	2026-11-22	operator claim	2, 12
Meteor-M N2-4 element set (NORAD 59051): mean motion 14.22444309 revolutions a day, inclination 98.7256 degrees; from it a mean altitude of about 824 km and a period of 101.2 minutes (calculated)	epoch 2026-11-23 07:06 UTC	SatNOGS DB, METEOR M2-4	2026-11-23	operator claim (community database)	2, 6, 12
Open decoders list Meteor-M LRPT pipelines at 72k and 80k, including Meteor-M N2-4, with a Reed-Solomon check	page read 2026-11-23	SatDump documentation, Pipelines	2026-11-23	operator claim (tool documentation)	7, 12
Iridium NTN Direct, a standards based narrowband service on Iridium's existing satellites, activated	2026-11-17	Via Satellite (trade press)	2026-11-22	operator claim (trade press)	8, EP
Kepler's optical data relay constellation announced as in commercial service	2026-08-24	Via Satellite (trade press)	2026-11-22	operator claim (trade press)	9, EP
O3b mPOWER reached 13 satellites with the launch of the last three	2026-09-13	Boeing, Leveling up service with launch of last satellites	2026-11-22	operator claim	8
Amazon Leo Ultra enterprise terminal described as up to 1 Gbps down and 400 Mbps up; an enterprise preview, not a general commercial service	2025-12-01	GSMA news item on Amazon's announcement	2026-11-23	operator claim	10

Fact	As of	Source	Read	Kind	Ch
Emergency messaging from iPhone 14 models to satellites available in the United States and Canada (the launch; historical)	from 2022-11-15	Apple Newsroom	2026-11-23	operator claim	1
Emergency SOS via satellite listed as available on an iPhone 14 or later in 21 countries and regions, among them the United States and Canada (iOS 16.1 or later there); for use with no cellular or Wi-Fi coverage. The status of LL-2022-01 rests on this row	2026-10-05 (page date)	Apple Support, Use Emergency SOS via satellite on your iPhone	2026-11-24	operator claim	1, 12
Galileo declared an initial service of Open Service Navigation Message Authentication (OSNMA), which authenticates Galileo's broadcast ephemeris and clock data	July 2025	Inside GNSS, Galileo OSNMA Looking Forward (trade press)	2026-11-23	operator claim (trade press)	11
Verizon and Skylo direct to device messaging announced; Skylo uses dedicated licensed mobile satellite spectrum	2024-08-28	Verizon News, Verizon and Skylo launch direct to device messaging for customers	2026-11-22	operator claim	12

Fact	As of	Source	Read	Kind	Ch
Verizon customers in the United States with select Galaxy S25 and Pixel 9 phones able to text any device by satellite outside terrestrial coverage; coverage "not complete, uniform, or comprehensive worldwide". Whether the service was still sold on the book's date was not confirmed: the carrier's own page could not be read	2025-03-19	Skylo newsroom	2026-11-23	operator claim	12
T-Mobile satellite texting with Starlink launched commercially in the United States	2025-07-23	Broadband Breakfast (trade press)	2026-11-22	operator claim (trade press)	12
Apple Messages via satellite available in the United States, Canada, Mexico and Japan on an iPhone 14 or later (iOS 18 or later in the United States); text only, outside with a clear view of the sky; SMS depends on the carrier; satellite network provided by Globalstar or third-party network providers. The 2026 thread scene rests on this row	2026-05-15 (page date)	Apple Support, About Messages via satellite	2026-11-24	operator claim	12
3GPP Release 17 supports transparent payloads only; Release 18 adds band n254; Release 19 adds regenerative payloads and store and forward	page read 2026-11-23	3GPP, Non-Terrestrial Networks (NTN) overview	2026-11-23	standard	8, C, EP

Fleets, companies and names

Fact	As of	Source	Read	Kind	Ch
Project Kuiper renamed Amazon Leo	2025-11-13	Amazon, Amazon Leo mission updates	2026-11-23	operator claim	3, 10
Amazon Leo V band authorizations, granted in part, within 37.5 to 42 GHz down and 47.2 to 52.4 GHz up	2026	FCC Order DA 26-553	2026-11-22	standard (regulatory document)	3
AST SpaceMobile: Block 2 array about 2,400 square feet, Block 1 about 700; BlueBirds 1 to 6 and 8 to 13 unfolded and in operation; BlueBird 7 written off; target about 45 BlueBirds in orbit by the middle of 2027	2026-11-09	AST SpaceMobile, Form 8-K exhibit 99.2 (business update)	2026-11-23	operator claim (securities filing)	4, EP, 12
BlueBird 7 lost after a New Glenn upper stage left it too low	April 2026	Spaceflight Now (trade press)	2026-11-22	operator claim (trade press)	12
One operator's authorized low orbit shells at 540 to 570 km; user terminals and gateways at 25 degrees elevation or more	2021-04-27	FCC 21-48, Order and Authorization	2026-11-23	standard (regulatory document)	10
The same operator's user uplink at 14.0 to 14.5 GHz, with further Ku and Ka band ranges in the grant	2018-03-29	FCC 18-38, Memorandum Opinion, Order and Authorization	2026-11-23	standard (regulatory document)	10
GPS commanded from a master control station at Schriever Space Force Base, with monitor stations. The status of LL-2000-02 rests on this briefing	2026-04-21	US Space Force briefing to the Civil GPS Service Interface Committee	2026-11-22	operator claim	11

