

THE SATELLITE SERIES, ERA BY ERA

From Telstar to the Phone in Your Pocket

How satellite systems divided the work

Every satellite system divides the same five things, power, antenna, processing, cost and risk, among three places: the user end, the satellite and the ground end. Each era had a limit that ran out first, and each system faced its own mix of constraints. Read that way, the history gives a test for any system offered today, with three verdicts kept apart: did the link work, did the service work, did the business work.

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BEFORE THE HISTORY

Reader's Brief: Five Things, Three Places, Six Questions



In July 1962 a small satellite carried a television picture across the Atlantic because a ground station in Maine did most of the work. In November 2026 a phone with no tower in reach can send a text through a satellite because the satellite and the carrier do most of the work. This book is the history between those two dates, read one way: who carried the load, and why.

Five things, three places

Every satellite system has to supply the same five things: **power** to send a signal, **antenna** area to send and to hear it, **processing** to do anything to the signal beyond filtering it, amplifying it and shifting its frequency, **cost**, and **risk**. There are only three places to put them: the user end, the satellite, and the ground end. Each system splits them differently. That split is what this book calls the division of labor.

Each system is read with one question: how was the work divided between user, space and ground, what limits drove that split, and did it work? In this book's reading each era had a limit that ran out first, and the chapters name it as a headline, an interpretation, not a finding of the record. Under the headline each system faced its own mix of constraints, and each case names its own, with a source. Figure R.1 collects the eras.

FIGURE R.1

The division of labor, era by era: each era had a limit that ran out first

Era	Limit that ran out first (other constraints)	User end	Space	Ground end	Ch.
1957 to 1964: store, reflect, repeat	Launch mass and power in orbit (reliability in the radiation belts)	Nothing new; the call or picture rode existing networks to one station	Tape, a mirror, then Telstar 1: 2 W radiated, 6390 MHz up, 4170 MHz down, minutes per pass	A 380 ton horn with a maser receiver at Andover	2, 3
1965 to 1980s: the geostationary trunk	Continuous coverage and circuits per satellite (treaty, ownership, national policy)	A telephone on a national network	Early Bird, 1965: 240 voice circuits or one television channel	National stations owned under the Intelsat agreements; state networks in the Soviet system	4, 5, 6
1970s to 1990s: the user that stays still	Size and cost of the user's antenna	Village antennas of 3 m (1975); a 60 cm dish (1978)	More power in orbit: ATS-6's 9.14 m reflector, down at 860 MHz in India (1975); Hermes at 12 and 14 GHz (1978)	Uplink centers	7
1970s to 1990s: the user that moves	The terminal a ship, an aircraft or a spacecraft can carry	A ship terminal; a spacecraft's own antenna	L band to ships; relay satellites	Shore stations; relay ground stations	8

Era	Limit that ran out first (other constraints)	User end	Space	Ground end	Ch.
1990s to 2010: the first low orbit wave	Money and paying customers; the handset	A handset at 3,000 dollars or more at retail (1998)	Iridium: 66 satellites, crosslinks. Globalstar: a bent pipe	Iridium: 12 gateways (1998). Globalstar: 25 in service (end of 2001), mostly owned by local providers	9
2010s to 2026: broadband	Cost of launch, of satellites in volume, and of the terminal	A dish, then a flat array	Spot beams in geostationary and medium orbit; then low orbit constellations, with and without routing in orbit	Gateways, factories, launch	10, 11
2022 to 2026: direct to device	The phone cannot grow	A phone with no external satellite terminal	Very large arrays (one design: about 2,400 square feet, 2026)	The carrier's core network and spectrum	12

The limit in the second column is a headline; each chapter names the other constraints of each case, with sources.

Author's table based on: Bell System Technical Journal, July 1963 (Telstar, Tables I and III); NASA SP-4217, chapters 6, 9 and 14; Iridium Form 10-K405 for 1998; Globalstar Form 10-K for 2001; AST SpaceMobile Form 8-K exhibit 99.2, November 2026. Checked 2026-11-23.

Three verdicts, kept apart

"Did it work?" has three answers, and this book never merges them.

- **The link:** did the signal arrive with the quality the receiver needed, at a stated operating point?
- **The service:** did users get what was promised, where and when it was promised?
- **The business:** did the owners recover what they spent?

The three can disagree. Iridium and Globalstar both put working links into service around 1998 to 2000, and both operating companies were in bankruptcy within a few years; neither filing blames the physics. Chapter 9 tells both from the filings.

A verdict always names the objective it is measured against. A design can be judged against the constraints its builders faced, against the alternatives they had, and only then against what we know now. Sometimes a design turns out to have been a poor fit even for its own time, and the book says so when a source supports it.

Six questions

The series asks six questions of every system. In this book they are asked of the past, but they are written for the reader who must judge a proposal next week.

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 Link Ledger in two minutes

The series tool is a two-page form called the Link Ledger. The first book of this series, *The Bit's Path*, explains it with the radio theory behind it; this book uses it as a reading tool for old systems and does not repeat the theory.

Page 1 describes a service in ten fields: the requirement; the ends and the path; the orbit and the time; the band and the permission to use it; capacity; who owns each end; trust; how it fails and how anyone would see it; the shape of the cost; and the numbers that carry the argument, each with its source. **Page 2** is the hop budget: one block per radio hop, adding gains and losses in decibels until it shows whether the receiver gets what it needs, at a stated operating point (the stated conditions, such as range, weather and bandwidth, under which the budget is worked), 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, for example because no primary record gives the numbers. A **budget** form has page 2 only.

Every page 2 in this book is one of two kinds, and the book says which one in the ledger's system line (printed in its header and in the index of Appendix A), in the chapter text and in the caption of every budget figure.

- **An archival budget.** Every line that decides the result comes from a builder's report, a filing, a standard or a peer-reviewed paper, and any recalculation is shown. Telstar's budget (LL-1962-01), from the Bell System's own tables, is the archival budget in this book.
- **An illustrative model.** A budget built from a standard's representative values, from values solved backward, or from labeled assumptions. It shows how such a link can close under the stated assumptions and which line decides it. It does not show that a real service met its target, and a "closes" printed on such a page means only that the model closes. The Iridium handset call (LL-1998-01) and the text from a phone over carrier spectrum (LL-2026-02) are illustrative models.

Where neither kind can be built honestly, the system gets page 1 only, and the form says so instead of guessing. Most of the systems in this book are in that position.

Read a page 1 in this order: field 1, the requirement, because a link that meets its error rate can still fail its users (chapter 5 has the case); field 6, who owns each end; field 8, how it fails; then field 10, the numbers. Read a page 2 from the bottom: the margin, then the operating point under it, then the line that decides the result.

Where each number comes from

Every line of a page 2, and every number in field 10 of a page 1, carries one of seven classes, a source and a date. Elsewhere, in the prose, the figures and the appendices, a number is attributed in its own sentence or source line, and the chapter's claim table, from which Appendix E is drawn, pairs it with its source, the date it was checked and its class.

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, builder or supplier stated it; no independent check is known to the sources read
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, such as NASA's *Beyond the Ionosphere* (SP-4217), or labeled historical scholarship; the work and the page are named

No number in this book was measured by its author. A builder's figure stays a builder's figure: when Bell Laboratories reports Telstar's transmitter power, the form says so and gives the journal and the page.

How dates and "firsts" are written

A history of technology is full of firsts, and many of them disagree. This book writes a first only with the qualifier its source uses, and names the source: NASA's history calls Telstar the first privately financed satellite, so the book says that NASA calls it so. Where two primary sources disagree and neither can be settled, the sentence names no first.

- A date is the date the source gives, with what it marks: a launch, the start of commercial service, an agreement opened for signature, an agreement in force. Intelsat's interim arrangements of 1964 and its definitive agreement in force in 1973 are two different things, and chapter 4 keeps them apart.
- Announced, filed, launched and in service are four different words, the announcement status of a plan (the epilogue); a fleet's deployment status has its own four words (chapter 11). A count in orbit carries its number, its date and who counted. A price carries its date

and what it leaves out.

- "In service" for a phone service needs four words: country, operator, device and date.
- Trade press is labeled as trade press in the text, and narrative history from scholarship is labeled as such.

A thread through the book

Five times the book stops for a scene marked "Reconstruction". Each follows one invented, illustrative insurer, founded in 1898, that needs a report from a place the ground network does not reach: a casualty report from a ship in the 1970s (chapter 8), an adjuster's voice call from a flood zone in 1999 (chapter 9), claim photos from a truck in a hurricane zone in 2012 (chapter 10), a policyholder's emergency text in 2022 and the adjuster's own phone in 2026 (chapter 12). The insurer is invented. The link in each scene is a documented service of that year, or, in 2012, a documented class of service under the regulator's rules, and the scene appears only where such a service existed. In 1962 there is no scene, because no service could have carried the message.

How the book is built

Chapter 1 sets out the frame and the test. Chapters 2 and 3 cover the years when the ground did nearly all the work. Chapters 4 to 8 follow five tracks that ran side by side from 1965: who owned the link, the geostationary trunk, the national programs, broadcast to small dishes, and users that move or are themselves satellites. Chapters 9 to 12 follow the switch into orbit, broadband, and the phone that cannot grow. Chapter 13 asks when processing in orbit pays. Chapter 14 sets out which old answers came back and where the frame stops working.

Each numbered chapter carries a failure, a recovery or a trade-off from the record, told from its sources; a security note on who may use and command the system, who can intercept or interfere, and how service is recovered; and, last, a **Monday rule**: one sentence a reader can act on the next working week.

What the sources reach, and what they do not

The book is written from records a reader can open: filings with American and European regulators, annual reports filed with the US Securities and Exchange Commission, official agency histories, standards and peer-reviewed papers. That choice has a geography, and the reader should know it before chapter 2.

- **The Soviet Union and Russia.** Molniya, Orbita and the later Soviet geostationary series are told mainly from US tracking records declassified in 2015 and from NASA's official history; no Soviet or Russian primary record was read, so the Soviet design reasons and dates are given only where those records state them (chapter 4).
- **National and regional programs.** Canada, Europe, Indonesia, India, Japan and China are told from NASA's official history and operator pages; several other programs of the 1980s and 1990s are named without dates (chapter 6 and the open entries of Appendix B).
- **Direct-to-home television.** The American services and Astra's early years rest on the operators' filings and SES's own history; European subscription businesses, their subscriber counts and the year any of these services first made a profit were not found, and no hop budget for a broadcast satellite was read (chapter 7).
- **Military systems.** Only the public record is used: NASA's official history, US Government Accountability Office reports and UK government pages. No military service's fact sheet could be read, later launch dates and fleet sizes are not printed, and no figure for how well any system resists jamming was found in the public sources read (chapter 8).
- **The constellations of China and Russia today.** Fleet counts come from independent trackers and the trade press; no operator or regulator record was read (chapter 11).
- **The costs behind the constellations.** No comparable figures for satellite unit cost, terminal cost or financing across the 1990s and the 2020s were read, so chapter 11 sets out its explanation as hypotheses and says which the records support.
- **Events of 2026.** Most are taken from filings; where a primary record did not load when checked on 23 November 2026, the text keeps the trade press label and says so.
- **Broadband before the constellations.** The Ka band satellites of 2005 to 2012 are told from the operators' filings; IPSTAR's design and KA-SAT's service date rest on trade press, and data caps, fair-use rules and cost per bit were not found in a primary source (chapter 10). The results of NASA's ACTS experiments are told from the official history and the reports' published abstracts; the full reports could not be reached (chapter 13).

Where a gap matters to an argument, the chapter says so at that point, and Appendix B lists the systems whose dates remain open.

Prologue: Two Calls, Sixty-Four Years Apart



Telstar 1 was launched on 10 July 1962. On the first pass that the station at Andover, Maine could use, its engineers sent speech and television to an audience in Washington, and during the program word came that the French station at Pleumeur-Bodou was receiving picture and sound. The next day television came back across the Atlantic from both European stations. That is the account in the builders' own report, published by the Bell System Technical Journal a year later. The people who watched at home did nothing new. They switched on the same set, tuned to the same networks, and saw a picture that had been to space.

1962: the ground did the work

The satellite was a sphere of about 170 pounds. It received near 6390 MHz, shifted the signal to a lower frequency inside, amplified it and sent it back near 4170 MHz, with a radiated power of about 2 watts through antennas that radiated about equally in every direction. It did not decode anything. The first book of this series, *The Bit's Path*, works Telstar's link line by line; this book asks a different question about the same machine: who carried which part of the load, and who paid for it.

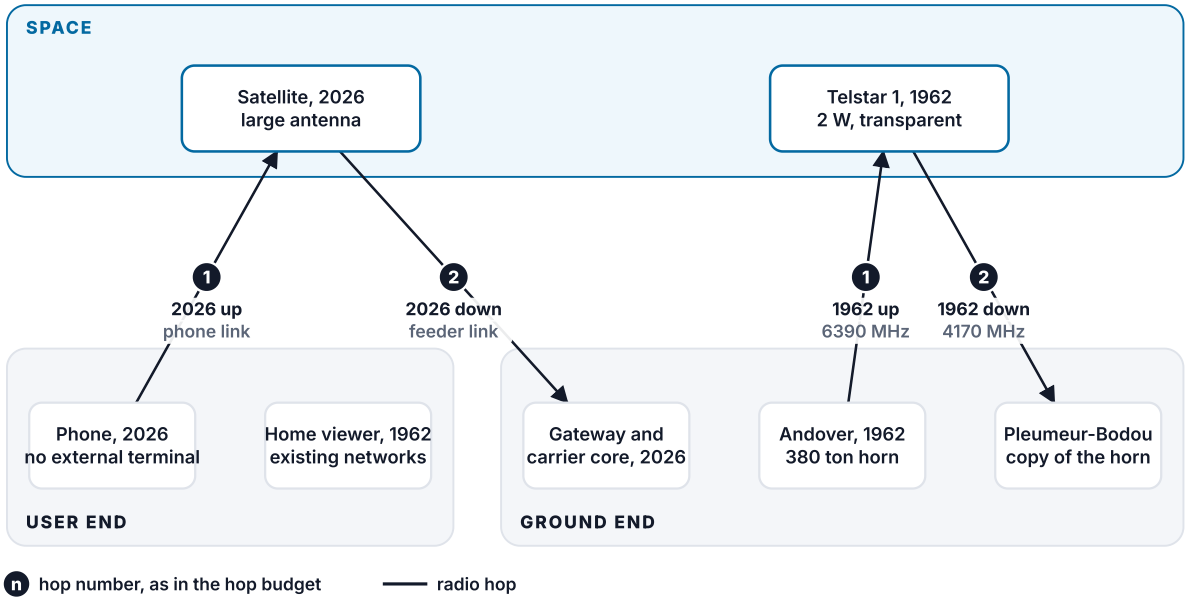
Almost everything was on the ground. Andover's horn antenna had 3,600 square feet of aperture and weighed 380 tons, according to the builders' table. It transmitted with 2 kilowatts, a thousand times the satellite's output, and its receiver began with a maser cooled in liquid helium. The French station used a copy of the Bell horn, according to NASA's history. Between the stations and the viewers stood the existing networks of the telephone and television companies. The satellite was the small and risky part. The large pieces were the stations, each built by its own country's operator, and the networks that already linked them to viewers.

The money for the satellite came from one company. NASA's history records that Bell Laboratories built Telstar with corporate funds, that AT&T built six spacecraft and launched two, and that AT&T reimbursed NASA 6 million dollars for the launch and tracking. NASA calls Telstar the first privately financed satellite. The operational system AT&T envisioned after it was never built; chapter 4 tells what became of the plan.

Telstar also showed what the ground could not supply. It flew an elliptical orbit, so a transatlantic link existed only when both stations could see it at once: in the first weeks three or four times a day, for 10 to 20 minutes, by the builders' count. Inside those windows the link worked. Between them there was no service at all. The telephone company had proved a repeater, not a business.

FIGURE P.1

Two calls: in 1962 the ground carried the load; in 2026 the satellite and the carrier carry it



Left, the 2026 text in one of its designs: phone up to a satellite with a large antenna on the carrier's spectrum, down to a gateway and the carrier's core (services on a satellite operator's own spectrum divide the work differently, chapter 12). Right, the 1962 picture: Andover's horn up to Telstar 1, down to Pleumeur-Bodou; the home viewer was reached by existing networks.

Author's diagram based on the Bell System Technical Journal, July 1963 (Telstar, Tables I and III); NASA SP-4217, chapter 6; AST SpaceMobile Form 8-K exhibit 99.2, November 2026 (the large array); 3GPP NTN overview. Checked 2026-11-23.

2026: the work moved up and out

Now move the user end. Picture someone in the United States in November 2026, in a valley that no mobile tower reaches, with a phone in hand. The phone sends a short text message through a satellite, on one of the services chapter 12 names; Appendix D dates the newest record read for each. There is no dish, no separate satellite terminal and no horn the size of a building.

The phone is not unchanged, and this book never says it is. Some phones are built for a satellite operator's mobile satellite spectrum: Apple's emergency service via satellite started on 15 November 2022 in the United States and Canada, on the iPhone 14 line, with the maker's own components and software, according to Apple. On 19 March 2025 Verizon extended satellite texting to Samsung Galaxy S25 and Google Pixel 9 phones through Skylo, according to Skylo's announcement of that day, which also says the coverage comes from Skylo's partners and is not complete worldwide. Other offers use the carrier's own terrestrial spectrum, relayed by satellites with very large antennas; chapter 12 keeps the two kinds apart. Which service works on which phone, in which country, from which date, is a dated fact that chapter 12 sets out as far as the record allows on the book's date.

What changed is where the five things sit. The phone cannot grow its antenna or its battery, so gain moved to the satellite, timing and frequency correction moved into the phone's software and the network, and the call lands in a carrier's core network on the ground. One satellite design for phones has an array of about 2,400 square feet, according to its operator's filing of November 2026, which reports such satellites unfolded and operating in orbit: about two thirds of the area of the Andover horn's aperture.

The money moved too. In 1962 one telephone company paid for the satellite, the launch and its own station; the British and French stations were their own operators'. In 2022 Globalstar disclosed that Apple would pay 95 percent of the approved capital spending on its new satellites and receive 85 percent of the network's capacity. In 2024 the two companies agreed an infrastructure prepayment of up to 1.1 billion dollars. In this case the maker of the user's device was paying for most of a new space segment; other services in chapter 12 are funded differently.

What moved, what did not, and who paid

Two calls, the same five things

What the link needs	1962, Telstar	2026, a phone to a satellite
Power	Ground: 2 kW at Andover. Satellite: 2 W	Phone: up to about 0.2 W for a handset of power class 3 (3GPP). Satellite: the transmit power and gain the phone lacks
Antenna	Ground: a 3,600 square foot horn	Satellite: arrays of up to about 2,400 square feet in one design that uses the carrier's spectrum
Processing	Ground: the demodulator at each station	Phone and network: coding, timing and Doppler correction; in orbit too in some designs
Cost	Satellite and Andover: one telephone company, its own funds. Europe: the national operators' stations	Satellite operators, carriers, phone makers and their investors
Risk	The telephone company: one experimental satellite and its own station. Europe's agencies: their stations	Spread across companies, with filings, launches and spectrum rights at stake

Some things did not move. A ground station still connects the satellite to the rest of the world, a spectrum right still decides who may transmit where, and someone still decides who may command the satellite. In 1962 the viewer could not see any of it. In 2026 the user sees a little more, in some services a guide on the screen to point the phone at open sky, and still none of the ownership.

The chapters that follow walk the sixty-four years between the two calls. At each step they ask what had to be supplied, where it was put, who owned each end, and whether it worked: as a link, as a service and as a business.

CHAPTER ONE

The Division of Labor, and How to Read a Satellite System



On 1 November 1998 Iridium began commercial telephone service from 66 satellites in low orbit, linked to each other by radio and to the ground through 12 gateways, according to its annual report for that year. Its operating company was in Chapter 11 by August 1999, according to Motorola's report for the next year. Was Iridium a good design? The question has no answer until it says good for what, judged against what, and with what the designers knew. This chapter sets out how this book asks it.

Five things, three places

A satellite service has to supply five things. **Power** puts a signal into the air. **Antenna** area concentrates that power toward the receiver, and on the other side collects it. **Processing** is anything done to the signal beyond filtering it, amplifying it and shifting its frequency: demodulating it to bits, switching it between beams, routing it to another satellite, storing it, computing on it. **Cost** is who pays, when and in what form. **Risk** is who loses if a launch, a satellite, a market or a permission fails.

There are three places to put them: the **user end**, the **satellite**, and the **ground end**, which may be a gateway, a national earth station, a control center or a carrier's network. A design is a choice of where each of the five sits. Figure 1.1 is the grid this book fills for every system.

FIGURE 1.1

Five things, three places: the grid this book fills for every system

	User end	Satellite	Ground end
Power	The transmitter in a terminal or a phone; limited by battery, heat and safety	Solar arrays and amplifiers; limited by launch mass and heat	Station transmitters; limited mainly by cost and permission
Antenna	A dish, a flat array, or a phone's built-in antenna	Reflectors and arrays, from small antennas to very large arrays	Large dishes and horns at gateways and earth stations
Processing	Coding, timing and frequency correction in the terminal	Filtering, amplifying and shifting only (transparent), or demodulation, switching, routing, storage	Demodulation, switching and the network behind the gateway
Cost	Terminal price and subscription	Building and launching the satellites	Stations, gateways, networks and operations
Risk	A terminal that becomes useless if the service ends	Launch failure and failure in orbit, where repair is rarely possible	A failed station can be reached and repaired; a failed company or permission ends the service

What each place can contribute; the chapters mark, for each system, which place carries most, which shares and which carries little (qualitative levels, not numbers).

Author's table. Processing defined after 3GPP, Non-Terrestrial Networks (NTN) overview (transparent and regenerative payloads), checked 2026-11-23.

A zero is a choice too. A satellite that only filters, amplifies and shifts frequency carries no processing at all. The standards body for mobile networks, 3GPP, calls such a payload **transparent**, an analog radio repeater with no processing on board, and calls a payload that demodulates, switches and modulates on board **regenerative**. Telstar in 1962 was

transparent. So, by its own filing, was Globalstar's first generation in 2000. Neither was a less finished design. Each put the processing on the ground on purpose, where it could be reached, repaired and upgraded.

The limit that ran out first, and the ones under it

In this book's reading, each era of this history had one limit that ran out first. That is an organizing headline, not a finding of the record. Before 1965 it was what a rocket could lift and what a satellite could power, so the ground did the work. For the geostationary trunk it was circuits per satellite. For direct broadcast it was the size of the dish a household would accept. For the handheld phones of the 1990s it was money and paying customers. For direct to device in the 2020s it is the phone itself, which cannot grow.

That headline is never the whole story. Constraints stack. A system faces the size of the user's antenna, the spectrum it may use, the reliability of parts in the radiation belts, access to a launcher, the capital it can raise, and the aims of the institution that pays. Telstar's builders faced launch mass and power, but also the radiation that damaged its command decoder within months, according to their own report. The chapters name each case's dominant constraints with a source, and keep the era's headline for orientation only.

The test: constraints, alternatives, objective, three verdicts

To judge a design, this book asks four things in order.

1. **The constraints its builders faced**, at the time, with a source: what could be launched, powered, bought and permitted.
2. **The alternatives they had**: what else was proposed or built in the same years. In 1962 AT&T envisioned 50 to 120 satellites in orbits about 7,000 miles high, according to NASA's history, while NASA and Hughes worked on Syncom, a satellite for the 24 hour orbit.
3. **The objective they stated.** Telstar's builders set out to test a wideband repeater in orbit, with television as the transmission objective. Against that objective it did what it was built to do. Against continuous service, an objective it never had, it could not: the link existed only during passes.
4. **Three verdicts, kept apart.** The link: did the signal arrive with the quality needed, at a stated operating point? The service: did users get what was promised? The business: did the owners recover what they spent?
   Only after those four does the book compare a design with today's. A design may still turn out to have been a poor fit for its own time; the book says so when a source supports it, and names the objective it is measured against.