Regulation and official findings

Fact	As of	Source	Read	Kind	Ch
The FCC adopted Part 100 to replace Part 25 for space licensing; the effective date was not set when checked, so Part 25 applies until then	adopted 2026-07-22	FCC 26-47, Report and Order	2026-11-23	standard (regulatory document)	EP
Supplemental coverage from space: phones may be licensed by rule; interim 911 call and text routing requirements	adopted 2024-03-14 , released 2024-03-15	FCC 24-28, Report and Order, GN Docket 23-65	2026-11-23	standard (regulatory document)	10
GPS civil signal interface: IS-GPS-200N, dated 2022-08-01 (L1 C/A minimum received power -158.5 dBW at a 3 dBi linear reference antenna; ten-bit week number in the legacy message)	revision N, 2022-08-01	IS-GPS-200N, GPS.gov	2026-11-23	standard	5, 7
DVB-S2 is ETSI EN 302 307-1 V1.4.1 (2014-11); DVB-S2X is EN 302 307-2 V1.4.1 (2024-08)	editions as read	ETSI	2026-11-23	standard	4, 5, 7
CCSDS telemetry synchronization and channel coding is 131.0-B-5, Issue 5 (September 2023); the Bundle Protocol is version 7, RFC 9171 (January 2022)	editions as read	CCSDS; IETF	2026-11-23	standard	5, 7
Radio noise: ITU-R P.372-7 (2001) was the edition read; later editions exist and were not read	2001 edition	ITU-R	2026-11-23	standard (superseded edition)	12
The Space Development Agency's Tranche 0 "has not yet fully demonstrated laser communications technology in space"	2025-02-26	GAO-25-106838, an audit report	2026-11-23	published history	9

Measurements of networks as they were

A measurement describes a network at the time of the campaign. The operators change routing, ground stations and software continuously, so these rows age fastest.

Fact	As of	Source	Read	Kind	Ch
Low orbit broadband, terminal to point of presence: 36 to 48 ms round trip, median about 40 ms; 50 to 100 Mbit/s down and 4 to 12 Mbit/s up at the 75th percentile of public speed tests; round trips 2 to 4 times higher during downloads in those tests	speed tests from 2021; paper first posted October 2023, published 2024	Mohan and others, ACM Web Conference 2024	2026-11-23	measured (by the authors)	10
A local point of presence in the Philippines cut latency to in-country servers by about 90 percent	May 2023	Mohan and others, same paper	2026-11-23	measured (by the authors)	10
In a scan of 39 geostationary satellites, 25 longitudes and 411 transponders, "50% of GEO links contained cleartext IP traffic" (a sample, not a census)	published 2025-10-13	Zhang and others, ACM CCS 2025	2026-11-23	measured (by the authors)	11
Earlier Meteor-M satellites' LRPT listed as unencrypted; such downlinks can be overshadowed with commercially available radio equipment	2023	Salkield and others, Firefly, SpaceSec 2023	2026-11-23	measured (by the authors; peer-reviewed paper)	7, 12

Facts this book does not print

Several volatile facts were read during the writing and left out because no primary source could be read on the day, or because a number from one source disagreed with another. They are listed so that a reader does not mistake their absence for an oversight.

- Satellite counts for broadband fleets other than those above, and subscriber counts: the sources found for this book on the day were trade press or independent trackers, which disagree with each other.
- Prices for terminals, plans, ground station minutes and launches: by quote, and changing.
- The cause and duration of a broadband network outage in July 2025: the operator's statement could not be read from a primary page on the date checked, so chapter 10 uses a filed case instead.
- Meteor-M N2-4's transmit power and antenna pattern, and the LRPT code chain from the format's own specification: the pages that would give them could not be read, so chapter 12 solves for the required satellite EIRP and names its code as a stand-in.
- The orbit of the satellites behind the 2026 texting service: Apple's page names the satellite network's provider but not its orbit.
- The status on the book's date of two ledgers dated to the past, and of their operators' current fleets: the EDRS relay path of chapter 9 (LL-2016-01, in service as of 2016), the low orbit broadband route of chapter 10 (LL-2026-04, as filed in 2018 and 2021 and measured from 2021 to 2023). The agency's EDRS pages could not be read on 2026-11-23, and no current status page was read for the broadband route, so both ledgers are marked historical, with their status not checked on the book's date.
- The number of Starlink satellites lost to the geomagnetic storm of February 2022: published counts differ (38 in one paper, 40 in a survey that cites a news magazine), and the operator's own update could not be read, so chapter 2 prints the physical event without a count.
- The exact day of the Galileo authentication service declaration: the agency's own notice could not be read on the date checked, so the register gives the month from trade press.

When this register is refreshed

The register is checked against its sources at each final build of the book, and the Read column records that check. A fact whose source can no longer be read is struck from the register and from the chapter that uses it, or rewritten without the number. The thread scene of 2026 (chapter 12) depends on the register more than any other page: its service, country, operator, device and date are read again at the final check, and the scene says only what that reading supports.

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 230 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 Ledger and Six Questions

- NASA History, Telstar Opened Era of Global Satellite Television https://www.nasa.gov/history/telstar-opened-era-of-global-satellite-television; Bell System Technical Journal vol. 42 no. 4, July 1963, The Telstar Satellite System https://bitsavers.mirrorservice.org/magazines/Bell_System_Technical_Journal/BSTJ_V42N04_196307_Part_1.pdf
- 3GPP TS 38.101-5 V17.8.0 (ETSI TS 138 101-5, 2024-08) https://www.etsi.org/deliver/etsi_ts/138100_138199/13810105/
- Calculated in chapter 4 and Appendix B (ITU-R P.525 formula) https://www.itu.int/rec/R-REC-P.525
- The model hop of chapter 4 (hypothetical)

Prologue: One Picture in 1962, One Message in 2026

- Bell System Technical Journal vol. 42 no. 4, July 1963, Part 1, The Telstar Experiment https://bitsavers.mirrorservice.org/magazines/Bell_System_Technical_Journal/BSTJ_V42N04_196307_Part_1.pdf
- NASA History, Telstar Opened Era of Global Satellite Television https://www.nasa.gov/history/telstar-opened-era-of-global-satellite-television
- Calculated from the journal's values, 1 nautical mile = 1.852 km
- NASA SP-4217, Beyond the Ionosphere, chapter 6 https://www.nasa.gov/wp-content/uploads/static/history/SP-4217/ch6.htm
- NASA, 65 Years Ago: Sputnik Ushers in the Space Age https://www.nasa.gov/history/65-years-ago-sputnik-ushers-in-the-space-age/
- 3GPP, Non-Terrestrial Networks (NTN) overview https://www.3gpp.org/technologies/ntn-overview; 3GPP TS 38.101-5 V17.8.0 (ETSI TS 138 101-5, 2024-08) https://www.etsi.org/deliver/etsi_ts/138100_138199/13810105/
- 3GPP TS 38.101-5 V17.8.0 (ETSI TS 138 101-5, 2024-08) https://www.etsi.org/deliver/etsi_ts/138100_138199/13810105/
- Calculated (Appendix B)

Chapter 1. What Must Be Delivered

- Apple Newsroom, Emergency SOS via satellite available today on the iPhone 14 lineup, 2022-11-15 https://www.apple.com/newsroom/2022/11/emergency-sos-via-satellite-available-today-on-iphone-14-lineup/
- Globalstar, Inc., Form 8-K dated 2022-09-07 https://www.sec.gov/Archives/edgar/data/1366868/000136868220000059/gsat-20220907.htm
- Globalstar Telecommunications Ltd and Globalstar, L.P., Form 10-K for 2001 https://www.sec.gov/Archives/edgar/data/0001037927/000095012302003826/y59129ae10-k.txt
- Iridium World Communications and Iridium LLC, Form 10-K405 for 1998 https://www.sec.gov/Archives/edgar/data/948421/000095013399001138/0000950133-99-001138.txt

- Motorola, Inc., Form 10-K for 1999 https://www.sec.gov/Archives/edgar/data/0000068505/000095013100001895/0000950131-00-001895.txt
- Iridium Communications Inc., Form 10-K for 2009 https://www.sec.gov/Archives/edgar/data/1418819/000119312510058393/0001193125-10-058393.txt
- GPS.gov archive, Space Segment https://archive.gps.gov/systems/gps/space/
- Copernicus SentiWiki, S1 Mission https://sentiwiki.copernicus.eu/web/s1-mission
- Calculated from 8,766 hours per year (Appendix B)
- Apple Support, "Use Emergency SOS via satellite on your iPhone" https://support.apple.com/en-us/101573 (published date 2026-10-05)