THE SYSTEM'S FAILURE

Iridium is the case that forces the three verdicts apart. Its links carried commercial service from 1 November 1998 on 66 satellites in low orbit, by its own annual report; the book's budget for its handset call, in chapter 9, is an illustrative model, not a record. Its operating company, carrying large debt, was in Chapter 11 within ten months, by Motorola's report for 1999, and neither filing attributes the failure to the link. The satellites outlived the company: a new owner acquired them in December 2000, and the system was still offering new services in 2026. Chapter 9 takes the causes from the filings. Read narrowly, the case says one thing: a link that works and a business that works are two separate findings, and neither proves the other.

Four path shapes

The path of a signal through a system takes one of four shapes, and most systems in this book are one of them or a mix. They are not one scale: transparent or regenerative says what the payload does to the signal, crosslinked says whether satellites pass it to each other, and store and forward says when it is delivered, so Iridium, for one, was regenerative and crosslinked at once. The first book of this series, *The Bit's Path*, explains the radio behind each; here one paragraph each is enough.

Transparent. The satellite receives, shifts the frequency, amplifies and sends on. The noise of the way up travels with the signal on the way down. Telstar and Globalstar's first generation are transparent, by their builders' own descriptions.

Regenerative. The satellite demodulates the signal to bits, so it can switch them between beams and modulate them again for the next hop; the noise of the way up is not passed on as noise, though a bit decoded wrongly is passed on wrong. The 3GPP standards added regenerative payloads for phones in Release 19, according to 3GPP's own overview.

Crosslinked. Satellites pass traffic to each other, so a call can travel through space to a distant gateway. Iridium's 23 GHz links between satellites are the first large case in this book.

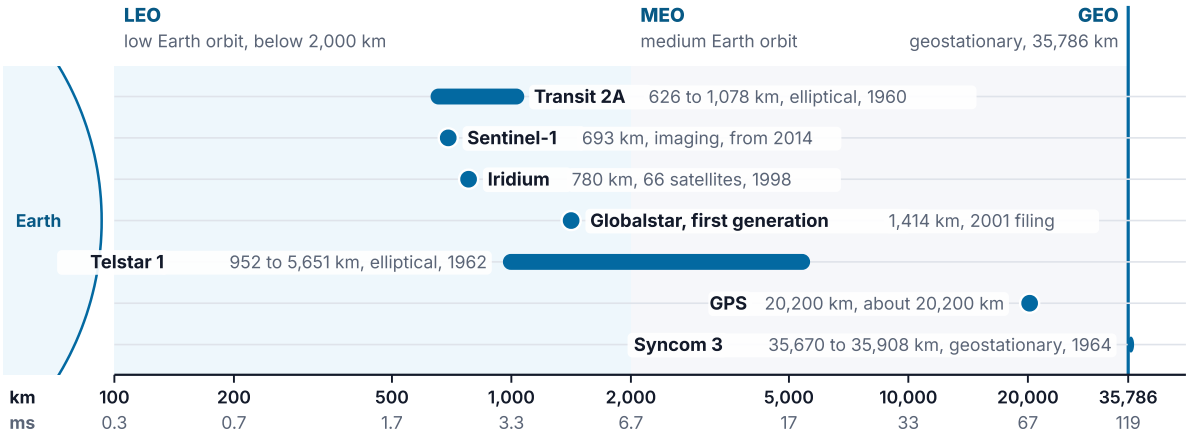
Store and forward. The satellite records a message and plays it back later, where a station can hear it. The US Army describes Courier 1B of 1960 as an experiment with delayed-repeater satellites: it would receive, store and transmit messages, and was loaded with traffic in teletype code during the 14 minutes it stayed in range of a station. A message waits; a link need not exist end to end at any instant.

Orbits, and what they cost in time

The orbit decides how long the signal travels, how many satellites a service needs and how long one satellite stays in view. Figure 1.2 places the systems of this book by altitude. A geostationary satellite stays over one point of the equator at 35,786 km, so one satellite serves a large part of the Earth and a ground antenna need not track it, at the price of a delay, from propagation alone, of about a quarter second one way, half a second for a reply. A low orbit satellite at 780 km is a few milliseconds away but crosses the sky in minutes, so a continuous service needs many of them. Telstar's ellipse sat in between and gave minutes a day. The Molniya orbit that the Soviet Union chose, told in chapter 4, made another trade, an ellipse that dwells over high latitudes.

FIGURE 1.2

Altitude sets the delay, the number of satellites and the time in view



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

Systems of this book by altitude; the second axis gives the light time straight up, one way, calculated by the kit; a slant path and a hop through the satellite take longer.

Sources: Johns Hopkins APL Technical Digest 19(1), 1998 (Transit 2A); Copernicus SentiWiki, S1 Mission; Iridium Form 10-K405 for 1998; Globalstar Form 10-K for 2001; Bell System Technical Journal, July 1963, Table I (Telstar, converted from nautical miles); GPS.gov, Space Segment; NASA NSSDCA, Syncom 3. Checked 2026-11-23.

The two-page form as a reading tool

For each system the book fills the series form, the Link Ledger, as far as primary records allow. Page 1 is ten fields about the service; page 2 is the hop budget. For an old system the form is a reading tool, not a design tool: it shows which facts the record holds and which it does not. When the builders published their numbers, as Bell Laboratories did for Telstar in

July 1963, page 2 can be worked from them. When they did not, the book prints page 1 alone and says why. A gap on the form is a finding, not a failure of the method: a missing page 2 says that no primary record read gives the numbers.

The source classes matter more in history than anywhere else. A builder's figure is the builder's claim, an official agency history is printed as published history, and an author's arithmetic is marked "calculated". Nothing is promoted on the way into a table.

Drivers that are not limits

Some forces shaped satellite systems more than any physical limit, and the frame must not hide them.

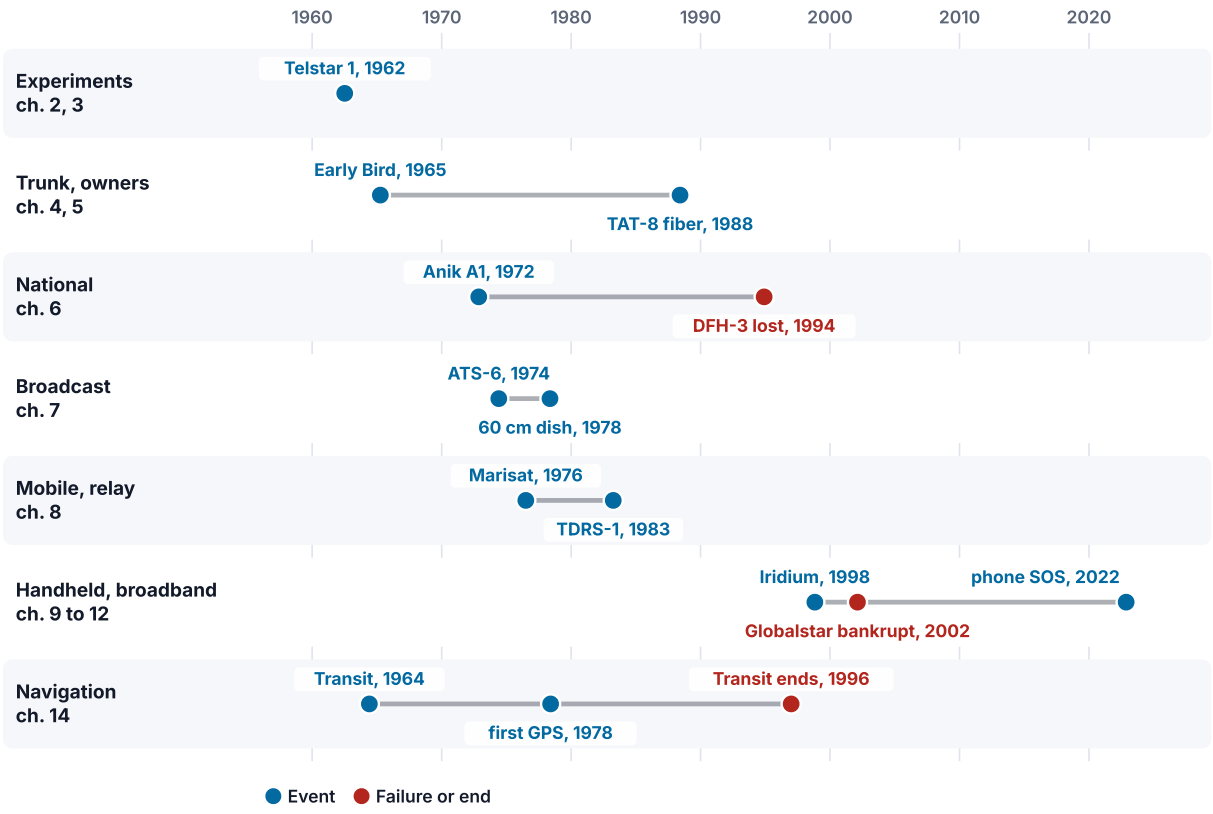
- **Law and treaty.** The Communications Satellite Act of 31 August 1962 created a corporation for profit that "will not be an agency or establishment of the United States Government". That one sentence shaped who could own the Atlantic link (chapter 4).
- **Spectrum.** On 31 January 1995 the FCC authorized Motorola's 66 satellites under a band plan that split the 1.6 GHz band between systems with different access methods, according to a later FCC order. The plan was a fact of the era before any satellite flew (chapter 9).
- **Industrial policy and national aims.** Several countries bought or built satellites to build an industry or connect a nation as much as to carry circuits (chapter 6). The book states such aims only from sources.
- **Military need.** Protection against jamming and independence can justify designs no commercial constraint would; chapters 4 and 8 treat public architecture cases from official descriptions only.
- **Demand.** Ground networks that grow faster than expected can empty a business plan, as Globalstar's 2002 filing says they did.

Parallel tracks

After 1965 the history stops being one line. The geostationary trunk, the national programs, broadcast to small dishes, service to ships and aircraft, relay for other satellites, and military systems all ran in the same decades, each with its own limit. Chapters 4 to 8 each follow one track across overlapping years, and each opens with a short note of what the other tracks were doing. Figure 1.3 shows the tracks side by side.

FIGURE 1.3

From 1965 the history runs on parallel tracks



One lane per track, with the chapters that follow it; two or three dated events per lane, failures and endings in red.

Sources: Bell System Technical Journal, July 1963; NASA SP-4217, chapters 6, 9, 14, 15 and 21; NASA History, Communications Satellites; NASA STS-6 page; Iridium Form 10-K405 for 1998; Globalstar Form 10-K for 2001; Apple Newsroom, 15 November 2022; Johns Hopkins APL Technical Digest 19(1), 1998 (Transit); NASA, Global Positioning System History. Events dated only to a month or a year are placed inside it. Checked 2026-11-23.

What would prove the frame wrong

A frame earns its place only if it can fail. This one fails where the outcome was decided outside the division of labor. Applied to Iridium in 1998, it could not have predicted the filing of 1999 (chapter 14 returns to this). It fits navigation badly, because a navigation satellite does not know its users exist: there is no user uplink, no subscription and no gateway in the user's path, though a receiver is still real engineering. It fits Earth observation partly, because the "user end" is a data product far from the link. And it says little about spectrum, law, prestige and plain demand, which often mattered more than any satellite.

The book names those misfits now so the reader can watch for them, and chapter 14 works one on purpose: Transit, the Navy's navigation system, in service from 1964, whose satellites spoke to their users and never heard from them; only the ground stations that loaded each satellite's navigation message spoke to it.

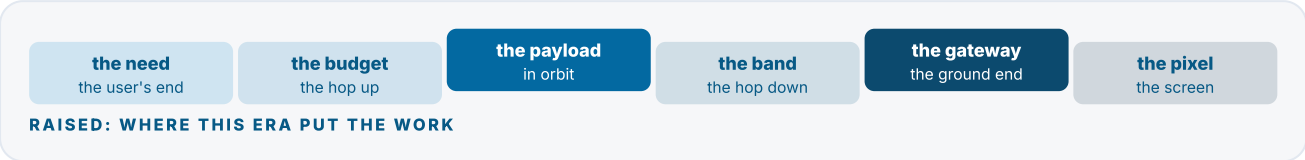
SECURITY NOTE

Who can interfere or command. The three places are also three places to attack: the user's terminal, the satellite and its command link, and the ground network that connects and controls it. For each system the book asks five questions as far as public sources allow: who is authorized to use it and to command it; who can intercept it; who can interfere with it; how a user or station is authenticated; and how service is recovered. A claim that holds only under a condition carries the condition. Two answers hold for most systems in this book and are stated here once. A transparent satellite repeats whatever arrives in its receive band and beam, so anyone with enough power there can occupy or jam it; the satellite's own beam, polarization and filters set how much power that takes, and the main remedies are on the ground, in monitoring, geolocation of the interferer and the regulator's enforcement. And the public record rarely says how commands were authenticated; the chapters mention that gap only where it matters to the case. Each chapter's note keeps what is particular to its own systems. **How it is seen.** In the public record, often only through a failure, such as Telstar's command channel in November 1962 (chapter 3). **How it is recovered.** By the owner who holds the command link and the stations, which is why field 6 of the form, who owns each end, is read before field 8: a satellite that cannot be commanded cannot be managed, whatever its radio can still do.

Monday rule: before judging a satellite system, write its row of five things in three places and the constraints its builders faced, with a source for each.

CHAPTER TWO

1945 to 1961: Store, Reflect, Repeat



On 12 August 1960 a recorded message from President Eisenhower left a 26 meter antenna at Goldstone, California, struck a balloon 30 meters across in orbit, and arrived at a Bell Laboratories antenna in Holmdel, New Jersey. The balloon added no power and did no processing. It had no receiver, no amplifier and no power for the message at all. It was a mirror. Two months later the US Army launched a satellite that did the opposite: it recorded messages on tape as it passed one station and played them back as it passed another. Between the mirror and the tape recorder lay the question of this chapter: before anyone could build a live wideband repeater in orbit, what could a satellite do with a message? The one decision it changes is simple. Before asking for a live link, ask whether a delayed one would do.

The era's row: 1957 to 1964, first half

The limit that ran out first	User end	Space	Ground end
Launch mass and power in orbit; also reliability in the radiation belts	None: the message rode wires to one station	Tape (SCORE, Courier 1B) or a mirror (Echo 1)	Large stations owned by the Army, NASA and the Bell System

An idea on paper, and a price

In October 1945 the British magazine *Wireless World* printed four pages by Arthur C. Clarke under the title "Extra-Terrestrial Relays". Clarke placed three stations in an orbit of 42,000 km radius, with a period, in his words, of exactly 24 hours, so that over the equator they would appear fixed in the sky. (The engineering condition is one sidereal day, about 23 hours 56 minutes, in a circular orbit over the equator.) He put them at 30 degrees east, 150 degrees east and 90 degrees west, and worked his example at 3,000 Mc/s. NASA's official

history credits Clarke with publishing the idea of a synchronous communications satellite in 1945; this book quotes that attribution and claims no first of its own. Nobody in 1945 could launch anything into that orbit, and the article said nothing about who would pay.

The question of money came from inside the telephone business. In 1955 John R. Pierce of AT&T's Bell Laboratories compared the cost of a satellite with that of the first transatlantic telephone cable, TAT-1, then being laid. The cable would carry about 36 voice circuits for around 35 million dollars. As NASA's history quotes him, Pierce asked whether a channel 30 times as wide, enough for 1,080 conversations or one television signal, would be worth 30 times as much: about a billion dollars. TAT-1 was laid in 1956. AT&T, with net sales of over 7 billion dollars in 1959, could think about a sum like that; NASA's entire budget, in the words of NASA's own history, was only a few hundred million.

So the requirement was clear before the satellite existed. A link across an ocean had to carry many voice circuits, or television, at a cost per circuit that could compete with cable. Whether a satellite could do that depended on what could be lifted into orbit and powered there.

Orbit is reachable, and the belts are there

The Soviet Union launched Sputnik 1 on 4 October 1957. NASA describes it as the world's first artificial satellite: a sphere 58 cm across, 83.6 kg, circling the Earth in about 98 minutes. In NASA's words it carried no scientific instruments, only a transmitter that sent a "beep-beep" signal that observers around the world could monitor with a suitable receiver. Its batteries ran out on 26 October and it re-entered on 4 January 1958. Pierce later wrote that the "necessary spurs to concrete action" on communication satellites came with that launch.

Explorer 1, launched by the United States on 31 January 1958, answered a second question. Its cosmic ray detector gave a count far lower than expected, and James Van Allen proposed that charged particles trapped by the Earth's magnetic field had saturated it. Those trapped particles, the radiation belts, would shape the next five years. Every satellite in this chapter and the next was built to survive them, and one of the most famous was damaged by them.

Store: a tape recorder in orbit

The earliest relay in this chapter was a military experiment. SCORE was launched on 18 December 1958 on an Air Force Atlas, as an Advanced Research Projects Agency project carried out by the Army Signal Corps. It carried President Eisenhower's recorded Christmas message. The Army's history says the experiment demonstrated worldwide communications

"in delayed and real time mode by means of relatively simple active satellite relays". NASA's history adds that SCORE's performance had already shown the active approach to be viable, almost two years before Echo.

Courier 1B, launched by the Army on 4 October 1960, made the delayed mode a system. It was a 51 inch sphere of 500 pounds, covered with 19,200 solar cells that gave 62 watts in sunlight. Inside were five tape recorders, four receivers and four transmitters. Each time it passed over Salinas, Puerto Rico or Fort Monmouth, New Jersey, the Signal Corps loaded it with teletypewriter traffic, which the satellite stored and played down at the next station. The Army gives its rate as slightly more than 67,000 words a minute. In the 14 minutes a station could see it, Courier could take or give the 773,693 words of the King James Bible, or both at once, with time to spare. The Army's figure for the traffic it handled is roughly six million words a day. Nine days after launch it relayed a photograph from Fort Monmouth to Salinas with no substantial loss in quality.

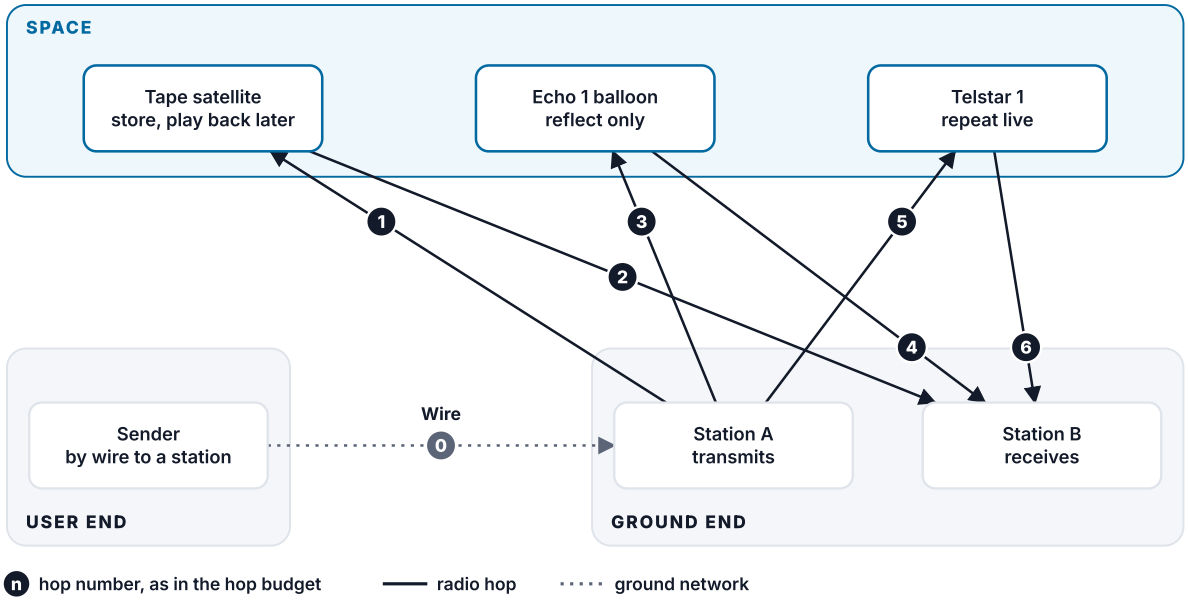
Courier's division of labor is plain. The satellite carried the storage and a modest transmitter. The ground carried the timing: stations had to be in the right place when the satellite came over, and the message waited on tape between them. The user never touched the satellite. A message went by wire to a Signal Corps station, and arrived at the other end when the satellite next passed a receiving station.

Who carried the five things, 1958 to 1962 (qualitative, from the sources in this chapter)

	User end	Space	Ground end
Power	carries little	shares (tape, Telstar); carries little (Echo)	carries most
Antenna	carries little	carries little (Echo presents about 730 square meters to the beam, its cross section, but scatters in every direction, with no amplification)	carries most
Processing	carries little	shares (tape: store and play back); carries little (Echo, Telstar)	carries most
Cost	carries little	shares	carries most
Risk	carries little	carries most (a failure in orbit cannot be repaired)	shares

FIGURE 2.1

Store, reflect, repeat: three ways to move a message through orbit, and the ground did the work in all three



Hops 1 and 2: a tape satellite (SCORE 1958, Courier 1B 1960), in its stored-message mode, loads at one station and plays back later at another; hops 3 and 4: the Echo 1 balloon reflects; hops 5 and 6: Telstar 1 repeats live. Hop 0 is the terrestrial wire; in every case the user reached the satellite only through a large station.

Author's diagram based on US Army, Early Signal Corps satellite programs remembered (2010); NASA NSSDCA, Echo 1; Bell System Technical Journal, July 1963.

The table and figure 2.1 set the grid that every path figure in this book reuses: the user end on the left, space at the top, the ground end on the right, and under each the five things in three plain levels. The levels are a reading of the sources, not a measurement.

Reflect: a mirror anyone could use

Echo began in 1956 as an experiment of the National Advisory Committee for Aeronautics to study the upper atmosphere. Pierce and Rudolf Kompfner of Bell Laboratories saw that the sphere would make an excellent test mirror and proposed a communications experiment; a meeting sponsored by the National Academy of Sciences defined it on 28 August 1958, and it became a NASA project. Echo 1 was launched on 12 August 1960: a balloon 30.48 m across, of polyester film 0.0127 mm thick, 180 kg in all. Its only electronics were beacon transmitters at 107.9 MHz for tracking, powered by 70 solar cells.

All the work of the link was on the ground. Goldstone transmitted with a 26 meter antenna at 2.39 GHz, which NASA calls very sophisticated for its time, and Holmdel received with an antenna built for the purpose. NASA's history reports two way voice links of "good" quality between Holmdel and Goldstone, and some transmissions from the United States received at Jodrell Bank in England. The balloon re-entered on 24 May 1968.

A mirror has two properties that a designer can use. It needs nothing in orbit that can fail electrically, and with no tuned electronics it can serve a wide range of frequencies. It also has a cost the designer cannot avoid. A passive reflector returns only a tiny part of the power that reaches it, so the stations at both ends must supply enormous transmitter power and receiving aperture. Echo 2 followed on 25 January 1964 with a smoother, rounder balloon, and its investigations concerned the dynamics of large spacecraft more than communications. After Echo 2, NASA's history says, the agency abandoned passive systems in favor of active satellites. Leonard Jaffe, who directed NASA's communication satellite program, wrote that Echo's success "had more to do with the motivations of following communications satellite research than any other single event".

Repeat: why the live repeater scaled

A store and forward satellite and a mirror each solved one part of the problem and left another to the ground. Courier could carry a great deal of text, but every message waited for the next pass. Echo was live, but it gave nothing back to the signal, so the stations had to be very large and the capacity small. Neither could carry a telephone conversation across an ocean at every hour, which is what the business case of 1955 required.

The answer was a satellite that received, amplified and retransmitted in real time: an active repeater. In 1958 NASA and the Department of Defense agreed that the military would develop active satellites and NASA passive ones; by August 1960 NASA had decided to pursue active research too, though not yet at synchronous altitude. AT&T began developing Telstar in the fall of 1960, with its own capital. Chapter 3 tells what that repeater could do with about 2 watts.

The live repeater did not make store and forward obsolete. It made it a different answer to a different requirement. Where a message can wait minutes or hours, a satellite that stores it needs no station in view at both ends at once, and that is still the design of many sensor and messaging satellites in 2026. Chapter 14 follows that idea through the decades.

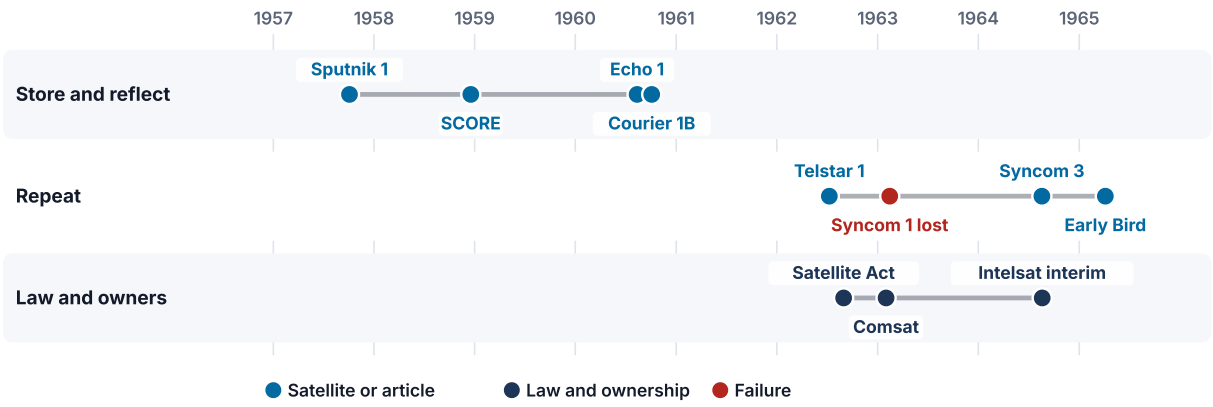
The satellites that only spoke

One more kind of satellite began in these years and fits none of the three. Transit, a US Navy navigation system developed by the Johns Hopkins Applied Physics Laboratory, put its first satellite in orbit on 13 April 1960 and entered operation in 1964. A Transit satellite broadcast

its orbit and two tones; the ship's receiver listened and never answered. There was no user uplink and no subscription, though the receiver itself was real engineering. The division of labor of this book describes it badly, and chapter 14 uses it to show where the frame stops.

FIGURE 2.2

From Sputnik to a sold circuit in eight years



Dated events of chapters 2 to 4 (Clarke's article of 1945 is off the left edge); failures in red.

Sources as in the claim tables of chapters 2 to 4 (NASA SP-4217 chapters 6, 9 and 13; US Army; NASA NSSDCA).

THE SYSTEM'S FAILURE

Courier 1B's communication system broke down after 17 days of operation, according to the Army's own history. This was a failure of the satellite, not of the launch; the source does not give the failed part. In its 17 days it had shown that tape storage in orbit could move text and pictures between stations at the rate the Army reported. The record allows only a narrow lesson. A satellite in 1960 could not be visited or repaired, so a system built on one satellite lost its whole service when one part in orbit failed.

SECURITY NOTE

Who can interfere or command. SCORE and Courier were military projects. The stations that loaded and unloaded Courier were Signal Corps stations, and the traffic was the Army's own. The command link was the Army's to protect, and the public record of the experiment does not say how it did. Echo was the reverse case. A passive reflector has no command link and nothing on board to admit or refuse a user: any station with enough power and aperture could bounce a signal off it, and any station under it could hear the result, as Jodrell Bank did. **How it is seen.** Courier's failure was seen at the ground stations when the satellite stopped answering. Echo's owner could not control who used it. **How it is recovered.** Courier's service was not recovered from the ground. Echo's open access was its design, not a fault to recover from.

Monday rule: when a link cannot be live, ask whether store and forward meets the requirement; it did for the Army's experiment in 1960, and it does for many sensors in 2026.

CHAPTER THREE

1962 to 1964: Telstar, Relay and Syncom, or the Ground Does the Work



Telstar 1 was launched in the early morning of 10 July 1962. On the first pass that Andover, Maine could use, its builders report, speech and television went between audiences in Washington and Andover, and word came that the French station at Pleumeur-Bodou was receiving picture and sound. The satellite radiated about 2 watts. Two years later Syncom 3 relayed television of the Tokyo Olympic Games from a fixed point over the Pacific. Between those two dates the industry learned that a wideband repeater in orbit worked, and then had to choose where to put it: many satellites low down, with many tracking stations, or a few satellites very high, with a delay in every conversation. The one decision this chapter changes: before asking how fast a link is, ask how many minutes a day it exists.

The era's row: 1957 to 1964, second half

The limit that ran out first	User end	Space	Ground end
Launch mass and power in orbit; then orbit and circuits per satellite	A telephone or a television set on a national network	Telstar 1: about 2 W radiated, 6390 MHz up, 4170 MHz down, minutes per pass. Syncom: one two way telephone channel at 24 hour altitude	A 380 ton horn at Andover; stations in France and Britain

Telstar as built

NASA calls Telstar the first privately financed satellite. Bell Laboratories designed and built it, AT&T paid for it under an agreement with NASA, and NASA's part was the launch on a Delta rocket and some tracking and telemetry, for which AT&T reimbursed 6 million dollars. Of six flightworthy Telstars that AT&T built with its own funds, two were launched. The satellite was a sphere of about 34.5 inches and 171 pounds.

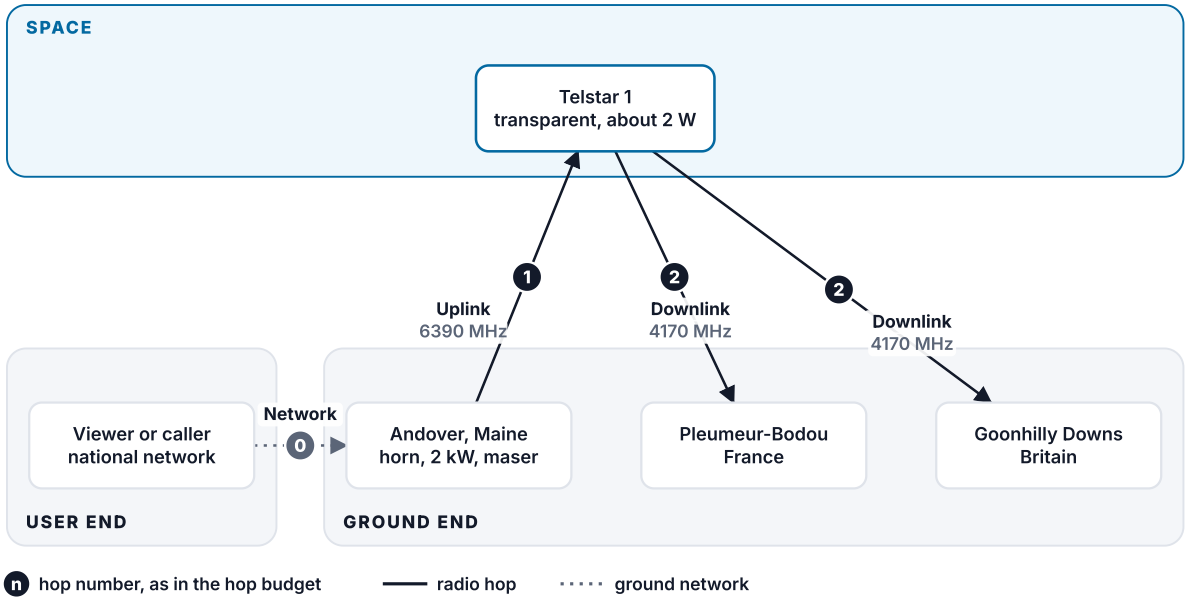
Its builders listed the constraints in the *Bell System Technical Journal* of July 1963. To give mutual visibility across the Atlantic for useful periods, they wrote, the satellite had to be placed in an orbit above 2,000 miles, a height Telstar's ellipse reached only toward its apogee; but the weight that the available rockets could put into such an orbit was limited. The frequencies had to have low sky noise and low atmospheric absorption, with bandwidth enough for television, which narrowed the choice to between one and ten gigacycles. The path losses were very great, and the satellite's radiated power was limited by the primary power that its weight allowed and by "the impracticality of using directive antennas in the satellite". And it had to survive the launch and the radiation belts. Those belts were not only natural that summer: the builders' radiation paper reports that particles put into the belts by US and Soviet high-altitude nuclear explosions played a major role in the radiation effects on the satellite's electronics.

The result was a transparent repeater. Telstar received a frequency modulated carrier at 6390 Mc, converted it to 90 Mc, amplified it, and retransmitted it at 4170 Mc, with a tone at 4080 Mc as a tracking beacon. The traveling-wave tube produced 35 dBm, about 3 watts, which is the figure NASA's history gives; after the losses of a separation network and the antenna cables, the builders put the radiated power at 33.2 dBm, about 2 watts. The antennas radiated almost equally in every direction. The solar plant delivered slightly under 15 watts when new, less than half of what all the subsystems would draw at once, so the tube ran only part of the time, switched on and off by command from the ground. The builders say they chose ground sequencing "to permit the simplest possible satellite electronics system".

The objective was high quality television with sound, or the equivalent of 600 one way telephone channels; 12 two way telephone channels were also tested. In the months after launch Bell Laboratories ran more than 250 technical tests and some 400 demonstrations, and showed transatlantic television 47 times, five of them in color.

FIGURE 3.1

Telstar 1: a 2 watt satellite between ground stations that carried the power, the aperture and the low noise



Hop 1 is Andover's uplink near 6390 MHz and hop 2 the downlink near 4170 MHz; the hop budget in this chapter takes the builders' own case, down to Andover's receiver, while the drawing shows the European stations that received the same carrier.

Author's diagram based on the Bell System Technical Journal, vol. 42 no. 4, July 1963, Table I and Table III.

Telstar 1 in the grid of figure 2.1 (qualitative)

	User end	Space	Ground end
Power	carries little	shares: about 2 W radiated	carries most: 2 kW up
Antenna	carries little	carries little: no directive antenna	carries most: 3,600 square feet
Processing	carries little	carries little: frequency shift and gain only	carries most: the FM demodulator
Cost	carries little	shares: six satellites built	shares: three stations
Risk	carries little	carries most	shares

The ground end: why the horn weighed 380 tons

Everything the satellite could not supply, the ground supplied. Andover's horn reflector had an aperture of 3,600 square feet, a length of 177 feet and, in the builders' Table III, a weight of 380 tons. It had very low side and back lobes and could be connected to its receiver with short, low-loss connections, so the system noise stayed low. Its gain was 58 dB at 4170 Mc and 61 dB at 6390 Mc, and its beam was less than a quarter of a degree wide, so the 380 tons had to track a satellite crossing the sky at up to 1.5 degrees a second. The transmitter gave 2,000 watts. The receiver began with a traveling-wave maser in liquid helium, and the station's noise temperature at zenith was 32 kelvin. The builders wrote that this research reduced the power required on the satellite by two or three orders of magnitude.

The European ends were built by the national telecommunications agencies. NASA's history says the French station at Pleumeur-Bodou used a duplicate of a Bell horn antenna, while the British station at Goonhilly Downs used a parabolic dish. On the first day Goonhilly received the signal but could not use it, because of what the builders called "a turnover in polarization at the antenna"; television came from both European stations the next day.

This is the division of labor of 1962 in its purest form. The satellite was small because a rocket could lift only a small satellite, and its power was small because the solar cells on a small satellite gave little. The margin came from the ground, where a telephone company could spend on steel, helium and klystrons what it could not put in orbit. The user, a viewer in front of a television or a caller on an ordinary line, did nothing new.

Minutes per pass, and the system AT&T envisioned

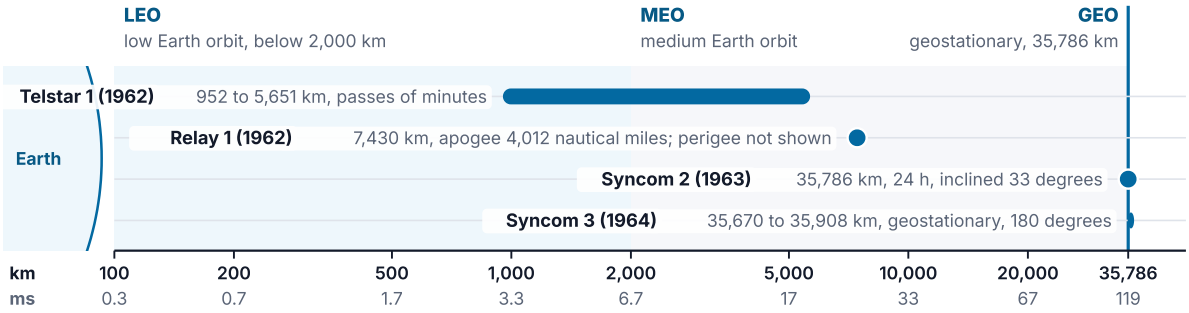
Telstar's orbit ran from 952 km to 5,651 km, once every 158 minutes. A transatlantic link needed the satellite above 7.5 degrees at Andover and at a European station at the same time. In the first weeks that happened three or four times a day, for 10 to 20 minutes each; seven weeks later there were four or five such passes a day of 20 to 40 minutes. NASA's history gives about 18 minutes at a time. Between passes there was no link.

AT&T's answer to that limit was more satellites. NASA's history records that the operational system was to consist of 50 to 120 active satellites in orbits about 7,000 miles high, and quotes Bell Laboratories: a "system of 40 satellites in polar orbits and 15 in equatorial orbits would provide service 99.9 per cent of the time between any two points on earth". Pierce explained that AT&T proposed about 25 ground stations for global coverage, and in 1961 he estimated the cost at 500 million dollars. NASA's historian adds an interpretation: as a regulated monopoly, AT&T could recover such costs through its rates, as it did for undersea cables, so the price was no deterrent to the company.

That plan put the work in a particular place. Each satellite would stay simple and low, but every station would need antennas that tracked a satellite across the sky and handed the traffic to the next one rising, and there would be dozens of stations. The ground carried the tracking, the switching between satellites and most of the cost. Chapter 4 tells why it was not built.

FIGURE 3.2

Telstar's low ellipse against the 24 hour orbit that Syncom reached a year later



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

Altitudes from the builders and NASA's catalogue; Telstar gave transatlantic passes of 10 to 40 minutes; the light time is calculated from altitude, straight up.

Source: Bell System Technical Journal, July 1963, Table I; NASA SP-4217 chapter 6; NASA NSSDCA, Syncom 2 and Syncom 3 (read 2026-11-22).

Relay: the same ground, a different builder

NASA chose RCA, not AT&T or Hughes, to build its own medium altitude experiment, Relay. Relay 1 was launched on 13 December 1962, a satellite of 170 kg, into an elliptical orbit whose apogee NASA's history gives as 4,012 nautical miles, deliberately through the inner radiation belt so that it could measure the effects of radiation on electronics. It used the same primary ground stations as Telstar, in the United States and in Europe, Brazil and Japan, and carried television between the United States, Europe and Japan.

Relay shows what an experimental satellite is for. Its primary transponder's power supply failed and the backup took over. A leaking high-power regulator made the first two weeks of operation useless. Its traveling-wave tube normally took three minutes to warm up, but could take sixteen, in a pass of only about thirty minutes. And it responded to commands that nobody had sent: it recorded 401 command anomalies in its first year. Relay 2, launched on 21 January 1964, carried a filter and better circuits on its command receiver and recorded 62.

Syncom: one telephone channel at 24 hour altitude

Hughes Aircraft had worked on a small synchronous satellite with company funds from 1959. Contemporary experts did not agree that it could be built. In 1962 Lawrence Lessing, an observer quoted in NASA's history, summed up the view that the medium altitude repeater was "the best bet" for a first venture, while "other experts" held that the synchronous satellite was "still some order of magnitude beyond present technology". NASA gave Hughes a sole-source contract for three Syncom satellites in 1961.

Syncom 1 was lost in February 1963 (the failure box below). Syncom 2, launched on 26 July 1963 with an improved nitrogen tank, reached a 24 hour orbit inclined 33 degrees, so that from the ground it traced a figure eight over the Atlantic and Brazil near 55 degrees longitude; it began regular service on 16 August. It was a cylinder of 39 kg in orbit, with 29 watts from its solar cells and two traveling-wave tubes of 2 watts each. It received near 7360 Mc and retransmitted at 1815 Mc, and its repeater was designed for one two way telephone channel or 16 one way teletype channels. Voice, teletype, facsimile and data went between Lakehurst, New Jersey and the ship USNS Kingsport off Africa, and television from Lakehurst to Andover.

Syncom 3, launched on 19 August 1964, added a wideband channel for television. Its orbit was brought to an inclination of 0.1 degree, so it was geostationary, not only geosynchronous, and it was stationed at 180 degrees longitude by 23 September. It relayed the Tokyo Olympic Games to the United States through a new station at Kashima and the Navy station at Point Mugu, California; NASA's history notes the picture was not up to "commercial quality", and that the Games went on from the United States to Europe through Relay. Both Syncoms were later handed to the Department of Defense.

The trade: many low satellites, or one high one

By the end of 1964 two Telstars, two Relays and two Syncoms had worked in orbit, and the two designs divided the work in opposite ways.

Two ways to divide the work, as argued in 1962 to 1964

	Medium altitude (Telstar, Relay; AT&T's plan)	Synchronous (Syncom 2 inclined, Syncom 3 geostationary; Hughes's case)
Satellites for continuous service	Dozens; 50 to 120 in AT&T's plan	Three, which NASA's history says cover the entire globe; the polar regions are in fact out of sight of a geostationary satellite
Ground antennas	Track across the sky; a station might need two, to hand over between satellites	Point at a nearly fixed spot if the orbit is geostationary (Syncom 3); Syncom 2's figure eight still had to be followed
Time in view	Minutes per pass for each satellite	Always in view, for stations inside the satellite's coverage
Delay	Short	About a quarter second one way, half a second for a reply (calculated)
What was proven by 1964	Wideband television and many telephone channels	One telephone channel; television of less than commercial quality

Hughes's case, as its managers put it to a House subcommittee in 1962, was that a synchronous system could be installed sooner because fewer satellites had to be launched and the ground stations were simpler. The launch record of the time pointed the other way: Telstar and Relay had worked, Syncom 1 had not, and Syncom's light weight held its payload to a single circuit. In September 1963 Siegfried Reiger of Comsat wrote that most engineers agreed a medium altitude system could be made operational sooner, "but there also appears to be general agreement that in the long run the [geo-]stationary-satellite concept offers the greatest promise and growth potential". The delay was the price. From 35,786 km a signal takes about 0.12 seconds to go up and as long to come down, so about a quarter second one way between stations and half a second before a reply can arrive. Chapter 5 shows what that delay later cost a telephone company.

One sentence of timing belongs here. The Senate debate on the Communications Satellite Act resumed on 26 July 1962, sixteen days after Telstar's launch, and President Kennedy signed the Act on 31 August 1962, seven weeks after the launch. Chapter 4 tells that story.

This chapter has no thread scene, because the satellite replaced a cable for the telephone company, not for its customers.

THE SYSTEM'S FAILURE

Syncom 1 was launched on 14 February 1963. When the motor that was to circularize its orbit fired, the satellite fell silent. NASA's history gives the most likely cause as a failure of the high-pressure nitrogen tank, one of two attitude control propellant systems the satellite carried. This was a failure of the satellite, at the moment of orbit insertion, not of the launch vehicle. Its consequence was architectural as well as technical: in the months when the industry was choosing between orbits, the synchronous case had a lost satellite against two working medium altitude ones, until Syncom 2 flew in July with an improved tank. The lesson: a design that depends on one high satellite depends on every step of getting it there.

SECURITY NOTE

Who can interfere or command. Telstar took 15 commands near 123 Mc, pulse-duration modulated. Its builders chose the command code structure to match NASA's Minitrack network, "in order that the far-flung Minitrack stations would have command capability", so authority to command lay with the Bell command stations and NASA's tracking network. The papers say who could command, not how anyone else was kept out: they give the shared command code as a convenience for the tracking network and do not describe it as a protection. **How it is seen.** On Relay 1, ground stations saw command anomalies during the 15 percent of the orbit when the satellite was in view; the main cause was interference from the satellite's own wideband subsystem. On Telstar, the command channel began to act erratically in November 1962 and stopped responding on 23 November; telemetry pointed to radiation damage in the command decoder. **How it is recovered.** Relay 2 carried a filter and better circuits to tell noise from commands. Telstar's engineers devised special codes that bypassed the suspect transistors, sent one successfully on 20 December 1962, and had normal commanding back by early January 1963, until the command system failed again in February.

Telstar's Link Ledger is used elsewhere in this series with the same numbers. Page 1, the service ledger:

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.

Page 2 is an archival budget, the builders' own case from their Table V: up from Andover and back down to Andover, both hops at the worst-case range of 5,000 nautical miles, with the free-space losses recalculated and the satellite's output taken from the repeater paper (33.2 dBm radiated, where Table V uses 33 dBm). The satellite's receiver had a noise figure of 16.5 dB; the receiver adds 290 K times (10 to the power 1.65, less 1), about 12,664 K, to the 290 K of the warm Earth it looks at, for a system noise temperature of about 12,954 K, which is why the uplink needed 2 kW and a 61 dB horn. C/N0 is the carrier power over the noise in one hertz of band, in dBHz; less 10 log of the bandwidth, 74.0 dB for 25 MHz, it gives the carrier to noise ratio C/N. Free-space loss is 20 log10(4 pi d f / c) (ITU-R P.525). The uplink reaches 90.6 dBHz at the satellite and the downlink 88.6 dBHz at Andover. Through a transparent satellite the two noises add, so the inverse ratios add, 1/(C/N0) = 1/(C/N0 up) + 1/(C/N0 down), in plain ratios, not decibels, and the circuit reaches 86.5 dBHz, below either hop, against 79.0 dBHz needed to stay above the threshold of the FM demodulator in a 25 MHz band: 7.5 dB to spare, while the satellite is in view. That margin is against the demodulator's threshold, not against commercial quality: at this range the builders judged the picture a slight impairment, and the noisiest telephone channel 6 dB above the tentative CCIR objective for a commercial grade circuit. Figure 3.3 draws that circuit.

FIGURE 3.3

Two hops that each have room to spare make one circuit with 7.5 dB above the threshold



Required for: an FM television picture above the threshold of the frequency compression demodulator (about 5 dB C/N in 25 MHz).
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.
Source of the required value: BSTJ 1963, p. 796: FM threshold 10 dB less about 5 dB, 2026-11-23.

An archival budget: the builders' Table V at 5,000 nautical miles on both hops, free-space losses recalculated and the repeater paper's 33.2 dBm radiated; the uplink and downlink C/N0 combine to 86.5 dBHz against 79.0 dBHz needed (all C/N0 values in dBHz; only the margin is in dB).

Bell System Technical Journal, July 1963, Table V and p. 796; free-space loss by ITU-R P.525-5; arithmetic recomputed for this book.

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.

Monday rule: ask how many minutes per day the link exists before asking how fast it is.

CHAPTER FOUR

1962 to 1973: Who Owns the Link? COMSAT, Intelsat, Molniya and Intersputnik



On 31 August 1962, seven weeks after Telstar's launch, President Kennedy signed the Communications Satellite Act. It authorized "a communications satellite corporation for profit which will not be an agency or establishment of the United States Government". The company that had built Telstar with its own money would not be the United States participant in the system; a new corporation would, holding and managing the American share of the space segment, and the telephone carriers together could hold no more than half of its voting shares. AT&T became one of Comsat's shareholders (with RCA it held a third of the shares by 1965, in NASA's history) and stayed a carrier, not the owner of the system. Nor did the Act give Comsat every American earth station: section 201(c)(7) left the FCC to license each station to the corporation, to authorized carriers or to both jointly. Three years later the Soviet Union answered the same question in a different way, with satellites owned by the state, in a different orbit, for a different map. Once the link worked, who was allowed to own it? The one decision this chapter changes: find out who owns each end, and under which agreement, before reading the link numbers.