Chapter 2. Orbits and Passes

- NASA SP-4217, Beyond the Ionosphere, chapter 6 https://www.nasa.gov/wp-content/uploads/static/history/SP-4217/ch6.htm
- Wireless World, October 1945, Extra-Terrestrial Relays, pp. 305 to 308 (scan of the original) https://lakdiva.org.lk/clarke/1945ww/1945ww_oct_305-308.html
- NASA NSSDCA Master Catalog, Syncom 2 https://nssdc.gsfc.nasa.gov/nmc/spacecraft/display.action?id=1963-031A
- Calculated with an Earth radius of 6,371 km (6,378.137 km for the geostationary geometry), the WGS 84 gravitational parameter, a sidereal day of 86,164.09 s and the speed of light (Appendix B)
- Iridium World Communications and Iridium LLC, Form 10-K405 for 1998 https://www.sec.gov/Archives/edgar/data/948421/000095013399001138/0000950133-99-001138.txt
- Globalstar Form 10-K for 2001 https://www.sec.gov/Archives/edgar/data/0001037927/000095012302003826/y59129ae10-k.txt
- GPS.gov archive, Space Segment https://archive.gps.gov/systems/gps/space/
- European Space Agency, What is Galileo? https://www.esa.int/Applications/Satellite_navigation/Galileo/What_is_Galileo
- US Geological Survey, Landsat 9 https://www.usgs.gov/landsat-missions/landsat-9
- Bell System Technical Journal vol. 42 no. 4, July 1963, The Telstar Satellite System https://bitsavers.mirrorservice.org/magazines/Bell_System_Technical_Journal/BSTJ_V42N04_196307_Part_1.pdf
- Instability of Self-Driving Satellite Mega-Constellation, arXiv 2406.06068 https://arxiv.org/abs/2406.06068
- NASA, 65 Years Ago: Sputnik Ushers in the Space Age https://www.nasa.gov/history/65-years-ago-sputnik-ushers-in-the-space-age/
- Distributed Coordination for Heterogeneous Non-Terrestrial Networks, IEEE Communications Magazine (2025) https://doi.org/10.1109/mcom.001.2500265; author version https://arxiv.org/abs/2502.17366
- Expanding Internet Access with Low Earth Orbit Satellites (survey; cites a news magazine for the count) https://openalex.org/W7133047527
- WMO OSCAR, Satellite: Meteor-M N2-4 https://space.oscar.wmo.int/satellites/view/meteor_m_n2_4
- Calculated from the public element set of 2026-11-23 in the SatNOGS DB, as used for the bench link in chapter 12 https://db.satnogs.org/

Chapter 3. Bands and Antennas

- NASA SP-4217, Beyond the Ionosphere, ch. 21 (Martin) https://www.nasa.gov/wp-content/uploads/static/history/SP-4217/ch21.htm
- NASA SP-4217, ch. 21
- ESA, Satellite frequency bands https://www.esa.int/Applications/Connectivity_and_Secure_Communications/Satellite_frequency_bands
- WMO OSCAR, Satellite: Meteor-M N2-4 https://space.oscar.wmo.int/satellites/view/meteor_m_n2_4
- Danchik, "An Overview of Transit Development", Johns Hopkins APL Technical Digest 19(1) https://secwww.jhuapl.edu/techdigest/Content/techdigest/pdf/V19-N01/19-01-Danchik.pdf
- IS-GPS-200N (2022-08-01) https://www.gps.gov/sites/default/files/2025-07/IS-GPS-200N.pdf
- Iridium World Communications and Iridium LLC, Form 10-K405 for 1998 https://www.sec.gov/Archives/edgar/data/948421/000095013399001138/0000950133-99-001138.txt
- Hoth, O'Neill and Welber, "The Telstar Satellite System", Bell System Technical Journal 42(4), July 1963 https://bitsavers.mirrorservice.org/magazines/Bell_System_Technical_Journal/BSTJ_V42N04_196307_Part_1.pdf
- NASA SP-4217, ch. 14 https://www.nasa.gov/wp-content/uploads/static/history/SP-4217/ch14.htm

- NASA SP-4217, ch. 6 https://www.nasa.gov/wp-content/uploads/static/history/SP-4217/ch6.htm
- FCC, Order DA 26-553 https://docs.fcc.gov/public/attachments/DA-26-553A1.txt
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