The era's row: 1965 to the 1980s, the trunk and the ownership question

The limit that ran out first	User end	Space	Ground end
Continuous coverage and circuits per satellite; also treaty, ownership and national policy	A telephone on a national network	Early Bird: 240 circuits or one television channel (1965). Molniya 1: a 12 hour elliptical orbit	National stations, in national hands; state networks in the Soviet system

Meanwhile, on the other tracks

When	What	Told in
1964	The Transit navigation system enters operation for the US Navy	Chapter 14
1965	Syncom 2 and 3 pass to the Department of Defense	Chapter 3
June 1967	France and Germany agree on the Symphonie satellites	Chapter 6
July 1969	Intelsat III completes coverage of the Indian Ocean, days before Apollo 11 lands on 20 July	Chapter 5
1 September 1969	Canada creates Telesat for a domestic satellite system	Chapter 6

The Act: a corporation that is not an agency

The question of ownership was open before Telstar flew. NASA's history records that the Eisenhower administration, in December 1960, stressed the American tradition of private telecommunications under government licensing, and seemed willing to let AT&T extend its monopoly into space. President Kennedy's policy statement of 24 July 1961 still favored private ownership, but with features meant to avoid a monopoly. AT&T was then the largest US common carrier and the only international telephone carrier, and was spending its own money on satellites, so, in the words of one history NASA cites, commercial satellite use "would very likely become AT&T utilization".

The bill that became the Act passed the House 354 to 9 on 3 May 1962. In the Senate, Estes Kefauver and his allies attacked the bill and filibustered it. The debate resumed on 26 July, sixteen days after Telstar's launch, and on 14 August the Senate voted cloture 63 to 27, then passed the bill 66 to 11 on 17 August. Kennedy signed it on 31 August 1962 as Public Law 87-624.

The Act's own words set the division of ownership. Section 102 declares the policy of establishing, "in conjunction and in cooperation with other countries", a commercial communications satellite system, with US participation "in the form of a private" corporation. Section 303 gives the board three directors appointed by the President, six elected by the shareholders that are communications carriers and six by the other shareholders, and forbids a carrier to vote for more than three candidates. Section 304 lets

the public hold shares and lets a carrier hold them only if the FCC authorizes it; after the first issue the authorized carriers together may hold no more than 50 percent of the voting shares, and any other holder no more than 10 percent.

Comsat: carriers and the public as owners

On 4 October 1962 Kennedy named thirteen incorporators. The corporation was incorporated in the District of Columbia on 1 February 1963, and Joseph V. Charyk, Under Secretary of the Air Force, became its president. The first five million shares, at 20 dollars, were reserved for communications carriers. By May 1964 AT&T had offered to buy 85 million of the 100 million dollars reserved for carriers; because the issue was oversubscribed it was allowed 57.9 million dollars of shares, 29 percent of the 200 million dollars of the two issues together. ITT took 11 percent, GTE 4 percent and RCA 3 percent. The second five million shares went to the public on 2 June 1964; there were about 130,000 shareholders, most with fewer than 100 shares, and the price rose from 20 to 48 dollars by mid August.

So the American end of the space segment was owned by a corporation whose largest shareholder was AT&T, but which AT&T did not control. NASA's historian of Telstar puts the result plainly: between the success of Telstar 1 and the launch of Telstar 2 on 7 May 1963, "AT&T lost its chance to control commercial satellite communications". That is a later judgment, written in the 1990s, and it is labeled as such here.

Intelsat: shared ownership in space, national ownership on the ground

The Europeans did not want to join an American system as customers. In December 1962 the European Conference of Postal and Telecommunications Administrations began formal studies, and the Europeans decided to negotiate as a bloc. They preferred a consortium, with shared ownership, to a series of bilateral agreements. The first formal meeting, in Rome in February 1964, agreed on an interim system, with Comsat, the US participant, also acting as manager on behalf of all the participants.

The hard points were the length of the interim period, the shares and the votes. Ownership was to follow each country's share of international traffic, measured from the International Telecommunication Union's projections for 1968; the United States had more than half. The settlement gave Comsat a 61 percent undivided interest in the space segment, a share that could fall as new members joined but never below 50.6 percent. On important decisions, such as system choice, rates, ground station standards and contracts, the governing committee needed 12.5 votes above those Comsat controlled. A clause asked that contracts be spread among member countries in rough proportion to their shares when bids were comparable. The ground stations were not part of the shared ownership: they stayed in national hands.

Thirteen governments and Vatican City initialed the "Agreement Establishing Interim Arrangements for a Global Commercial Communications Satellite System" on 24 July 1964, and it was opened for signature on 20 August 1964. Intelsat was founded then as an interim consortium, not as a permanent organization. The definitive agreement was signed on 20 August 1971 and entered into force on 12 February 1973.

Early Bird: circuits for sale

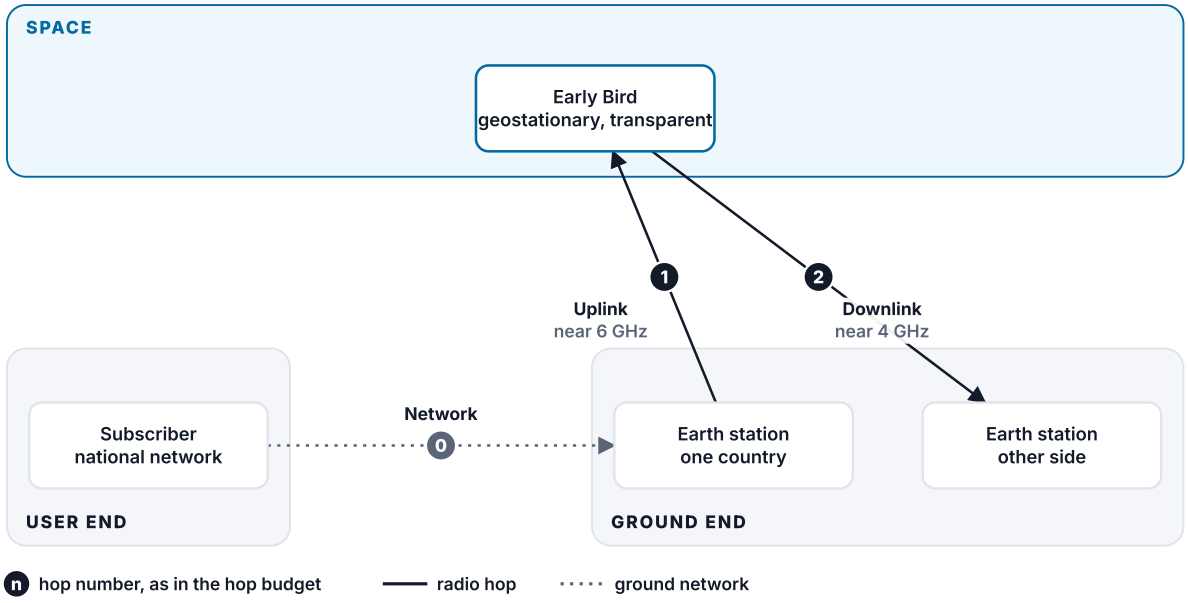
Comsat had not chosen a system when it bought its first satellite. On 4 March 1964 it asked the FCC to launch a small synchronous satellite over the Atlantic in early 1965; the FCC approved in April, and noted that it preferred Comsat to own and operate its own ground stations rather than use AT&T's. The satellite came from Hughes and was almost identical to Syncom 3, but it used what NASA's history calls the commercial frequencies, near 6 and 4 GHz, instead of the military frequencies near 8 and 2 GHz that Syncom had used. The bands themselves were set by international allocation: the Soviet delegation in 1964 asked whether the allocations of the Extraordinary Administrative Radio Conference were definitive enough to build an operational system on, a question chapter 5 and the later books of this series take up. Comsat treated it as both experimental and commercial, and NASA's history lists it as the first commercial communications satellite.

Early Bird was launched on 6 April 1965 into a geostationary orbit over the Atlantic. It weighed 85 pounds (38.6 kg) and could carry 240 voice circuits or one television channel. NASA's history compares that with the 317 channels of all the Atlantic telephone cables together; the satellite and its launch cost Comsat around 7 million dollars. NASA launched it and gave basic tracking; Comsat's own staff performed all orbital and control functions.

The dates of first service differ by source and by meaning. NASA's history gives 1 June 1965 for commercial service and 27 June for the official start, brought forward by an emergency FCC permission after a transatlantic cable failed days earlier. ESA dates the first commercial transatlantic telephone conversation by satellite to 28 June 1965. Carriers asked for 226 of the 240 circuits; the FCC allocated 75 to AT&T, ten each to ITT, Western Union International and RCA, and six to Canada. The European stations were not yet ready for the full load. By the end of 1965 Early Bird had provided 150 telephone half circuits and 80 hours of television, and Comsat's first quarterly report showed 966,000 dollars of revenue. ESA records that the satellite outlived its planned 18 months by two years.

FIGURE 4.1

Early Bird: one satellite in a fixed place, owned in common, between stations owned by each country



Hop 1 is the uplink near 6 GHz and hop 2 the downlink near 4 GHz; the satellite was owned by the interim consortium, each earth station by its own country.

Author's diagram based on NASA SP-4217, chapters 9 and 13.

Early Bird in the grid of figure 2.1 (qualitative)

	User end	Space	Ground end
Power	carries little	shares	carries most
Antenna	carries little	carries little	carries most
Processing	carries little	carries little: frequency shift and gain	carries most
Cost	carries little	shares: owned in common	carries most: one station per country
Risk	carries little	carries most: one satellite	shares

Early Bird's service ledger shows how much of its record is about ownership and how little about radio. No hop budget is printed: no readable source gives the hop numbers.

LINK LEDGER · LL-1965-01 · SERVICE LEDGER

1965-06-28

System: Early Bird (Intelsat I): a transatlantic telephone circuit through one geostationary transparent satellite

Retired | Class: service only

1 Requirement	Carry telephone circuits, and at times one television channel, between North America and Western Europe at every hour, on a satellite its owner treated as both experimental and commercial. The unit sold was a voice circuit leased to a carrier.
2 Ends and path	A subscriber reaches a national earth station over the ordinary telephone network at both ends. Earth stations already existed in the United Kingdom, France, Germany, Italy, Brazil and Japan, besides the United States. **Path:** Transparent: the satellite receives near 6 GHz and sends near 4 GHz, the commercial frequencies, where Syncom had used military frequencies near 8 and 2 GHz.
3 Orbit and time	Geostationary over the Atlantic Ocean. The exact longitude is not in the sources read. **Time:** Continuous. About 0.24 s from station to station at the shortest path, so about half a second before a reply can arrive (calculated from 35,786 km and the speed of light).
4 Band and permission	**Uplink.** near 6 GHz; exact frequencies and the coordination record not read **Downlink.** near 4 GHz; as above
5 Capacity	**Up.** 240 voice circuits, or one television channel instead. **Down.** The same capacity, shared by the stations. By the end of 1965: 150 telephone half circuits and 80 hours of television.
6 Who owns each end	**Space segment.** Interim Intelsat consortium; Comsat held 61 percent and managed it. Built by Hughes **Ground segment.** National: each country kept its own station **Customer relationship.** Carriers leasing circuits (75 to AT&T in the FCC's 1965 allocation) **The exit.** The Atlantic cables
7 Trust	Comsat staff performed orbital and control functions; NASA launched the satellite and gave basic tracking. Access was by membership; each station stayed in national hands.
8 How it fails, and how we would see it	One satellite in the ocean region: its loss takes every circuit at once. Planned life 18 months. Commercial risk: low fill in the first months. **How we would see it:** At the earth stations and in the carriers' circuit records.
9 Cost shape	About 7 million dollars for the satellite and its launch, a small part of the 200 million dollars Comsat raised in its first share issues. Revenue in Comsat's first quarterly report: 966,000 dollars.
10 Evidence	240 circuits or one TV channel published history NASA SP-4217, ch. 9, p. 118, 2026-11-23 Near 6 and 4 GHz published history NASA SP-4217, ch. 9, p. 121, 2026-11-23 About 7 million dollars published history NASA SP-4217, ch. 9, p. 121, 2026-11-23 0.24 s station to station calculated 35,786 km twice, at 299,792 km/s, 2026-11-23

Service only, no hop budget: No readable source gives the hop numbers (transmit power, antenna gains, receiver noise); a Comsat technical paper of 1965 would settle them.

The Soviet answer: Molniya and Orbita

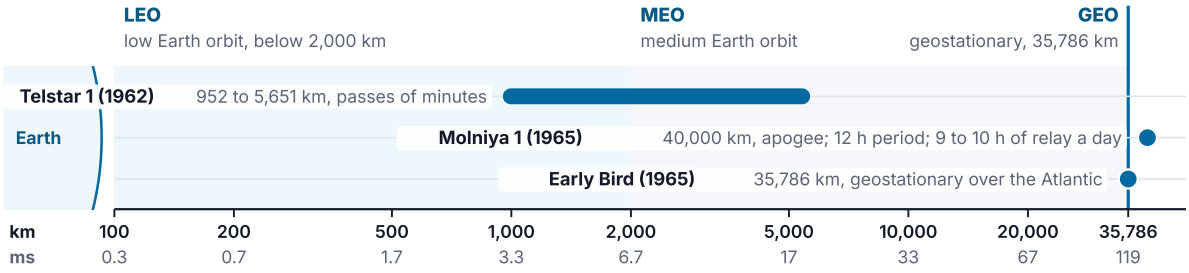
The Soviet Union was invited to the talks and declined. In Geneva in June 1964 its delegation called the negotiations "an American or U.S. inspired experimental program" and said it was "not really very interested in it at this time". That autumn, at the United Nations and elsewhere, Soviet and other Communist delegates attacked the interim arrangements as a way of handing space communications to US private capital, and weighted voting as a breach of sovereign equality.

Its own system was built for its own map. US tracking records of the time, declassified in 2015, describe Molniya 1, launched on 23 April 1965, as a communications satellite in a highly eccentric orbit with an apogee of nearly 40,000 km and a period of 12 hours: US tracking, which measured the orbit but could only infer the mission. A report of January 1966 says the two Molniyas of 1965 could each give about 9 to 10 hours of relay a day between the easternmost and westernmost parts of the country, and that the Soviets claimed to have used them for black and white and color television and for telephone calls. The same records judged that Cosmos 41, launched in August 1964 into a nearly identical orbit, had been an unsuccessful attempt, and noted that the first Molniya 1 had not been heard from since 15 August 1965; the record shows only that US monitoring heard nothing more, not why. A second was launched in October. On 29 November 1965, NASA's history notes, color television experiments between the Soviet Union and France began through a Molniya satellite.

The division of labor was the reverse of Early Bird's in one respect. A geostationary satellite sits over the equator and appears low in the sky from far northern latitudes; a long elliptical orbit can instead spend most of its time high over the northern hemisphere, near its apogee. The price is on the ground: the satellite moves, so stations must track it, and one satellite cannot cover all day. No Soviet statement of the reason for the choice was read for this book, so the geometry is given as the property of the orbit, not as the designers' stated motive. NASA's official history calls the domestic receiving network, Orbita, "quite successful and extensive"; its start date, its stations and the satellite's frequencies are not in any source that could be read, so they are left out.

FIGURE 4.2

Two answers to continuous coverage: a fixed point over the equator, and a long loop that hangs over the north



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

Molniya 1 is drawn at its apogee only, because its perigee is not in the sources read; Telstar is shown for scale.

Source: NORAD Weekly Intelligence Reports 44/65 (29 October 1965) and 1/66 (7 January 1966), declassified 2015; NASA SP-4217 chapters 6 and 9; Bell System Technical Journal, July 1963.

The service ledger for Molniya is printed from those records. It is thinner than Early Bird's, and the gaps are shown rather than filled: no primary Soviet or Russian record could be read, so the ledger carries no budget and names what would settle it.

LINK LEDGER · LL-1965-02 · SERVICE LEDGER

1965-04-23

System: Molniya 1: television and telephone across the Soviet Union through a satellite in a 12 hour elliptical orbit

Retired | Class: service only

1 Requirement	Relay television and telephone calls between the western and eastern ends of the Soviet Union, including high latitudes; inferred from the service recorded at the time.
2 Ends and path	Soviet ground stations at both ends. NASA's official history calls the domestic receiving network, Orbita, quite successful and extensive. Station sizes, sites and start dates are not in the sources read. **Path:** A relay of television and telephone calls between ground stations. The payload design (transparent or not) is not in the sources read.
3 Orbit and time	Highly eccentric: apogee nearly 40,000 km, period about 12 hours (US tracking, 1965). Perigee and inclination are not in the sources read. **Time:** About 9 to 10 hours of relay a day between the easternmost and westernmost parts of the country, per a US assessment of January 1966. Near apogee, at least 0.27 s station to station (straight up and down; calculated).
4 Band and permission	**Uplink.** not in the sources read **Downlink.** not in the sources read
5 Capacity	**Up.** Black and white and color television, and telephone calls, as Soviet statements claimed (reported in the same US assessment). **Down.** As above. Channel counts are not in the sources read.
6 Who owns each end	**Space segment.** The Soviet state **Ground segment.** The Soviet state: the Orbita network and its stations **Customer relationship.** State television and the state telephone network **The exit.** Not applicable
7 Trust	Command and authorization are not in the sources read. The 1966 US assessment noted that the satellites could also carry military traffic inside the country.
8 How it fails, and how we would see it	US tracking had not heard the first Molniya 1 since 15 August 1965 (no cause was established). A second followed in October. The same source judged Cosmos 41 (1964), in a nearly identical orbit, an unsuccessful attempt. **How we would see it:** By its own signals. Outside observers followed its orbit and its radiation counters.
9 Cost shape	Not published in the sources read.
10 Evidence	Apogee nearly 40,000 km; 12 hours measured NORAD tracking, weekly report 44/65, 29 Oct 1965, p. 9, 2026-11-23 About 9 to 10 hours of relay a day assumption A US assessment, NORAD weekly report 1/66, 7 Jan 1966; a Soviet operating record would settle it, 2026-11-23 Color television with France, 29 Nov 1965 published history NASA SP-4217, ch. 13, note 65, 2026-11-23 0.27 s up and down at apogee calculated 40,000 km at 299,792 km/s, 2026-11-23

Service only, no hop budget: No readable Soviet or Russian source gives the band, transmit power or antenna size; a Russian archive record would settle them.

Intersputnik: one state, one vote

On 5 August 1968 the Soviet Union, Bulgaria, Cuba, Czechoslovakia, Hungary, Mongolia, Poland and Romania submitted a draft agreement for an international system, Intersputnik, to the United Nations. NASA's official history sets out how it differed from Intelsat. Only states could be members, and each had one vote, with a two-thirds majority for decisions. The satellites could belong to the organization or be leased to it by member states. The ground stations would be the property of the states that built them. The draft's preamble contemplated direct broadcasting from satellites, and it allowed for more than one international system, where Intelsat's signatories had committed to one.

The same history records the draft's handicaps: the invasion of Czechoslovakia in the same month, ambiguities over who owned the space segment, and no requirement of nondiscriminatory access. The final agreement is dated 15 November 1971, the same year as Intelsat's definitive agreement. NASA's chapter, which restates its author's work of 1972, says it had not come into force by mid 1972; the date it did enter into force is not in a source read for this book. Intersputnik's own history gives its registration with the UN Secretariat as 27 March 1973, which is a registration, not an entry into force.

FIGURE 4.3

Two organizations for one technology: who joined, who voted, who owned the ground

	Intelsat, interim arrangements (1964)	Intersputnik, draft (1968) and agreement (1971)
Founding parties	13 governments and Vatican City initialed, 24 July 1964	Soviet Union and 7 states submitted the draft, 5 August 1968
Members	Governments or their designated communications entities	States only
Voting	Weighted by ownership; Comsat 61 percent, never below 50.6; important decisions need 12.5 votes above Comsat's	One vote per state; a two-thirds majority
Space segment	Owned in common, managed by Comsat	Owned by the organization or leased to it by member states
Ground stations	Stay in national hands	Property of the state that built them
Legal form	Interim; definitive agreement signed 20 August 1971, in force 12 February 1973	Agreement of 15 November 1971; not in force by mid 1972, per NASA's history; registered with the UN 27 March 1973 (Intersputnik)

Intelsat's interim arrangements of 1964 against the Intersputnik draft of 1968, as NASA's official history describes them.

Source: NASA SP-4217 chapter 13 (Galloway); definitive agreement dates from US GAO report GAO-04-891.

Military systems leave the commercial road

The US military had been expected to be a large customer. NASA's history puts its share of all US overseas traffic at 30 percent. But Intelsat's partial foreign ownership meant, in that history's words, that it "could not provide communications services for the U.S. military", and on 15 July 1964 Defense Secretary Robert McNamara announced that the Department

of Defense would build its own satellite system. Philco won the contract; Comsat's own bid for the military business delayed the launch from 1964 to 1966. The Army's history names the program the Initial Defense Communications Satellite Program. The Department did not abandon commercial carriers: by January 1971 its satellite communications system leased 62 percent of its two way channel miles from them, and owned the other 38 percent.

This book gives the military systems only as public architecture. The reasons for a separate system are stated here only as far as the official history states them: ownership, and who could be allowed to carry the traffic. Britain's own military satellites belong in the same story; chapter 8 takes up the military systems, from the first US defense satellites of 1966 to Skynet, as far as their public record goes.

The system that was not built

AT&T's medium altitude system of 50 to 120 satellites, described in chapter 3, was never built. The documented influences are several, and the sources do not rank them, so they are set out side by side.

- **Law and the carriers.** The Act created a corporation in which carriers could hold no more than half the voting shares, and Kennedy's policy of 1961 was openly against extending AT&T's monopoly into space. AT&T would be a shareholder and a customer, not the system's owner.
- **Procurement.** NASA chose RCA for Relay in May 1961, not AT&T, and gave Hughes a sole-source contract for Syncom. When Comsat asked for designs for its basic system, the four answers of February 1964 included only one synchronous design, from Hughes. Comsat bought Early Bird from Hughes without committing to an orbit and gave study contracts for medium altitude systems to AT&T with RCA, and to TRW with ITT.
- **Syncom's demonstration.** On 25 February 1963 NASA announced that it would concentrate on synchronous satellites, and the successful launch of Syncom 2 on 26 July 1963, in NASA's history's words, "made it clear that geosynchronous satellites were practical". The same history adds that Syncom's light weight had limited its payload to a single telephone circuit, far less than Relay or Telstar carried: the orbit was proven before the capacity was.
- **The cost of the ground.** A medium altitude system needed tracking antennas and many stations; a synchronous one needed few satellites and simpler stations. NASA's history says that "for a variety of reasons, including costs", Comsat rejected the joint AT&T and RCA offer.

The decision came in steps. AT&T and RCA proposed eighteen satellites in random polar orbits, TRW and ITT twelve in controlled, phased orbits. In May 1965 Charyk announced that Comsat was no longer considering the random approach. On 17 August 1965 Comsat, for Intelsat, asked for proposals for a satellite that could work in either a synchronous orbit or a phased system between 6,000 and 12,000 miles, and on 29 December 1965 it asked for designs of a fourth generation of 6,000 voice circuits that would be synchronous. NASA's historian writes: "Comsat had finally chosen a system!"

Contemporary explanation and later interpretation should be kept apart. In 1963 Comsat's own engineer wrote that a medium altitude system could be operational sooner, but that the stationary satellite offered the greatest long-run promise; that was a technical judgment made before the choice. In NASA's history published in 1997, the historian of the period wrote that without government intervention "an AT&T-dominated medium-altitude system would almost certainly have been launched in the mid-1960s". That is a counterfactual, written three decades later. Neither is a single cause, and this book does not name one.

THE TRADE-OFF, AND WHAT IT COST

The lead case of this chapter is a trade-off, not a failure. The medium altitude system that AT&T envisioned was not built, and its designer lost the ownership of the system to a corporation created by statute. What the choice of a synchronous system bought is documented: few satellites, a fixed antenna at each station, continuous service from the first satellite, and an end to the tracking networks that a medium altitude system would have needed. What it cost is documented too, and later chapters count it: a propagation delay of about a quarter second each way, half a second before a reply can arrive, which chapter 5 shows driving telephone traffic back to cable; and a system whose whole service in one ocean region rested, at first, on one satellite. The medium orbit returned decades later in a different form, as chapter 10 tells.

SECURITY NOTE

Who can interfere or command. In Intelsat, authorization to use the system worked by membership: a contractual control, not a technical one, which did nothing by itself to stop reception or an unauthorized transmission. Comsat, as manager, commanded the satellites; the earth stations stayed in national hands, under each country's own arrangements (in the United States, the FCC licensed each station to Comsat, to carriers or to both), and those arrangements decided who reached the system. States outside the arrangement could not use it on those terms, and the Soviet Union and its partners built another. In the official history's words, Intelsat's partial foreign ownership and operation meant it "could not provide communications services for the U.S. military"; the Department of Defense built its own system for that reason while still leasing commercial circuits for much of its traffic. **How it is seen.** Through the ownership records: who is a signatory, who manages, who holds the station. **How it is recovered.** In 1965, by the cables that still carried most transatlantic traffic, and by the next satellite. Interception and interference on shared wide beams are taken up in chapter 5.

Monday rule: find out who owns each end, and under which agreement, before reading the link numbers.

PART II: POWER MOVES TO ORBIT

CHAPTER FIVE

1965 to 1988: The Geostationary Trunk, and the Cable That Took the Dense Routes Back



In February 1983 MCI announced what NASA's history of the company calls "the largest purchase of satellite transponder capacity in telecommunications history": twenty-four transponders on two Hughes satellites, carrying 48,000 circuits. Both satellites reached orbit and began to operate. By the end of 1984 the same company had a single-mode fiber route running between Washington and New York, customer complaints about delayed voice had, in the history's word, "skyrocketed", and after 1988 MCI left satellites as far as it could. Nothing in the record says a satellite failed. The requirement did. This chapter asks why the geostationary satellite won so much of the long distance telephone trunk, and why, on the dense routes where fiber arrived, it lost its place again. The evidence is one company's domestic network and one ocean's first fiber cable; it shows where the turn came, not how large a share of all traffic moved.

The row for this chapter

Era	Limit that ran out first	User end	Space	Ground end
1965 to the 1980s: the geostationary trunk	Continuous coverage and circuits per satellite; also treaty, ownership and, at the end, the delay a talker will accept	An ordinary telephone on a national network	A transparent repeater in geostationary orbit; from 240 circuits on Early Bird to thousands	National gateways and carriers' earth stations, owned by the carriers

Meanwhile. Canada puts up the first Anik in November 1972 and other countries buy satellites of their own (chapter 6). Broadcast experiments to small dishes begin with ATS-6 in 1974 (chapter 7). Ships get Marisat in 1976 (chapter 8). Navigation satellites are already in

service for the US Navy (chapter 14). MCI's first single-mode fiber route opens in 1984, in this chapter.

Global coverage, and the price of a circuit

Chapter 4 ended with an interim consortium, a single satellite and 240 circuits. Early Bird cost COMSAT about 7 million dollars with its launch, according to NASA's official history, and its 240 voice circuits (or one television channel instead) almost equaled the 317 channels of all the Atlantic telephone cables then in use, in the history's own units; neither number is defined further, so the comparison is rough. That history adds that the newest cable "carried fewer channels and cost about ten times as much the satellite". By the end of 1965, in the same page's words, Early Bird had provided 150 telephone "half-circuits" and 80 hours of television service. The sources count in different units, circuits, half circuits, channels and transponders, and do not define them; this book does not divide one by another to get a fill rate.

A worldwide network needed a satellite over each of the three ocean regions. NASA's history page records that the Intelsat III series "was the first to provide Indian Ocean coverage to complete the global network", and that the coverage was complete "just days before" the Apollo 11 landing of 20 July 1969. From then on, two national gateways under the same satellite could be connected directly, without a cable between them; gateways under different satellites still needed a relay on the ground and a second trip through a satellite, up and down again, which at least doubles the propagation delay. The polar regions, which cannot see a geostationary satellite, stayed outside.

The economics are the part of the story the same page puts in one line: from "a few hundred telephone circuits and a handful of members in 1965", Intelsat grew to a system "capable of providing hundreds of thousands of telephone circuits", and the "cost to carriers per circuit has gone from almost $100,000 to a few thousand dollars". The page gives no year for the low end; it was written in the 1990s. Figure 5.1 collects the points this book could source, cable and satellite side by side.

FIGURE 5.1

Circuits per system grew from dozens to thousands, and the capital cost per circuit fell

Year	System	Kind	Circuits or channels, as stated	Cost as stated	Capital cost per circuit (calculated)
1956	TAT-1	Transatlantic cable	About 36	About 35 million dollars	About 970,000 dollars
1965	All Atlantic telephone cables in use	Cables	317 channels (the history's unit)	Not stated	
1965	Early Bird (Intelsat I)	Geostation-ary satellite	240, or one television channel	About 7 million dollars with launch	About 29,000 dollars
1965	Intelsat III, request for proposals	Design requirement	1,000 two-way voice circuits	About 20 million dollars for at least six satellites (contract under nego-tiation)	
1965	Intelsat IV, request for proposals	Design requirement	6,000 voice circuits, or ten televi-sion channels	Not stated	
1970	TAT-5	Transatlantic cable	720	79 million dollars	About 110,000 dollars

Year	System	Kind	Circuits or channels, as stated	Cost as stated	Capital cost per circuit (calculated)
1976	US domestic satellites, all transponders	Geostationary satellites	1,500 telephone channels per transponder; 120 transponders	Not stated	
1983	MCI purchase on Galaxy II and III	Transponders on geostationary satellites	48,000 on 24 transponders (2,000 each)	200 to 300 million dollars planned for the satellite part of the network	
1988	TAT-8	Transatlantic fiber cable	Not stated in the source read	Not stated	

Sourced points only. Design requirements are marked as such; capital cost per circuit is a calculation (cost divided by circuits), not a price, and leaves out operations and ground stations.

Source: NASA SP-4217, Beyond the Ionosphere (1997), chapter 9 (Whalen) and its note 12, chapter 22 (Gruen); NASA History, "Communications Satellites: Making the Global Village Possible". Calculations by the author.

The capital cost per circuit in the table is a crude measure, and it is labeled as a calculation: the cost the source reports, in the dollars of its own year, divided by the circuits the system could carry. It is not a price, the scope of each cost differs, it leaves out operations and the satellite's ground stations, and a satellite's life was shorter than a cable's. It shows scale, not a lifetime cost advantage. TAT-1 in 1956 works out at about 970,000 dollars per circuit, Early Bird in 1965 at about 29,000, and TAT-5 in 1970, with 720 circuits for 79 million dollars, at about 110,000. NASA's history says the price advantage of satellites over cable lasted "until the laying of TAT-8 in the late 1980s".

How capacity grew

A transparent repeater carries what its power and its bandwidth allow (the first book of this series, *The Bit's Path*, works the hop budget). Between 1965 and the 1980s the trunk satellites grew along three roads at once.

- **Power.** Larger satellites carried larger solar arrays and more amplifiers. NASA's history notes that the early traveling-wave tubes gave as little as 1 W, and that tubes of 50 to 300 W were available when the page was written, in the 1990s.
- **Antennas that point.** The same history explains the gain of a directed antenna: focusing a 1 W transmitter on the Earth's disk "is equivalent to having a 100-watt transmitter radiating in all directions", and focusing it on the eastern United States, to 1,000 W. More gain in orbit meant smaller and cheaper stations on the ground: from 100 foot dishes with cooled masers costing as much as 10 million dollars (1960 dollars) to dishes of about 15 feet costing about 30,000 dollars (1990 dollars), in the same page's figures.
- **Reuse of the same frequencies.** A band can be used more than once if the signals are kept apart: in space, by beams that point at regions far enough apart, or over the same region, by two orthogonal polarizations. Neither separation is perfect, so each reuse adds interference to the budget. Which Intelsat generation introduced which technique is disputed between sources, and this book names no first until the primary engineering record has been read.

The design targets show the scale. In December 1965 COMSAT, on behalf of Intelsat, asked for designs of a fourth generation, Intelsat IV, with "a capacity of 6,000 voice circuits (or ten TV channels)", geosynchronous, and lighter than 2,300 pounds. The request for Intelsat III that August had specified 1,000 two-way voice circuits. These are requirements in requests for proposals, not counts of circuits in use, and Figure 5.1 marks them that way. No capacity figure by generation is printed here from a secondary source.

Analog and digital, a stated gap

This book could not read a primary record that says how telephone channels were carried on the trunk satellites of these years, analog or digital. Nor could it read one that dates the move to digital carriers and to time division access, where stations take turns in short bursts on one carrier. So the chapter gives no date for either. One nearby fact shows the choice was open on the ground too. In NASA's history of MCI, an analog FM microwave radio could carry 2,100 circuits, single sideband radio about 5,400 "with some loss of transmission quality", and the digital radios of the time only 1,344. MCI needed voice circuits quickly and cheaply, and kept analog microwave for voice.

The domestic trunk

Inside the United States, satellites began to carry long distance traffic in the mid 1970s. NASA's history lists Western Union's Westar I, launched 13 April 1974, as the first US domestic communications satellite; RCA launched Satcom F-1 in December 1975, while it leased circuits on Canada's Anik before that; AT&T and COMSAT launched the first Comstar in early 1976. "By the end of 1976," the page says, "there were 120 transponders available over the U.S., each capable of providing 1500 telephone channels or one TV channel." The same page adds that television "very quickly" became a major user, and that cable television's growth depended on that cheap distribution.

Here the division of labor is plain. The user end did nothing new: a subscriber picked up an ordinary telephone. The carrier owned or leased the earth stations and the transponders, and the satellite was a transparent repeater: it filtered, amplified and shifted the frequency of what it received, with no demodulation, decoding or switching on board. The ground did the switching, the multiplexing and the billing. The 1983 MCI purchase sits at the end of this line: 48,000 circuits on 24 transponders is 2,000 circuits per transponder, a third more than the 1976 figure.

LINK LEDGER · LL-1984-01 · SERVICE LEDGER

1983 to 1988 System: MCI domestic telephone trunk on purchased transponders (Galaxy II and III)

Retired | Class: service only

1 Requirement	Long distance voice circuits for MCI's national network, built quickly and cheaply after 1982, plus redundancy against a partial network failure. Two executives objected before the purchase that delay and echo would irritate customers.
2 Ends and path	An ordinary telephone at each end; MCI earth stations and switches between the satellite and the terrestrial network. **Path:** Transparent: the satellite amplifies and shifts frequency; switching and multiplexing are on the ground.
3 Orbit and time	Geostationary, 35,786 km above the equator. **Time:** Up and down at least 238.7 ms, 263.9 ms with both stations at 20 degrees; a reply at least 477.5 ms (calculated, propagation only).
4 Band and permission	**Earth station to satellite and back.** Band not stated in the history read; transponders on Hughes's Galaxy II and III, US domestic satellites licensed by the FCC (license record not read)
5 Capacity	**Up.** 48,000 circuits on 24 transponders, 2,000 per transponder. **Down.** As up: each circuit is two way. For comparison, NASA's history gives 1,500 telephone channels per US domestic transponder at the end of 1976.
6 Who owns each end	**Space segment.** Hughes built and operated Galaxy II and III; MCI bought 24 transponders **Ground segment.** MCI **Customer relationship.** MCI **The exit.** Single-mode fiber from March 1984; MCI leased circuits back to Hughes and rented transponders to others
7 Trust	Hughes commanded the satellites; MCI controlled its stations. How commands and circuits were protected is not stated in the source read.
8 How it fails, and how we would see it	Not as a link: both launches worked and the satellites operated. As a service: conversation across a quarter second each way, with echo, which two MCI executives had predicted customers would reject. **How we would see it:** Customer complaints about delayed voice, which the history says rose sharply in 1984.
9 Cost shape	MCI planned 200 to 300 million dollars for the satellite part of its network (1983).
10 Evidence	48,000 circuits on 24 transponders (1983) published history NASA SP-4217, ch. 22, p. 285, 2026-11-23 Delay complaints rose, 1984 published history NASA SP-4217, ch. 22, p. 286, 2026-11-23 477.5 ms for a reply calculated Slant range on a 6,371 km sphere to 35,786 km, over c, 2026-11-23

Service only, no hop budget: the case is a failure of the requirement, not of the link; the transponder and earth station numbers were not read in a primary source.

Status: MCI withdrew from satellites as far as it could after 1988. MCI agreed in June 1985 to buy Satellite Business Systems (completed March 1986).

The quarter second

A geostationary satellite is 35,786 km above the equator. A signal that goes straight up and straight down, with both stations directly below the satellite, travels 71,572 km, which at the speed of light takes 238.7 ms. That is a floor set by propagation alone. With both stations at 20 degrees of elevation the same trip is 263.9 ms. A conversation needs a reply: the talker's words go up and down, and the answer comes back up and down, so the round trip propagation delay is at least 477.5 ms, and 527.7 ms with both stations at 20 degrees. These are calculations from the geometry (a spherical Earth of 6,371 km radius and the speed of light), not measurements; switching, multiplexing and the terrestrial tails add to them, and how long a talker waits for a reply also depends on the people talking. About a quarter second one way, about half a second for a reply.

Inside MCI, in NASA's account, the argument was made before the purchase. The chief operating officer and the chief of transmission systems "argued against using satellites for voice on the very simple basis that they caused a delay and an echo, which most customers would find unacceptably irritating". The echo is the talker's own voice returned from the far end of the circuit; it arises on the ground, and the longer the delay, the more an echo that is not controlled is heard. The counter-argument, in the same history, was redundancy: customers "would be willing to suffer the indignity of a delay or an echo rather than face the outright loss of service in the event of a partial network failure." The decision was William McGowan's, and he chose satellites. The history also states that he had said in 1979 that fiber would take generations to matter for long distance traffic.

The cable takes the trunk back

MCI's single-mode fiber between Washington and New York was operational by March 1984, and by the end of that year, the history says, MCI had shown that single-mode cable "was enormously profitable". In the same year complaints about delayed voice rose. MCI leased circuits back to Hughes and rented transponders to other companies, agreed in June 1985 to buy the loss-making Satellite Business Systems, a deal completed in March 1986 and made, in the history's reading, for its business customers rather than its transponders, and "got out of the satellite business as much as it possibly could after 1988".

Across the Atlantic the same turn came with TAT-8 in 1988, which NASA's history lists as the first fiber-optic transatlantic telephone cable. The move was gradual. Telephone traffic on the densest routes went to cable over years; thin routes, islands and the distribution of television stayed on satellites much longer, and NASA's page names the two advantages it saw satellites keep: reliability, and the ability to serve many points at once. How much traffic moved, route by route, is not measured here: no source this book read gives a traffic share, so the claim is limited to what the two cases show.

Read with the three verdicts of chapter 1, the case separates cleanly. The link worked: the satellites operated and the circuits carried traffic. The service, for MCI's customers, fell short: they complained about delayed voice, as two of its executives had predicted. Geostationary telephone circuits served many other routes for decades; what failed here was the fit between this service and these users, who had a lower delay alternative. The business turned on that alternative: MCI found its single-mode fiber route profitable within a year and withdrew from satellites. Measured against the objective of crossing an ocean in 1965, against cables of a few dozen circuits each, the geostationary repeater was a strong fit; measured against a dense domestic voice route once fiber existed, it was a poor one.

THE SYSTEM'S FAILURE

MCI, 1984: a service failure, not a link failure. NASA's history of the company records the purchase of 24 transponders (48,000 circuits) in February 1983, two Delta launches in 1983 and 1984 that "worked perfectly", and in 1984 a sharp rise in customer complaints "about delayed voice transmission". Nothing in the source says the circuits missed their technical objectives. The failure sits in field 1 of the ledger, the requirement: the delay MCI's customers would accept on a domestic call, with fiber in prospect, was shorter than a geostationary hop gives, and two of MCI's own executives had said so before the purchase. What the case teaches, and no more: write the delay into the requirement before comparing prices.

SECURITY NOTE

Who can interfere or command. The satellite operator commanded the satellite; the carriers controlled their earth stations and their circuits. MCI's case adds one point to the general picture of chapter 1: buying transponders outright, as MCI did in 1983, gave a carrier ownership of capacity but not of the satellite's command link, which stayed with the satellite's operator. A domestic beam covering the continental United States also put every analog voice carrier within reach of any station in the footprint with a suitable antenna and receiver. **How it is seen.** Passive reception leaves no trace in the satellite's own traffic or telemetry, so the satellite cannot show it; finding an interception takes other evidence, such as the receiving installation itself. **How it is recovered.** Against interception the choice was encryption or a different medium; MCI's move to fiber changed who could reach the traffic, which is not the same as securing it.

Monday rule: put delay in the requirement, in milliseconds for a reply, before comparing prices.

CHAPTER SIX

1972 to 1995: A Satellite of One's Own, the National and Regional Programs



On 1 August 1975 a satellite that India did not own began to send television into villages that had never had it. For a year, NASA's ATS-6 relayed programs from a ground uplink to villages with direct reception sets, about 2,000 of them in one chapter of NASA's own history (another counts 2,400 villages served), and on 31 July 1976 the experiment ended on schedule. NASA moved the satellite away from India. By then Canada had run a domestic satellite system since 1973 and India's space agency was planning one; Indonesia launched its own, Palapa 1, in the same year, 1976. This chapter asks why so many countries bought or built a satellite when Intelsat already sold circuits, and what "our own satellite" did and did not give them.

The row for this chapter

Era	Limit that ran out first	User end	Space	Ground end
1965 to the 1980s, national variant	Coverage of a whole country or region, on terms the state set; also money, launch access and industrial aims	A telephone, a community television set, later a receive-only dish	A transparent geostationary repeater whose owner is a state or a national company, not a consortium	National earth stations, moving closer to the user: many small receive stations instead of a few gateways

Meanwhile. Intelsat's trunk grows and then loses dense routes to fiber (chapter 5). Hermes puts 12 GHz television into a 60 cm dish in 1978 (chapter 7). Inmarsat forms around ships between 1976 and 1982 (chapter 8). The first low orbit handheld systems are still a decade away (chapter 9).

Why a country bought a satellite

Intelsat was built to connect countries. Inside a country, a satellite competed with microwave towers and cables, and in most of Europe and the populous parts of North America the terrestrial network was already there. The national programs of this chapter answered a different question. Each section below asks the same four things: which constraints the country faced, how the work was divided, who owned each end, and what came of it. The reasons the sources give are of three kinds, and they are kept apart here. Geography: distances, islands or mountains that terrestrial networks reached slowly or at high cost. Policy: national television, national language, education, sovereignty over the network. Industry: building a space industry, or qualifying it to bid for others' contracts. A program can have all three.

Canada: distance, and a company half owned by the state

Constraints. NASA's history, in a chapter by a Canadian engineer, describes a country spanning six time zones with most people in a thin strip near the US border, and puts the gap plainly: satellite communication "offered the only practical solution" for reliable telecommunications to "the 20 percent of Canadians" who had none. **Division and owners.** Telesat Canada was created on 1 September 1969, "initially half owned by government and half by the private sector". Anik A1 was launched in November 1972 and service began in 1973; two more Anik A satellites followed in April 1973 and May 1975, all in C band. The same chapter calls Canada "the first country in the world to implement a domestic commercial geostationary satellite system", and Telesat's own history describes Anik A1 in similar terms. **Result.** RCA, NASA's other history page records, leased circuits on the Canadian satellite until it could launch its own. Anik B, launched 15 December 1978, carried 14 GHz up and 12 GHz down transponders next to its C band ones, as a backup for the experimental Hermes; the chapter states that this made Anik B "the first satellite in the world to operate in both the C-band and the Ku-band", and its own chronology words it more narrowly, as "the first commercial hybrid satellite". This book keeps the narrower wording: experimental satellites before it had used several bands. By 1983, by another chapter's count, Canada had launched seven Anik satellites.

The Soviet Union: a domestic network before the geostationary arc

The Soviet answer for a large country came first in a different orbit. Chapter 4 told Molniya and its highly elliptical orbit; NASA's history of Intersputnik, written in the early 1970s context, records that "the Soviet Union had established a domestic system, Orbita, which was quite successful and extensive", while Intersputnik itself had not begun operations four years after its draft was submitted. The same chapter notes Soviet plans for a synchronous satellite, Statsionar 1, over the Indian Ocean, and Soviet help in building ground stations in

Mongolia, Cuba, the United Arab Republic and Mali. The geostationary series that followed in the 1970s, known as Raduga, Ekran and Gorizont, are described in accounts this book could not check against a primary source; their dates, bands and roles are therefore not given here. Chapter 7 names Ekran among the broadcast designs and states the same gap. The gap is stated, not filled.

Indonesia: islands, a language, and a regional market

Constraints. Indonesia is an archipelagic nation of, in the words of NASA's history of Asian satellites, "more than 300 ethnic groups with as many languages and dialects". The same chapter quotes a scholar who wrote that Palapa was "driven by political and ideological imperatives concerned with nation building and circulation of ideas of national culture". **Division and owners.** Palapa 1 was launched in 1976. The government funded eleven additional ground stations that distributed the state channel, TVRI, across the country; private capital built regional stations on the outer islands, which were barred by law from national broadcasting. **Result.** NASA's histories call Indonesia the third country with a domestic satellite system, after Canada and the United States. The chapter adds a footnote worth keeping: "The Soviet Union is usually written out of the equation." Two effects followed that nobody had planned. Private dishes spread in the cities from the early 1980s and let viewers receive any broadcaster beaming toward them. And Indonesia became a regional distributor: Intelsat's first approval for Palapa forbade international broadcasting, but by 1981 Thailand and Pakistan had booked time on the satellite for their own domestic programs, "because it was cheaper than Intelsat".

Europe: a satellite the users had not asked for

Constraints. Europe is the case where geography argued against a satellite. NASA's history of the European program reports that the state telecommunication administrations saw no economic case: over short distances between European centers, "it made no sense to put sophisticated transponders as high as 36,000 kilometers in the sky and to build huge antennas on the ground". A 1971 study of the European telecommunication administrations found that the system's operating cost in the 1980s would exceed the savings in terrestrial cable, and that the savings would not even cover the ground stations.

Division and owners. Two tracks ran side by side. France and Germany signed an agreement in June 1967 for two experimental satellites, Symphonie, which the German Aerospace Center describes as three-axis stabilized geostationary satellites working at 4 and 6 GHz, launched on US Thor Delta rockets in December 1974 and on 27 August 1975, and controlled jointly from German and French centers on a time-shared basis; both ended service in December 1984. The multinational track approved an experimental satellite, OTS, at the end of 1971; it flew in 1978. The operational ECS phase was approved in February

1978, and the first ECS reached orbit in 1983, with three more in 1984, 1987 and 1988. The users' terms came last: the administrations would build and run the ground stations, a new organization, EUTELSAT, would manage the space segment, and in May 1979 ESA agreed to contribute up to 60 percent of EUTELSAT's operating costs.

Launch, and why it mattered. The same history reports that the US government "would reserve the right to refuse launch facilities to European communications satellites potentially harmful to Intelsat's commercial interests", and that this position strengthened France's view that Europe needed its own launchers. In the 1973 package deal France took prime responsibility for Ariane and 63 percent of its cost, and the history closes by noting that "it was an Ariane rocket that put the ECS into orbit". What conditions, if any, were attached to Symphonie's own launch is not stated in the sources read here. **Result.** The author of the chapter concludes that none of the studies showed economic benefits above the cost of the space and ground segments, and lists the wider reasons that carried the decision, among them independence from the two superpowers, an aerospace industry able to bid for Intelsat contracts, and "autonomy of political and cultural expression".

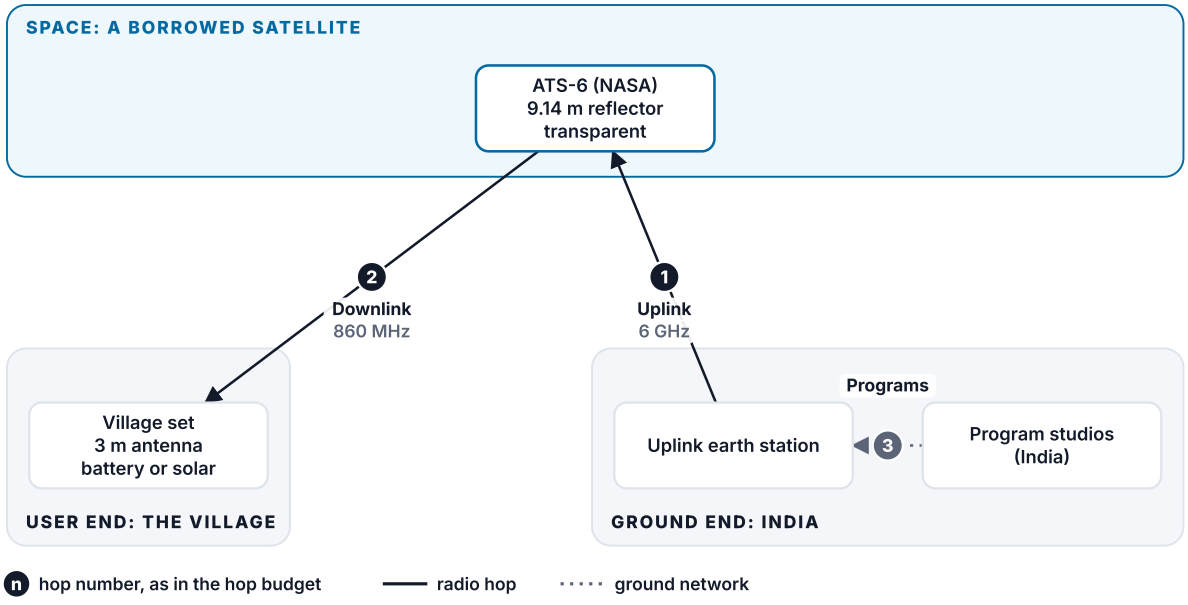
India: a borrowed satellite, then a satellite of four jobs

Constraints. India's constraint was not distance alone. The country wanted television for villages without electricity, and it wanted to learn to build and run a satellite system. NASA's history of the Indian program, by an Indian historian, describes the request: the use of an ATS satellite for a year, which the founder of the program saw as a chance "to learn the ground segment of a satellite system from the Americans". In that history's account, the Indian Department of Atomic Energy and NASA signed an agreement for the Satellite Instructional Television Experiment, SITE, in 1966. Other accounts date the formal agreement later; this book did not read the agreement itself, so the 1966 date is the history's.

Division and owners. The satellite was NASA's ATS-6, launched 30 May 1974 with a 9.14 m reflector, three-axis stabilized so that it could point that antenna. A 6 GHz uplink carried the programs to the satellite, and the satellite sent the picture down at 860 MHz, "directly to three-meter antennas installed in approximately 2,000 villages", in the words of NASA's engineering history. The large antenna in orbit is what let a village set with a three meter antenna receive a usable picture. India supplied the ground: the stations, the receivers and the programs. Its engineers rebuilt the television sets for village life; many ran on batteries and solar power. The agreement committed India to six hours of programs a day, in four languages, for 365 days. Figure 6.1 shows the division.

FIGURE 6.1

SITE put the large antenna in orbit so that a village set could use a three meter dish



The satellite was NASA's and the ground was India's: two hops of a transparent broadcast, with the 9.14 m reflector in orbit doing most of the antenna work.

Author's diagram based on NASA SP-4217, chapters 6 (Glover) and 16 (Srinivasan).

NASA's histories count different things in different chapters. One says television sets were placed in 5,000 villages in six clusters, about half of them modified to receive directly from the satellite; another says about 2,000 villages had three meter antennas for direct reception; a third says SITE "serviced 2,400 remote villages". The first two fit together, since half of 5,000 is close to 2,000 to 2,500; whether the third counts the same villages is not stated, so this book does not choose among them.

LINK LEDGER · LL-1975-01 · SERVICE LEDGER

1 August 1975 to 31 July 1976 System: SITE: village television through NASA's ATS-6 (India) Retired

Class: service only

1 Requirement	Six hours a day of educational television in four languages, for 365 days, to villages without terrestrial television and often without electricity.
2 Ends and path	A ground uplink fed by Indian program studios; community television sets in villages, half able to receive the satellite directly through a three meter antenna. **Path:** Transparent broadcast: one way, ground to satellite to village.
3 Orbit and time	Geostationary; ATS-6 lent for one year, then moved away from India. **Time:** Up and down at least 238.7 ms (calculated, propagation only); immaterial for one way television.
4 Band and permission	**Uplink.** 6 GHz; licensing record not read **Downlink to villages.** 860 MHz (UHF); licensing record not read
5 Capacity	**Up.** One television program with sound. **Down.** As up, to every receiver in the beam. Counts differ by chapter of NASA's history: about 2,000 villages with direct reception; 2,400 villages served, how not stated; 5,000 sets in six clusters.
6 Who owns each end	**Space segment.** NASA (ATS-6, lent for one year) **Ground segment.** ISRO, with All India Radio and Doordarshan **Customer relationship.** The village: a communal set under a custodian **The exit.** None for the satellite: the service ended when NASA moved ATS-6
7 Trust	NASA commanded the satellite. How the uplink and command link were protected is not stated in the sources read.
8 How it fails, and how we would see it	By ownership: the satellite was borrowed, so the service ended on schedule despite villagers' petitions. **How we would see it:** An agreed end date; villagers' delegations and postcards asking for continuation.
9 Cost shape	Not stated in the sources read. India paid for the ground, the sets and the programs; NASA for the satellite.
10 Evidence	6 GHz up, 860 MHz down, 3 m village antennas published history NASA SP-4217, ch. 6 (Glover), 2026-11-23 1 August 1975 to 31 July 1976; 5,000 sets published history NASA SP-4217, ch. 16 (Srinivasan), 2026-11-23 9.14 m reflector in orbit published history NASA SP-4217, ch. 6, 2026-11-23

Service only, no hop budget: no primary source read gives the satellite's transmit power and gain or the village receiver's noise temperature, so the hop numbers are not printed.

INSAT-1A, launched in 1982, was abandoned; INSAT-1B followed in 1983 with a different mix of jobs.

Result. SITE ended on 31 July 1976, as agreed. India's national satellite followed in a different shape. The original plan had been a direct broadcast satellite for village education; by 1977, the same history reports, the Ministry of Finance required INSAT to be a fully operational, revenue-earning satellite, the government's planning body refused money for village sets and antennas, and INSAT became a joint venture of five government clients and, in the history's description, a satellite of four payloads: television to relay stations and to

village sets, telephone and data between cities, a remote sensing package, and a meteorological package that imaged cloud cover and collected data from unmanned ground stations, which could also trigger cyclone warning sirens in coastal villages. The history counts functions; it does not say whether the remote sensing and the cloud imaging were one instrument or two, and this book does not count them as hardware. The first of the series, INSAT-1A, was launched by a Delta in April 1982 and was abandoned when its attitude control propellant ran out, in ISRO's own record; the date of abandonment is not printed here, because only one record of it was read. ISRO's page for INSAT-1B, launched by the Space Shuttle on 30 August 1983, records that it nearly suffered the same fate: its solar array was deployed only in mid-September. It was stationed at 74 degrees east, reached full operation in October 1983, and operated into 1990 with all its 4,375 two-way voice or equivalent circuits in use. A historian's chapter in the same NASA book adds a critical verdict: SITE was "a classic example of top-down planning", and its net effect was to lock India into terrestrial broadcasting until the 1990s. Both readings are in the official history, and both are kept.

China: a whole country in one beam

Constraints. The chapter of NASA's history written by a Chinese engineer states the motive as "the relatively underdeveloped state of its communications infrastructure", with long-distance telephone channels few and poor. China was outside Intelsat at the time: a NASA caption records that in 1974 China sought access to the system but "claimed it would not join as long as Taiwan was a member". The State Council approved the national plan for satellite communication in February 1975.

Division and owners. China built and launched its own satellites on its own Long March 3 rockets. After a test satellite in a nonsynchronous orbit on 29 January 1984, the first geosynchronous experimental communication satellite was launched on 8 April 1984 and stationed at 125 degrees east. The operational DFH-2 followed on 1 February 1986, at 103 degrees east, with "two transponders and a domestic beam antenna", an uplink of 6,225 to 6,425 MHz and a downlink of 4,000 to 4,200 MHz, and a beam that could "cover the whole territory of China", including the Xinjiang and Xizang autonomous regions, frontier stations and islands. It carried 1,000 telephone channels or two television channels. The improved DFH-2A, from 7 March 1988, had four C band transponders, 25 percent more power per transponder and 3,000 telephone channels or four television channels. The ground stations were state stations in Beijing, Kunming, Urumqi, Lhasa and on islands, used by the ministries for posts and telecommunications, petroleum, mining, water, power, news and the military; one DFH-2A transponder carried services for the Bank of China.

LINK LEDGER · LL-1986-01 · SERVICE LEDGER

1 February 1986 to 8 July 1989 System: DFH-2: China's domestic C band trunk and television satellite

Retired | Class: service only

1 Requirement	Long distance telephone, telegraph, facsimile, data and television for the whole country, including remote regions, frontier stations and islands.
2 Ends and path	State earth stations (Beijing, Kunming, Urumqi, Lhasa and others) and, for television, receive-only stations. **Path:** Transparent: two transponders, one domestic beam.
3 Orbit and time	Geostationary at 103 degrees east. **Time:** Up and down at least 238.7 ms (calculated, propagation only); a reply at least 477.5 ms.
4 Band and permission	**Up.** 6,225 to 6,425 MHz; Chinese state **Down.** 4,000 to 4,200 MHz; Chinese state
5 Capacity	**Up.** 1,000 telephone channels or two television channels. **Down.** As up. DFH-2A from 1988: four transponders, 3,000 telephone channels or four television channels.
6 Who owns each end	**Space segment.** Chinese state; built by the Chinese Academy of Space Technology **Ground segment.** State stations and ministries **Customer relationship.** Ministries and broadcasters **The exit.** None stated; DFH-2A satellites from 1988
7 Trust	Commanded by the Chinese state. How command and traffic were protected is not stated in the source read.
8 How it fails, and how we would see it	No failure recorded for DFH-2, which stayed in use until 8 July 1989. Its successor DFH-3 was lost to thruster leaks in 1994. **How we would see it:** Not stated in the source read.
9 Cost shape	Program estimate: trunks between provincial capitals by satellite 500 million yuan, against billions of yuan (nearly 1 billion dollars, the source's conversion) by microwave and cable.
10 Evidence	Two transponders; 6,225 to 6,425 and 4,000 to 4,200 MHz; 103 E published history NASA SP-4217, ch. 15 (Zhu Yilin), p. 206, 2026-11-23 1,000 telephone or two TV channels published history NASA SP-4217, ch. 15, p. 209, 2026-11-23 In use until 8 July 1989 published history NASA SP-4217, ch. 15, p. 206, 2026-11-23

Service only, no hop budget: the source gives frequencies and capacity but no transmit power, antenna gains or earth station figures.

The chapter on China in NASA's history was written by a Chinese engineer; its figures are the program's own.

Result. The same chapter gives the program's own cost comparisons: a national radio and television network for 80 percent of the country by microwave relay at about 2 billion yuan, against about 1 billion by satellite (1993 prices); trunks between provincial capitals by microwave and coaxial cable at "billions of yuan (nearly $1 billion)", against 500 million yuan (93 million dollars, in the chapter's own conversion) by satellite. These are the author's

estimates, not audited costs. By the end of 1995, the chapter reports, China had more than 30,000 receive-only stations, more than 100 stations with antennas over five meters, and 35,000 very small aperture terminals.

Japan: buying a satellite to learn to build one

Japan's first operational communication satellites were bought from abroad and launched at home. NASA's engineering history records that Sakura 2a, launched on 4 February 1983, was built by Ford and Mitsubishi and launched on a Japanese N2 rocket; the history calls it "Japan's first commercial communications satellite" and "the first commercial Ka-band operational satellite". Sakura 3a replaced it on 19 February 1988. In the 1990s, the same page notes, Loral built Japan's Superbird and N-Star satellites while Japanese contractors and the national space development agency built the ETS-VI engineering satellite. The earlier experimental Sakura and the broadcast satellite Yuri are not dated here, because no primary record of them was read.

Mexico and the Arab satellite organization: one Shuttle flight

One launch shows how such satellites reached orbit in the mid 1980s. NASA's page for Space Shuttle mission STS-51G, launched on 17 June 1985, lists three communication satellites deployed: Morelos-A for Mexico, ARABSAT-A "for Arab Satellite Communications Organization", and Telstar-3D for AT&T. The crew included Sultan Salman Al-Saud of Saudi Arabia and Patrick Baudry of France. Other lists use different designations for the Arabsat satellites; this book uses NASA's. Brazil's first domestic satellite and the founding of the Arab satellite organization are not dated here, for want of a primary record. Launch was the segment most programs did not own. Symphonie flew on US Thor Delta rockets and INSAT-1B and Morelos-A on the Shuttle; China launched on its own Long March rockets and Japan's Sakura 2a on a Japanese N2; Europe's choice to build Ariane was, in the history's account, a reaction to that dependence.

FIGURE 6.2

National programs owned the satellite and the ground, and often bought the launch

Year	Country or body	Satellite	Launch	Band	Ground end owned by	Source
1972	Canada	Anik A1 (service 1973)	not found	C band	Telesat Canada, half government, half private	NASA SP-4217 ch. 14
1974 to 1975	France and Germany	Symphonie A and B (experimental)	US Thor Delta	4 and 6 GHz	National stations; joint control centers	DLR

Year	Country or body	Satellite	Launch	Band	Ground end owned by	Source
1975 to 1976	India (NASA satellite)	SITE on ATS-6	US (NASA)	6 GHz up, 860 MHz down	India: uplink and village receivers	NASA SP-4217 ch. 6, 16
1976	Indonesia	Palapa 1	not found	not found	Government stations; state television TVRI	NASA SP-4217 ch. 17
1978	Canada	Anik B	not found	C and Ku band	Telesat Canada	NASA SP-4217 ch. 14
1978 and 1983	Europe (ESA, then EUTELSAT)	OTS; first ECS (1983)	ECS on Ariane	not found	Telecommunication administrations; EUTELSAT runs the space segment	NASA SP-4217 ch. 10
1983	Japan	Sakura 2a (Ford and Mitsubishi)	Japanese N2	Ka band, per NASA	not found	NASA SP-4217 ch. 6
1983	India	INSAT-1B, 74 degrees east	Space Shuttle, PAM-D	not found	Government of India (five clients)	ISRO; NASA SP-4217 ch. 16
1984 and 1986	China	Experimental satellite, 125 E; DFH-2, 103 E	Long March 3	6.2 GHz up, 4 GHz down	State stations and ministries	NASA SP-4217 ch. 15
1985	Mexico; Arab Satellite Communications Organization	Morelos-A; ARABSAT-A	Space Shuttle STS-51G	not found	not found	NASA STS-51G page
1988	China	DFH-2A, 87.5 E	Long March 3	C band, four transponders	State stations; Bank of China network	NASA SP-4217 ch. 15

Dates and details as stated in the sources; "not found" means that no source this book read gives the detail.

Source: NASA SP-4217, Beyond the Ionosphere (1997), chapters 6, 10, 14, 15, 16, 17; German Aerospace Center, SYMPHONIE A+B; ISRO, INSAT-1B; NASA, STS-51G mission page.

What "our own" bought

Across the trunk and television cases the satellite looked much the same: a transparent C band repeater in geostationary orbit, later with Ku band beside it. The exceptions matter: SITE's 860 MHz downlink to villages, Japan's Ka band, INSAT's weather instruments beside its transponders, and the Soviet network's elliptical orbits. The larger change was on the ground. Instead of the few international gateways that each country's signatory ran under the treaty system of chapter 4, each country placed many smaller stations where its people were, and in India, Indonesia and China the satellite reached villages, islands and frontier stations that the terrestrial network had not. Ownership changed above all in space: the satellite now belonged to the state or a national company, as the ground stations already did; the launcher, in most cases, did not; the builder often did not; and the orbital position and frequencies still had to be coordinated internationally. A satellite of one's own was ownership of the space segment and of the ground. It was not, by itself, independence.

THE SYSTEM'S FAILURE

DFH-3, 1994: a satellite failure. China's second generation satellite carried 24 C band transponders, six of medium power for television and the rest for telephone, telegraph, facsimile and data, and was designed for 6 channels of color television and 8,100 telephone channels at once. It was launched on 30 November 1994, about a year late, on a Long March 3A, and the on-board propulsion raised it to a quasi-geosynchronous orbit. Then, in the words of NASA's history, it "could not maintain its orbital position. Leakage in its attitude control thrusters had drained its fuel supply." The in-orbit tests showed that the transponders and other subsystems were normal. A payload in working order was lost because the platform could not keep it in its slot. **SITE, 1976: a trade-off of ownership.** The second case is not a failure of any part. SITE ended on its agreed date because the satellite was borrowed: after a year NASA moved ATS-6 to a new orbit away from India, and the history records villagers' delegations and hundreds of postcards asking for the service to continue. The point the sources make is about the space segment: a service runs only as long as its owner keeps the satellite there.

SECURITY NOTE

Who can interfere or command. In each program the satellite was commanded by its owner: for Symphonie, French and German control centers sharing the time; for SITE, NASA, which moved the satellite away at the end. A national system gave the state authority over who could use national circuits and earth stations. It did not give independence from the builder, the launcher, the international coordination of frequencies and orbital position, or the makers of terminals, except where each of those was also owned. A beam does not stop at a border: Palapa's audiences could also receive foreign broadcasters' carriers. **How it is seen.** For a national owner, what showed was political rather than technical: whose programs reached whose viewers. **How it is recovered.** Command of the satellite and control of national earth stations let an owner act. For a borrowed satellite, recovery was not India's to decide.

Monday rule: when someone says "sovereign", ask which parts are actually owned: the satellite, the launch, the ground, the spectrum filing, the terminals, or only the contract.

CHAPTER SEVEN

1974 to 2000: Power in Orbit, Small Dishes on Earth



In May 1978 a Canadian hockey game was shown at a reception in Lima, Peru. The picture came from a satellite called Hermes, launched by NASA for Canada two years earlier, and it was received on a dish sixty centimeters across, set up at the home of a Canadian embassy official. NASA's history of the period says it is "believed" to have been the first direct to home satellite television broadcast. In 1962 a transatlantic picture had needed the great horn antenna at Andover, Maine (Chapter 3). The work had moved: the signal that the small dish could no longer collect was made up in orbit, by more power and a narrower beam. This chapter follows that move, and asks what it cost.

The row: 1970s to 1990s, the user that stays still

Limit that ran out first	User end	Space	Ground end
The size and cost of the user's antenna; also launch mass, spectrum and who pays for the receiver	A community dish of about 3 m, then a 60 cm dish at a house, then an 18 inch dish with a decoder and a card	Higher power, large reflectors, higher bands	An uplink center that compresses and encrypts, and a center that authorizes each receiver

Meanwhile. The telephone trunk across oceans peaks and fiber arrives (Chapter 5). Countries buy satellites of their own (Chapter 6). Ships get L band through Marisat in 1976 (Chapter 8). Satellites begin to relay for other satellites (Chapter 8). The handheld telephone in orbit is still a decade away (Chapter 9).

The trade, and its conditions

A receiving dish collects power in proportion to its area. For a given power radiated toward the receiver by the satellite, its EIRP (equivalent isotropically radiated power), and at a given distance in free space, the power that arrives at the dish depends on the dish's effective area, and not on the frequency (assuming the same aperture efficiency). The first book of this

series, *The Bit's Path*, sets out why; here only the consequence matters. A dish of half the diameter has a quarter of the area and collects 6.0 dB less power. Going from a 100 foot dish (30.5 m), the size NASA's history gives for earth stations around 1960, to a 60 cm dish costs 34.1 dB, a factor of about 2,600 in power.

FIGURE 7.1

Every halving of the dish's diameter costs 6 dB, whatever the band

Dish	Where the size comes from	Gain at 12 GHz (calculated)	Less than the 100 foot dish
30.5 m (100 ft)	Earth stations with maser receivers, about 1960 (NASA)	69.5 dBi	0
4.6 m (15 ft)	Typical dish for normal satellite services, 1990 (NASA)	53.0 dBi	16.5 dB
3 m	Village dishes of the 1975 to 1976 experiment in India (at 860 MHz there)	49.3 dBi	20.1 dB
60 cm	Hermes demonstration in Lima, May 1978	35.3 dBi	34.1 dB
1 ft (0.305 m)	NASA's expectation for direct broadcast antennas, mid 1990s	29.5 dBi	40.0 dB

Receive gain at 12 GHz for dish sizes named in NASA's histories, with an assumed aperture efficiency of 0.6; the last column is the signal the satellite or the margin must make up against the 100 foot dish, which depends only on the ratio of areas.

Sizes: NASA History, "Communications Satellites: Making the Global Village Possible"; NASA SP-4217, chapters 6 and 14. Gains calculated by the author with the formula G = efficiency times (pi D / wavelength) squared, efficiency 0.6 assumed.

Those 34 dB are received power; what the service needs is enough signal against the receiver's noise, so the missing amount can come from a few places. The satellite can radiate more power. It can concentrate the power it has into a narrower beam with a larger antenna,

which also covers a smaller area. The service can ask for less: a narrower bandwidth, a lower data rate, a lower picture quality. The receiver can add less noise of its own, and better modulation and coding can work at a lower carrier to noise ratio. Or the link can keep less margin and fail more often. A higher band helps only through the second of these, and only on conditions: at a fixed antenna size, a higher frequency gives the satellite a narrower beam and more gain, but the dish on the ground must then be pointed more precisely, and the rain on the path takes more. Computed from the coefficients of ITU-R Recommendation P.838-3, for circular polarization, for a heavy rain of 25 mm per hour, the loss is about 1.0 dB per kilometer of rain at 12 GHz and about 0.001 dB at 1.5 GHz. A higher band is not free margin.

The rule of this chapter follows: when a terminal gets smaller, find where the missing gain went. Every system in the chapter put it in a different place.

ATS-6: a large reflector in orbit, 1974

NASA launched ATS-6 on 30 May 1974. Its history describes the spacecraft as the largest geosynchronous communications satellite launched to that date: 1,336 kilograms in that history, against 431 kilograms for its predecessor ATS-5, with a parabolic reflector 9.14 m across. The large antenna, the history says, needed tight pointing, which is why the satellite was stabilized on three axes instead of spinning. The reflector was the point. In NASA's words, the nine meter antenna "enabled small ground receivers to pick up a good quality signal."

The best known use was in India in 1975 and 1976: television sent up at 6 GHz and relayed back at 860 MHz, directly to dishes 3 m across in villages. Chapter 6 tells that experiment as a question of ownership, because the satellite was borrowed. Here the question is the division of labor. At 860 MHz a 3 m dish has a gain of about 26.4 dBi and a wide beam that is easy to aim, calculated with an assumed aperture efficiency of 0.6. The 9.14 m reflector in orbit, at the same frequency and efficiency, has about 36.1 dBi. Most of the antenna gain on that path sat in space. The village paid for a modest dish and a television set; the United States paid for the satellite.

ATS-6 also relayed signals to aircraft in L band, between 1,550 and 1,650 MHz, and tracked other satellites (Chapter 8). It ended as satellites end: three of its four orbit control jets failed in May 1979, and the spacecraft was powered down on 3 August 1979.

The Soviet case

The Soviet Ekran satellites are usually counted in this story, as an early system of satellite television for community reception. Their link, band and receivers are not documented in any primary record available for this book, so they are named here and not described, and

no Link Ledger is printed for them. NASA's own history of the period records only that the Soviet Union had built an extensive domestic system, Orbita, which Chapter 4 describes.

Hermes: high power at 12 GHz, 1976 to 1979

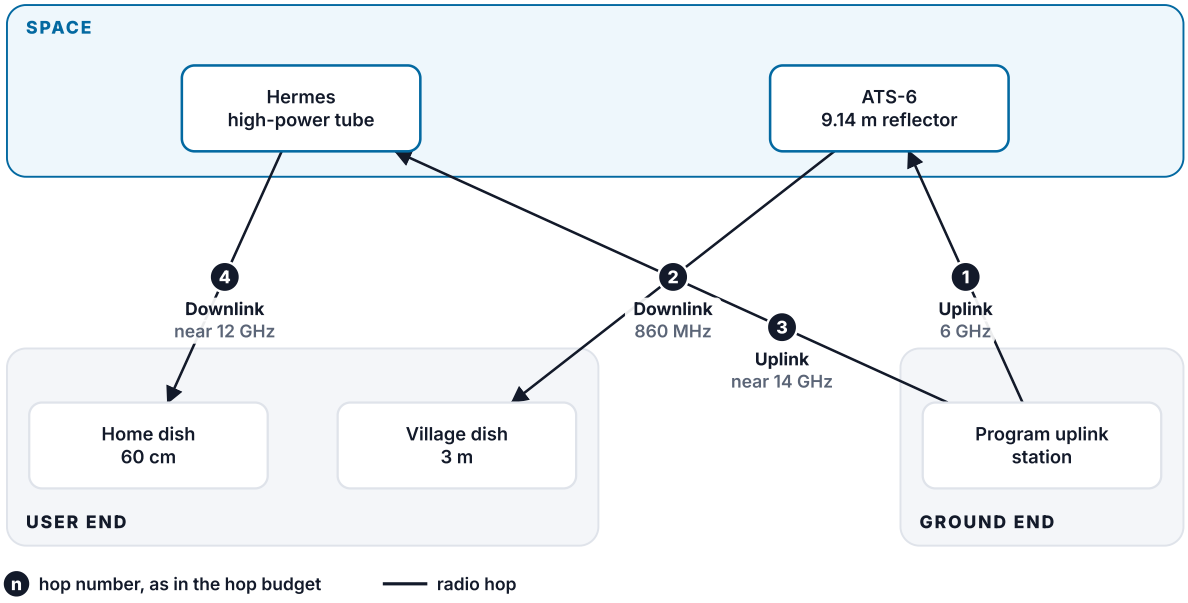
Canada and NASA agreed on 20 April 1971 to build the Communications Technology Satellite. Its stated objective, in the Canadian account in NASA's history, was to operate at higher powers and higher frequencies than existing systems, so that direct communication would become possible with ground stations in individual homes and communities that were low in cost for the time. It was also to test three axis stabilization, which keeps a narrow antenna beam pointed, and to build up Canadian industry. Canada designed and built the spacecraft. The United States supplied the high-power traveling-wave tube, the amplifier that carried the extra power, together with tests and the launch. The European Space Research Organization joined in May 1972 and supplied components.

The satellite's first design shows the trade in miniature. The Canadian proposal included a second payload for mobile service in L band. It was dropped in favor of the 12 and 14 GHz package, the history says, when it was learned that the launch vehicle the United States provided could not carry both. The rocket's capacity decided which kind of user the satellite would serve.

The satellite was launched on 17 January 1976 and renamed Hermes when service began on 21 May 1976. Blevis, the author of the Canadian chapter, describes it as the most powerful civilian spacecraft yet launched, measured by EIRP. Its experiments included medical and educational services to remote areas, community programs, the delivery of government services, and direct to home television with very small dishes. The Lima reception of May 1978 was one of them. In August 1979 Hermes, moved over the Pacific Ocean, served in a workshop with Australia and in a television demonstration in Papua New Guinea.

FIGURE 7.2

Broadcast moves the gain into orbit so the dish at home can shrink



Two broadcast experiments on one canvas: ATS-6 from a 6 GHz uplink to 3 m village dishes at 860 MHz (1975 to 1976), and Hermes to a 60 cm dish at 12 GHz (1978); each hop goes one way only.

Author's diagram based on NASA SP-4217, chapters 6 and 14 (Beyond the Ionosphere, NASA History, 1997).

Figure 7.2 puts the two experiments side by side. Both are one way. In both the program is uplinked by a station the viewer never sees, and the satellite does the hard part. What differs is how the satellite raised its EIRP and how large a dish it left to the viewer: ATS-6 used a large reflector at a low frequency and served a 3 m dish; Hermes used a high-power tube at a higher frequency and served a 60 cm dish.

LINK LEDGER · LL-1978-01 · SERVICE LEDGER

1978 System: Hermes (CTS) to a 60 cm dish: direct to home television, Lima, May 1978 **Retired**

Class: service only

1 Requirement	One television program, a Canadian hockey game, received on a 60 cm dish at the home of a Canadian embassy official in Lima, Peru, during a reception in May 1978. The objective was experimental: to show direct reception with very small, low-cost antennas.
2 Ends and path	A program uplink station (not named in the sources read) and one 60 cm dish with a television set in a private home. **Path:** One satellite between the two ends, carrying a high-power transmitting tube supplied by NASA. Whether the payload did more than amplify and shift frequency is not stated in the sources read.
3 Orbit and time	Geostationary; repositioned over the Pacific Ocean in August 1979. **Time:** About a quarter second from uplink to dish (239 ms on the shortest geostationary path, calculated); the program is one way.
4 Band and permission	**Uplink.** near 14 GHz; experimental use by Canada and the United States, license details not in the sources read **Downlink to the dish.** near 12 GHz; same
5 Capacity	**Up.** One television program for this demonstration. **Down.** One television program to the dish; channel bandwidth not in the sources read. The satellite's use was shared equally by Canada and the United States.
6 Who owns each end	**Space segment.** Title not stated in the sources read. Built by Canada's Department of Communications; NASA gave tube, launch, tests; ESRO parts **Ground segment.** The experimenters' uplink; the dish at the reception **Customer relationship.** None: an experiment, not a service **The exit.** Control was lost in late 1979; Anik B carried 14 and 12 GHz transponders as the government's backup
7 Trust	Commanded by the two governments' agencies. The sources read do not mention scrambling of the program; reception needed a suitable dish and receiver under the beam.
8 How it fails, and how we would see it	One Hermes; Anik B held backup Ku. At 12 GHz, rain on the path to the dish. Pointing of a narrow-beam dish. **How we would see it:** Not documented for the demonstration. Expected: the picture fills with noise, at the dish only in rain, everywhere at once if the satellite fails.
9 Cost shape	Not in the sources read. The United States supplied the tube and launch services; Canada built the spacecraft.
10 Evidence	60 cm dish, Lima, May 1978 published history NASA SP-4217, ch. 14, 2026-11-23 12 and 14 GHz; launched 17 January 1976 published history NASA SP-4217, ch. 14, 2026-11-23 Two-year design; lost late 1979 published history NASA SP-4217, ch. 14 and ch. 6, 2026-11-23 239 ms shortest path calculated Chapter 7, 2026-11-23

Service only, no hop budget: the satellite's EIRP toward Lima, the dish's noise temperature and the carrier's bandwidth are in NASA and Canadian technical reports that could not be read.

860 MHz or 12 GHz: the trade with numbers

Between ideal antennas, the free-space loss on the shortest geostationary path, straight down from 35,786 km, is 182.2 dB at 860 MHz and 205.1 dB at 12 GHz, a difference of 22.9 dB. That is not the whole story, because a dish of fixed size gains the same 22.9 dB when the frequency rises from 860 MHz to 12 GHz; at a fixed dish size the two cancel, and what remains is the area. A 60 cm dish has a twenty-fifth of the area of a 3 m dish, 14.0 dB less, at any frequency. For the same received power, at equal range and equal aperture efficiency, Hermes had to place about 14 dB more EIRP on Lima than ATS-6 placed on an Indian village, before rain and before any difference in noise or bandwidth, and then keep margin for rain at 12 GHz, which at 860 MHz hardly matters.

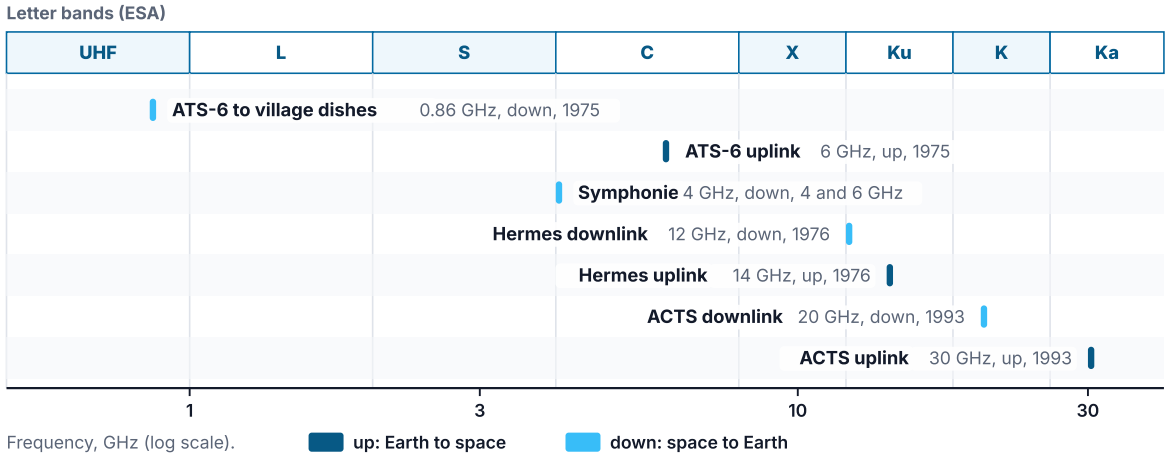
What the higher band bought was elsewhere. A reflector of a given size on the satellite makes a beam about fourteen times narrower at 12 GHz than at 860 MHz (the ratio of the two frequencies), so the satellite's power can be concentrated on a region instead of a subcontinent, and Ku band offered room for more channels. The cost was the satellite's power, the rain margin and the pointing of a narrow dish on a house. Neither history gives Hermes's EIRP toward Lima or the noise temperature of the dish, so the trade is shown in ratios and no hop budget is printed.

Japan and the Ka band

The next step up, to 30 GHz for the uplink and 20 GHz for the downlink, was taken commercially in Japan. NASA's history records Sakura 2a, launched on 4 February 1983 on a Japanese N2 rocket, as the first commercial Ka band operational satellite and as Japan's first commercial communications satellite, replaced by Sakura 3a, launched on 19 February 1988. When NASA's ACTS used the same frequencies in 1993, the history notes that they were new for United States satellites but that "the Japanese already had used them". The same history states the logic of the band: a given antenna makes a narrower beam at Ka band, narrow spot beams concentrate the signal against rain fade, and once there are spot beams it is natural to switch signals between them on board. Chapter 10 follows that logic into broadband.

FIGURE 7.3

Each step up in frequency bought narrower beams and more room, and paid for it in rain and pointing



Broadcast and trunk links of this chapter's era on one axis; uplinks dark, downlinks light.

Author's diagram based on NASA SP-4217, chapters 6 and 14, and DLR, "SYMPHONIE A+B" (checked 2026-11-22); letter bands from ESA, "Satellite frequency bands".

Figure 7.3 puts the bands of this chapter on one axis. Each step up bought a narrower beam from an antenna of the same size and room for more channels, and paid for it in rain and in pointing. Japan's broadcast satellites of the same years are left out, for want of a primary account.

Direct to home as a business

The demonstrations of the 1970s did not by themselves make a business. NASA's overview of communications satellites, written in the mid 1990s, put it plainly: direct broadcast had been "a recurrent theme, yet one never brought to fruition", and "the problems are not technical, they are political, social, and artistic. What will people be willing to pay for?" It noted competition from cable systems of 120 channels and that Hughes was "apparently about to enter this field". The same page expected direct broadcast antennas to be about a foot across and to cost a few hundred dollars, against typical 15 foot dishes at 30,000 dollars (1990 dollars) for normal satellite services.

From demonstrations to subscriptions, 1989 to 2000

In Europe the answer came from a company. SES, founded in Luxembourg in 1985 as Société Européenne des Satellites, launched its first satellite, Astra 1A, in December 1988; transmission began in February 1989, according to the company's own history. Astra 1A had

16 transponders, most aimed at the United Kingdom, Scandinavia and Germany, and by the end of 1990, SES states, it could reach over 16 million cable and direct to home households, a figure that does not separate the two. Astra 1B, 1C and 1D followed in 1991, 1993 and 1994 at the same position, 19.2 degrees East, a co-location SES calls a first in the industry. For the user end this meant that a dish pointed once saw more channels each year without being touched. SES's history covers its satellites, not the broadcasters' services on them; their records, and any European subscriber count for the period, were not read for this book.

In the United States the high-power service came in 1994. DBS-1, built by Hughes, was launched by Arianespace in December 1993, and DIRECTV, a Hughes company, launched its service in June 1994. Five of the satellite's 16 transponders belonged to a second company, United States Satellite Broadcasting (USSB), which sold its own programs to the same dishes. USSB's report for 1996 describes the receiving system, the Digital Satellite System (DSS), as an 18 inch dish using MPEG-2 digital compression. EchoStar followed (table). Its first two satellites each carried 16 Ku band transponders of 130 watts, "approximately eight times the power of typical C-band transponders", in the company's words. An 18 inch dish (45.7 cm) has about 2.4 dB less area than the 60 cm dish at Lima in 1978 (calculated): the demonstration had become a product sold in shops.

Three subscription systems as their own records describe them

System	Satellite and service start	User dish	Programs per transponder	Access control
Astra (SES), Europe	Astra 1A launched December 1988; transmission from February 1989	Not given in the history read	Not given	Not given
DIRECTV and USSB, United States	DBS-1 launched December 1993; DIRECTV service from June 1994	18 inch	Not given	Developed and operated by The News Corporation (News Datacom), from Castle Rock, Colorado
DISH Network (EchoStar), United States	EchoStar I launched December 1995; service from March 1996	18 inch	"Six or more" (1997); "approximately eight" (1998)	Smart cards from Nagra Plus (1997); later NagraStar, half owned by EchoStar (1998)

Power was not enough on its own; digital compression multiplied the programs each transponder could sell. EchoStar's 1997 prospectus says digital compression turned each frequency channel "on average into six or more digital channels of programming", and its annual report for 1998 gives "approximately eight digital video channels from each transponder." In Europe the Digital Video Broadcasting project wrote the transmission standard, ETSI EN 300 421 (the August 1997 version was read), for "Direct-To-Home (DTH) services for consumer Integrated Receiver Decoder", carrying MPEG-2 services over QPSK modulation. Its own example for a 33 MHz transponder gives a useful rate from 23.8 Mbit/s at inner code rate 1/2 to 41.6 Mbit/s at rate 7/8, for a carrier to noise ratio of 4.1 to 8.4 dB in the standard's simulation of a hypothetical satellite chain, an example and not a service threshold. That is the division of labor of the digital era: the uplink center compresses, multiplexes, encrypts and codes the signal, the satellite amplifies it, and a mass-produced decoder in the home demodulates and corrects errors, then picks out one program, decrypts it if the card allows, and decompresses it. The decoder's price moved quickly. EchoStar's average retail price for a receiver system was about 499 dollars in March 1996; by June 1997 retailers could offer one at a suggested 199 dollars.

Once viewers pay, the receiver must decide who may watch, and whoever controls that decision holds the revenue. USSB's report says the DSS conditional access system, "which controls the encryption and decryption of the television signal", was developed and is operated by The News Corporation Limited, from a management center in Castle Rock, Colorado, and that DIRECTV, not USSB, had primary responsibility for its security. EchoStar's smart cards "contain the authorization codes necessary to receive DISH Network programming"; by its 1998 report the company owned half of NagraStar, the joint venture that supplied them, and the cards could be "updated or replaced periodically". The keys stayed with the service and its supplier, and a replaceable card let them change the keys without changing the dish.

The three verdicts are kept apart. The link: no EIRP or receiver figure for these services was read, so no hop budget is printed. The service grew. EchoStar reported about 820,000 DISH Network subscribers on 30 September 1997 and about 1.9 million on 31 December 1998; its 1997 prospectus put DIRECTV at about 2.9 million on 30 September 1997, and Hughes reported about 11.2 million DIRECTV subscribers on 31 December 2002. The business took longer. EchoStar's net losses were 11.5 million dollars in 1995, 101.0 million in 1996, 312.8 million in 1997 and 260.9 million in 1998, years in which it cut the price of the receiver to win subscribers. For DIRECTV, the 2002 annual report says that DIRECTV U.S. increased its operating profit by 437 million dollars that year; the year it first made a profit was not found in the filings read. Who made money first, and when, remains open for both American services and for the broadcasters on Astra.

Small terminals for data

The same shift reached data. A **VSAT** (very small aperture terminal) network places many small dishes at the customer's sites, typically talking through a larger hub station that the operator runs. The hub's large antenna and quiet receiver make up much of what the small dish lacks on the path from the small dish to the hub; on the path toward the small dish, the satellite's downlink power and the small dish itself still set the limit. The hub cannot repair a weak way up: through a transparent satellite the noise of each hop adds, so the small dish's power and the satellite's receiver must first carry the signal to the satellite. NASA's overview records only that data "has grown tremendously with the advent of very small aperture terminals", and that small antennas for television receive and for VSAT had become a commonplace sight in the United States. The overview gives no date, terminal size or rate, and none is printed here. A modern enterprise VSAT service, as sold today, is covered in depth later in this series.

Who owns the ground end now

In 1965 the ground end was a national gateway owned by a treaty signatory (Chapter 4). In a broadcast system it splits in two. The operator owns the uplink center, where programs enter the system, and the control station that commands the satellite; the two need not be in one place. The household owns the dish and the receiver, bought in a shop. A subscription service adds a third piece, the center that tells each card what it may decode. Between them, the satellite now carries most of the power and most of the risk, and the business carries the cost of programs, which no link budget shows.

THE SYSTEM'S FAILURE

Hermes, 1979: an experimental satellite with no spare. Hermes was designed to last two years and operated for almost four. After its Pacific demonstrations of August 1979, the Canadian chapter of NASA's history records, "control of the satellite was lost, and all communications ceased"; NASA's own chapter gives October 1979 as the end of operation. This was a satellite failure, after the satellite had outlived its design. The history also records the preparation for it: because of "the need to have some back-up and follow-on capability for Hermes in the event of failure of any one of its many innovative subsystems", the Canadian government arranged with Telesat Canada to add 14 and 12 GHz transponders to the commercial Anik B, launched on 15 December 1978. Read narrowly, the record shows that a single experimental satellite carried every new service it demonstrated, and the follow-on capacity was placed in advance on a commercial satellite.

SECURITY NOTE

Who can interfere or command. Subscription moved the control point into a card in the receiver, and the card became the target. EchoStar's 1997 prospectus listed signal theft among its risks: "Recent published reports indicate that the DirecTv and USSB encryption systems have been compromised", and a Canadian court had ruled that pirating DirecTV programming was not illegal in Canada. EchoStar's own report for 1998 added that "our access control system may also have been compromised." **How it is seen.** In these filings theft appears through published reports and data the operator received, and as a business risk: lost revenue and a weaker position when contracting for programs, not as a fault in the link. **How it is recovered.** By changing what the receivers will decode: EchoStar's cards were designed so the access control system could be changed completely. Control of the cards could itself become a dispute: on 6 September 2002 DIRECTV sued NDS, the provider of its conditional access system, and NDS countersued over new conditional access cards that DIRECTV was developing with a chip manufacturer. What these filings show is that in a paid broadcast the keys carry the revenue, and recovery belongs to whoever can replace the card.

Monday rule: when a terminal gets smaller, find where the missing gain went: more power in orbit, a narrower beam (which a higher band makes easier to form), or a lower data rate, and ask who pays for each.

CHAPTER EIGHT

1976 to 2016: Ships, Aircraft, Soldiers and Other Satellites



In 1976 the ship ESSO Wilhelmshaven carried a radome on top of its antenna mast. Inside it, according to the caption of a photograph in NASA's history of satellite communication, was the first commercial ship installation of a mobile satellite terminal. Until then a ship far from shore talked to the land by high frequency radio, which reached far but depended on the state of the ionosphere. The terminal changed that, and it was not small: the first commercial terminals designed for ships, the same history says, weighed up to a ton and cost 50,000 to 75,000 dollars. When the user end moves, the terminal's size, power and price come first, and they decide the band and the rate. This chapter follows four kinds of moving user: ships, aircraft, military forces, and spacecraft that need a satellite to reach the ground.

The row: 1970s to 1990s, the user that moves, and the user that is a satellite

Limit that ran out first	User end	Space	Ground end
The terminal a ship, an aircraft or a spacecraft can carry; also spectrum, and who pays for a system few users share	A stabilized ship terminal; an aircraft antenna; a spacecraft's own antenna	L band for mobiles; UHF for fleets; X band and EHF for wideband and protected military links; relay satellites in geostationary orbit	Coast and shore stations; one or two relay ground stations

Meanwhile. Small dishes arrive for users who stay still (Chapter 7). National satellites multiply (Chapter 6). Fiber takes back the telephone trunk (Chapter 5). From 1990, handheld satellite telephones are announced (Chapter 9). Navigation satellites, which need no uplink from the user at all, run in parallel (Chapter 14).

Before Marisat: aircraft first, and a dispute about bands

The demand for mobile satellite links began in the air and in the military. Edward Martin's chapter in NASA's history, which its author says rests largely on his own recollection, describes the United States Air Force's search after 1945 for reliable contact with aircraft far beyond the line of sight, including bombers near the North Pole, where high frequency radio was especially unreliable. The first satellites offered no help: Syncom's communications transmitter, at 2 W in L band, was far too weak for a mobile user. A Hughes engineer, Roland Boucher, found that Syncom's VHF telemetry and command system could be made to relay a message, and in early 1965 a Pan Am Boeing 707 cargo aircraft flying out of Hong Kong sent a message through the Pacific Syncom to Camp Roberts, California. Martin calls it the first satellite message from a regularly scheduled airliner in flight.

NASA's Applications Technology Satellites followed. ATS-1 and ATS-3 carried VHF transponders that airlines and others used for extensive tests. ATS-5 had an L band transponder, but its gravity gradient stabilization failed and it spun with its antennas, which left it useful only as a "lighthouse beacon" and handicapped the tests. ATS-6, in 1974, established L band links to aircraft between 1,550 and 1,650 MHz and tracked several aircraft at once. Canada's account adds that two Canadian military aircraft held direct aircraft to aircraft voice contact by satellite on 16 May 1970, using LES-6, an experimental United States military satellite working at UHF.

The aviation system that should have followed never flew. In the late 1960s the airlines and the Federal Aviation Administration's operational staff wanted VHF, which the early Boeing 747s were wired for; European agencies favored L band, citing a shortage of VHF frequencies, ionospheric effects on North Atlantic routes, and the time their industry needed to catch up. A White House statement of early 1971 settled on L band only, and a joint program, Aerosat, was set up with the FAA, Canada and the European Space Research Organization as users. General Electric won the satellite contract in 1975, but the notice to proceed never came. Martin's account is direct: the airlines, which would pay through user fees, had had no voice in the planning; they lobbied Congress, which removed the FAA's share of the funding. The dedicated aviation satellite died there, and maritime service moved to the center.

Marisat, 1976: a hybrid built around a Navy contract

The maritime system began with a military need. In early 1972 the United States Navy asked COMSAT for UHF capacity to bridge the gap between its experimental satellites, TACSAT and LES-6, and its first operational system, FLEETSAT. COMSAT saw a chance to start a commercial mobile service on the same satellites. Each Marisat satellite could give up to 75 percent of its capacity at UHF to the United States government; the rest was L band, with

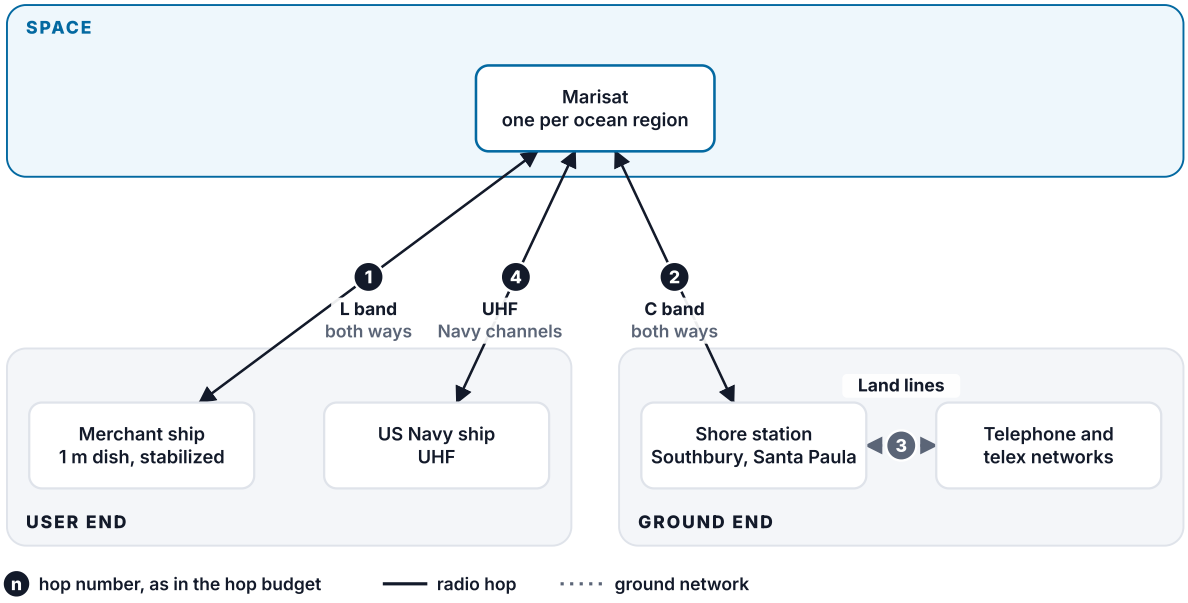
three levels of L band transmit power, so that commercial service could grow as the Navy withdrew. A first proposal, asking the Navy to commit 69.8 million dollars, was refused; a revised one of December 1972, at 27.9 million dollars for one wideband channel on each of two satellites for two years, was accepted.

The Federal Communications Commission required that other carriers be offered a share of ownership. AT&T declined, Martin records, because it judged the limited ship to shore L band telephone capability too small to support a viable business. RCA took 8 percent, Western Union International 3.41 percent and ITT 2.3 percent, with COMSAT General as investor and manager. In May 1973 COMSAT and Hughes signed for three satellites at just over 40 million dollars. The announcement, at a symposium in London in February 1973, put European agencies in what Martin calls "a state of shock": they had planned an orderly international system and were investing in their own industry to supply it.

The satellite had a shore to ship transponder from C band to L band and a ship to shore transponder from L band to C band, each 4 MHz wide. The division of labor is the one figure 8.1 shows: the large antenna and the connection to the telephone and telex networks stay at a few shore stations; the ship carries a small, stabilized L band terminal; the satellite translates between the two bands. The first book of this series, *The Bit's Path*, tells how COMSAT chose a one meter ship antenna against European advice for a lower gain. The design team mixed digital and analog techniques for a combined telephone and telex system, and had eighteen months to make it work.

FIGURE 8.1

Marisat put the small antenna on the ship and the large one on the shore



The Marisat path of 1976: L band between ship and satellite, C band between satellite and shore station, the same satellite also carrying US Navy UHF channels; Inmarsat took over the system on 1 February 1982.

Author's diagram based on NASA SP-4217, chapter 21 (Martin).

Commercial service opened in the Atlantic and Pacific regions in the summer of 1976, through COMSAT's stations at Southbury, Connecticut and Santa Paula, California. NASA's overview calls Marisat, launched in February 1976, the first mobile communications satellite; Martin's caption calls it the first commercial one. The Navy, pleased with its UHF channels, asked for the third satellite, held on the ground as a spare, to be launched over the Indian Ocean; COMSAT used the opportunity to open L band service there in November 1978, through a station at Yamaguchi, Japan, under an agreement with the Japanese carrier KDD.

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.

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 is a reconstruction. What it relies on is documented: a combined telephone and telex service to merchant ships from the summer of 1976 through the two COMSAT shore stations. What changed for a ship within a satellite's coverage was the link: it no longer depended on the ionosphere, as high frequency radio did, because the L band signal went in a straight line to the satellite instead of being reflected by the ionosphere; the satellite's fixed place in the sky made the dish easier to keep pointed; and the message arrived as text.

A treaty around a link: Inmarsat

The international system was negotiated in parallel. The maritime body of the United Nations, today the International Maritime Organization (IMO), studied satellites in a radio subcommittee from the 1960s. Martin records that the Soviet Union, which in his words would never get "a seat at the table" in Intelsat because its international traffic was too small to give it a large investment share, proposed a new organization and even its name. A conference met three times in 1975 and 1976 and adopted two agreements: a convention among governments and an operating agreement among the entities they designated. It copied Intelsat's two tiers, with one change aimed at the United States: no signatory could vote an investment share above 25 percent without first offering the excess to others. The convention was adopted in 1976 and entered into force on 16 July 1979.

It nearly did not. The system came into being only if commitments reached 95 percent of the capital by July 1979. In 1978 Congress named COMSAT the United States signatory under the Maritime Satellite Act, and COMSAT offered to take every unsubscribed share; European signatories raised their own bids to dilute it, and by the midnight deadline the bids totaled close to 300 percent. Inmarsat then had to choose its first satellites: European Marecs satellites, L band packages on Intelsat V, or the Marisats already in orbit. It negotiated contracts with all three, and all three Marisats were needed at the start. On 1 February 1982 it switched the whole world over at one moment. Marisat brought, in Martin's list, three satellites, an operating network and a first customer base of 1,000 ships.

Inmarsat launched the first of its own satellites, in the words of NASA's overview, Inmarsat-2 F-1, in October 1990, more than seven years after it had asked industry for proposals. Inmarsat-3, which Martin, writing in the mid 1990s, expected to deploy from 1996, was its first use of spot beams, and he expected them to make user terminals smaller and cheaper. The organization was renamed the International Mobile Satellite Organization in 1994, reflecting, in the IMO's words, the extension of its services from the maritime sector to other modes of transport; its member governments agreed to privatize the business from April 1999, and the company was fully private by the end of 2003. The ship terminal designed for Marisat, renamed Inmarsat-A, still brought about 90 percent of Inmarsat's revenue twenty years later, according to Martin.

Safety at sea as a public duty

The convention gave Inmarsat a public purpose before a commercial one: to improve maritime communications, "thereby assisting in improving distress and safety of life at sea communications", in the words the International Maritime Organization quotes. The 1988 amendments to the Safety of Life at Sea convention introduced the Global Maritime Distress and Safety System, the GMDSS, and, in the IMO's summary, required ships sailing in specified sea areas to carry Inmarsat equipment for distress and safety calls and to receive navigational warnings. When the business was privatized, the duty was not left to the company alone: a residual treaty body, IMSO, oversees the satellite part of the GMDSS. Its own page, read on 23 November 2026, gives 112 member states and names the current providers as Inmarsat Ltd and Iridium Ltd, the two the IMO has recognized under its criteria for GMDSS providers.

The user is a spacecraft

A satellite in low orbit circles the Earth in a few hours and, NASA's history notes, is in view of any one ground station for typically 20 minutes at a time. Without help in space, NASA needed ground stations all over the globe. ATS-6 tested the alternative: from geosynchronous orbit it tracked the Nimbus 5 and 6 and GEOS 3 satellites and relayed their data, pointing to better than 0.2 degree. The division of labor changes completely: the low satellite talks up to a relay high above it, and the relay talks down to one or two stations. One relay in geosynchronous orbit sees a low satellite for much longer than any ground station does, though not for the whole orbit, because the Earth blocks part of it; near-continuous coverage needs several relays spaced around the orbit.

The first Tracking and Data Relay Satellite, TDRS-1, rode the Space Shuttle Challenger on its first flight, STS-6, on 4 April 1983. Its upper stage malfunctioned and left it in an improper but stable orbit; the failure box below tells how it was recovered. NASA's page on the system, updated on 5 December 2025, describes a constellation of 7 satellites in geosynchronous

orbit over the Atlantic, Pacific and Indian Oceans, with ground stations at White Sands, New Mexico and Guam, giving near-continuous relay to more than 25 missions, including the Hubble Space Telescope and the International Space Station. The same page says NASA is moving to commercial relay services, and its note on user rates says no new customers will be onboarded.

Relays need not be radio. Europe's Sentinel-1 radar satellites send their data both by X band directly to ground stations and by an optical link through the European Data Relay System, according to the Copernicus mission page; *The Bit's Path* works that link. Soviet, Japanese and Chinese relay systems also exist; table 8.2 leaves them out because no primary page for them could be read.

FIGURE 8.2

When the user is a ship, a warship or a spacecraft, the work divides differently

System	Year	Orbit	What is done in orbit	What stays on the ground	Source
ATS-6 tracking tests	1974 (launch)	Geosynchronous	Tracked Nimbus 5 and 6 and GEOS 3 and relayed their data	One ground station instead of many	NASA SP-4217 ch. 6
Marisat	1976	Geostationary	L band and C band transponders; up to 75 percent of capacity at UHF for the US government	COMSAT shore stations; Navy terminals	NASA SP-4217 ch. 21
TDRS-1	1983	Geosynchronous (reached after an upper stage malfunction)	Relays between spacecraft in low orbit and the ground	NASA ground stations (today White Sands and Guam)	NASA STS-6 and TDRS pages
TDRS fleet	2025	Geosynchronous, 7 satellites	Near-continuous relay for more than 25 missions	No new customers; NASA moving to commercial relay	NASA TDRS page, updated 2025-12-05

System	Year	Orbit	What is done in orbit	What stays on the ground	Source
Sentinel-1 through EDRS	In use when checked, 2026-11-22	Low orbit user, through a relay satellite	Optical link to the relay	The relay's ground stations; X band direct to stations as well	Copernicus SentiWiki, S1 Mission

Systems of this chapter with a readable public source; what each did in orbit and what stayed on the ground.

NASA SP-4217, chapters 6 and 21; NASA, "STS-6" and "Tracking and Data Relay Satellites" (page updated 5 December 2025); Copernicus SentiWiki, "S1 Mission" (checked 2026-11-22).

Soldiers: UHF for fleets

Military mobile users chose UHF early. Canada's account describes trials from 1967 with the United States on experimental military satellites at UHF, such as LES-5, LES-6 and TACSAT, because UHF allowed small, light mobile or transportable terminals; demonstrations were carried out on land, at sea and in the air. Canada's defense forces went on using United States satellites and never built a military UHF system of their own; the idea led instead, through a civil proposal, to the commercial mobile satellites AMSC-1, launched on 7 April 1995, and MSAT-1, launched on 20 April 1996. The Navy's lease on Marisat shows the same choice from the other side: a fleet that needed UHF capacity quickly rented it on a commercial hybrid satellite, and, Martin wrote in the mid 1990s, was still using it.

Soldiers: protection paid for in capacity

The armed forces divided the work differently because the first limit they planned for was an adversary. Each protection put work somewhere, in the satellite, the waveform or the terminals, and each had its own price in capacity, cost or terminal size. David Spires and Rick Sturdevant, writing the Air Force's chapter in NASA's history of satellite communication, record how the services split the bands through the 1980s: "UHF for the Navy, SHF for DCA, and extremely high frequency (EHF) for the Air Force", DCA being the Defense Communications Agency. A GAO report of June 2003 sorted the same systems into three families: wideband, protected ("antijam, survivable") and narrowband.

Wideband at X band. The Initial Defense Satellite Communications System, launched in groups from 16 June 1966 to 13 June 1968, gave each satellite either eleven tactical-quality or five commercial-quality voice circuits, and, the same chapter says, "furnished the basic

design for British Skynet and NATO satellites." DSCS II, whose first pair was launched on 2 November 1971, carried 1,300 two-way voice channels or 100 million bits per second, with four channels shaped for terminals of different sizes. DSCS III, first launched on 30 October 1982 and complete as a five-satellite constellation on 19 July 1993, put protection into the satellite's antenna: its 61-beam uplink antenna could form "patterns with nulls in selected directions to counter jamming", reducing its gain toward a jammer. GAO's 2003 summary gives the price at the user end: these channels offered "the highest data capability" but needed antennas of 4 to 60 feet.

Narrowband at UHF. The fleet systems made the opposite trade. Lincoln Laboratory's history in the same volume, by William Ward and Franklin Floyd, records that after LES-6 and TACSAT the Department of Defense "procured large quantities of UHF terminals", served by the Marisat gapfiller, FLTSAT and LEASAT series. They are plain about the cost: it is "very difficult to defend a communications satellite with a UHF uplink against a determined jamming attack", because the military UHF band, 225 to 400 MHz, lacks the bandwidth for strong protection; the terminals' "relative simplicity and comparative cheapness" kept the band in use. In March 2005 GAO described the UHF Follow-On system as in operation and its planned successor, the Navy's MUOS, as a low rate service "capable of penetrating most weather, foliage, and manmade structures."

Protected at EHF. LES-8 and LES-9, launched in 1976, tested the protected design: EHF links, cross-links between the two satellites, and onboard signal processing. EHF, Ward and Floyd write, "supplies the band widths necessary to implement robust jam-proof systems based on spread-spectrum technologies": each signal is spread over far more spectrum than it needs, so a jammer that does not know the spreading must spread its power over that width, or strike only part of it, and either way does less harm once the receiver gathers the signal back, unless it is strong enough to overload the receiver. "Jam-proof" is their word for a design goal; spreading makes jamming harder and costlier, not impossible. The cost they name is rain, which forces a higher minimum elevation angle. Two EHF packages built by the laboratory flew on FLTSAT-7, launched on 4 December 1986, and on FLTSAT-8 in 1989; each had a computer-based controller that set up channels at the request of user terminals. Milstar, started in 1981, was planned as the full system: eight satellites with "cross-link capabilities and extensive hardening against radiation" and terminal antennas "as small as six inches". Spires and Sturdevant state the trade outright: "Because the primary objective was survivability, not high performance, the Milstar design did not include high data rates; each satellite was to serve no more than fifteen users simultaneously." After the Cold War the program was cut to six satellites, "without the vast array of survivability features"; the first was launched on 7 February 1994, seven years after its projected launch, and the last, GAO records, in April 2003.

The successors split the trade again. In December 2003 GAO described AEHF, Milstar's replacement, as geosynchronous satellites linked by radio frequency cross links, built for "the entire spectrum of conflict, including nuclear war", at about 250 megabits per second each. The Wideband Gapfiller Satellite, WGS, meant for "all levels of conflict, short of nuclear war", was to carry at least 2,100 megabits per second each, in X and Ka band, augmenting DSCS. Both are planned figures; their ratio, about eight, compares two planned systems with different jobs and is not a measured price of protection. WGS was "leveraging commercial methods and technological advances in the satellite industry", the same report says, and in March 2008 GAO left its production data unreviewed "because of the commercial nature of the WGS Block 1 acquisition". The first WGS was launched in October 2007; Australia signed a memorandum to join the program in November 2007. AEHF, with Canada, the United Kingdom and the Netherlands as partners, saw its planned first launch slip from 2006 (GAO, December 2003) to November 2008 (GAO, March 2008).

Skynet: the same trade, bought as a service. Britain's Skynet began on the IDSCS design; Skynet 4, whose first satellite was launched in December 1988, carried UHF provisions, according to Ward and Floyd. For Skynet 5 the Ministry of Defence changed who owns the space segment: a private finance initiative awarded in 2003 to the company that is now Airbus Defence and Space (originally Paradigm Secure Communications) delivered the service. Skynet 5A was launched in March 2007, and the ministry valued the program at 4 billion pounds when the fourth, Skynet 5D, went up in December 2012. The government's Skynet 6 page, updated on 4 August 2025, gives the four Skynet 5 satellites X band "strategic long-haul" and UHF "tactical" services and schedules the first Skynet 6 satellite for launch in 2027, promising "a step-change both in capacity and protection" without figures.

Military satellite families: where the protection sits, and what it cost

Family	Band	Work given to the satellite	What was traded
DSCS III (wideband)	X band (SHF)	Multibeam antenna with nulls toward a jammer	Large user antennas, 4 to 60 feet (GAO, 2003)
FLTSAT, UHF Follow-On (narrowband)	UHF, 225 to 400 MHz	Channels for cheap, simple terminals	Hard to defend against jamming (Ward and Floyd)
Milstar (protected)	EHF	Spread spectrum, cross-links, onboard processing, hardening	No high data rates; in the 1980s design, at most fifteen users at once per satellite (Spires and Sturdevant)
AEHF and WGS (successors)	EHF; X and Ka band	AEHF keeps protection and cross-links; WGS follows commercial methods	About 250 against at least 2,100 Mbit/s per satellite (planned, GAO, 2003)
Skynet 5 (United Kingdom)	X band and UHF	Satellites delivered as a contracted service	Ownership of the space segment left with the contractor

What a moving user costs

A moving user pays three ways. It pays in the antenna: a dish must be kept pointed while the ship rolls, which meant a stabilized platform under Marisat's one meter dish; an aircraft has room only for a small antenna on its fuselage. It pays in the band: lower bands such as L band tolerate a small, wide-beam antenna, at the price of gain, and usually of bandwidth. And it pays in the rate: with little gain at the user end, each channel needs more of the satellite's power for the same energy per bit, so a satellite supports fewer channels, or slower ones. The prices fell with time. Martin, writing in the mid 1990s, contrasts the first ship terminals of up to a ton and 50,000 to 75,000 dollars with a satellite telephone in a briefcase for under 10,000 dollars. He also records an exception to the rule of low bands: Qualcomm's messaging and position service, which used spread spectrum techniques through Ku band domestic satellites and had more than 100,000 units on trucks in the United States. A slow enough service can use a high band with a small antenna, because it asks for so little power.

THE SYSTEM'S RECOVERY

TDRS-1, 1983: a launch failure recovered from the ground. TDRS-1 was launched aboard the Shuttle on 4 April 1983, deployed in orbit, and then raised by an Inertial Upper Stage. NASA's mission page records that "a malfunction of the Inertial Upper Stage booster resulted in placement of the spacecraft into an improper but stable orbit", and that "additional propellant aboard the satellite was used over next several months to gradually place TDRS-1 into its properly circularized orbit." What failed was the launch, not the satellite. The recovery was done by command from the ground, with propellant the satellite carried for other purposes. The record supports one lesson: a relay that a whole program depended on was saved by margin carried on board, and the cost of that margin was paid in the months it took and in the propellant it used.

SECURITY NOTE

Who can interfere or command. The military systems give this chapter its public case of design against a jammer, and they placed the defense in three different parts of the satellite. DSCS III placed it in the antenna, with nulls steered toward a jammer. Milstar placed it in the waveform, spreading signals across EHF bandwidth that the military UHF band, in Ward and Floyd's account, does not have. The FLTSAT EHF packages placed it in onboard processing, opening channels on request from user terminals. Who may use AEHF was to be decided by a cryptographic suite that, GAO notes, "limits access to authorized users". Command had its own path: DSCS III carried an X band section that "provided redundant command paths", and on Marisat each UHF channel for the Navy could be activated independently by ground command. **How it is seen.** At sea, by a lost carrier or an unanswered call; at a relay ground station, by a lost link to a user spacecraft. **How it is recovered.** For the military systems, largely by what was built in before launch, such as a second command path, and by keeping routine traffic elsewhere: a Defense Department master plan drafted after 1994 recommended commercial satellites for "low-security missions", Spires and Sturdevant record. For ships, through a spare satellite or an overlapping ocean region, and through the high frequency radio still on board.

Monday rule: for a mobile user, write the terminal's size, power and price first; they constrain the band and the rate.

CHAPTER NINE

1990 to 2019: The Switch in the Sky, and Its Second Owners



On Friday 30 October 1998 the Vice President of the United States placed a call from the White House Rose Garden on a handheld Iridium phone; the White House release said the service would start on 1 November. Nine months later Iridium LLC was in Chapter 11. Its satellites kept flying, a second owner bought them, and by 2019 a second generation had replaced them with the same architecture. This chapter asks a narrow question about that decade: three teams answered "where does the work go for a handheld phone?" in three different ways; two of the companies failed and all three systems lived on. Why?

The row for this chapter: 1990s to 2010, the first low orbit wave

Limit that ran out first	User end	Space	Ground end
Money and paying customers; also the handset, and permission country by country	A handset at about 3,000 dollars at retail (1998)	Iridium: 66 satellites, crosslinks, switching on board. Globalstar: a bent pipe. Thuraya: one geostationary satellite with a 12.25 m antenna	Iridium: 12 gateways (1998). Globalstar: 25 in service (end of 2001), owned mainly by local providers

Meanwhile. Direct to home television grew on large geostationary satellites (Chapter 7). NASA's ACTS tested the Ka band from 1993 (Chapter 10). On the ground, cellular networks spread, and the filings of this chapter name that spread as a cause of their trouble. Inmarsat, once a treaty organization, was being turned into a company (Chapter 8). Navigation satellites, which need no uplink from the user, were already in daily use (Chapter 14).

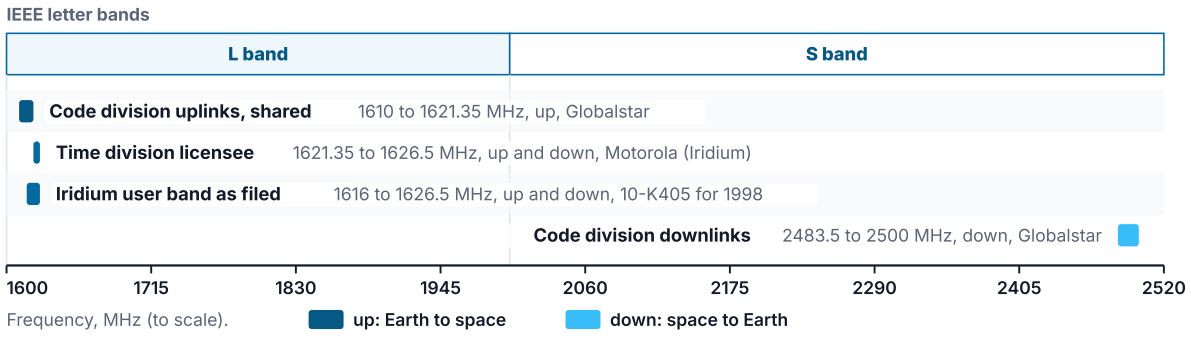
The promise, and the permission

Motorola announced Iridium in 1990, a global system of satellites in low orbit to which a person could talk with a handheld phone (NASA SP-4217, chapter 21). The design began with 77 satellites, which gave the system its name; it was cut to 66 in six planes of eleven (NASA history). Low orbit is what made the handheld easier to serve. At about 780 km a satellite is 2.6 ms away straight up (calculated), and its path loss is far smaller than to a geostationary satellite 35,786 km away. The price is motion: each satellite crosses the sky in minutes, so a call must be handed from satellite to satellite, and covering the whole Earth needs dozens of them.

Permission came band by band and country by country. In the United States the FCC adopted a band plan for the "Big LEO" systems: 1610 to 1621.35 MHz for systems that use code division access and share the band, 1621.35 to 1626.5 MHz for one licensee using time and frequency division, and 2483.5 to 2500 MHz for the code division downlinks (FCC order DA 96-1789). On 31 January 1995 the FCC authorized Motorola to build, launch and operate 66 satellites and 12 spares in orbit; the same order refers to the other two applicants it licensed. That is a US case. The Iridium filing lists what a working system needed on top of it: a license for the space segment in one country, a license in each country with a gateway or a control facility, and licenses in each country for the phones and the service.

FIGURE 9.1

The Big LEO band plan split one L band block between two kinds of access and paired it with an S band downlink



The US band plan as the FCC described it in 1996: code division systems share the lower L band block, one time and frequency division licensee holds the upper block, and code division downlinks use S band. Iridium's filing for 1998 lists 1616 to 1626.5 MHz; how its lower part was shared with the code division systems is not stated in the parts read.

Sources: FCC order DA 96-1789; Iridium Form 10-K405 for 1998; Globalstar Form 10-K for 2001. Checked 2026-11-23.

Iridium as built: the switch in the sky

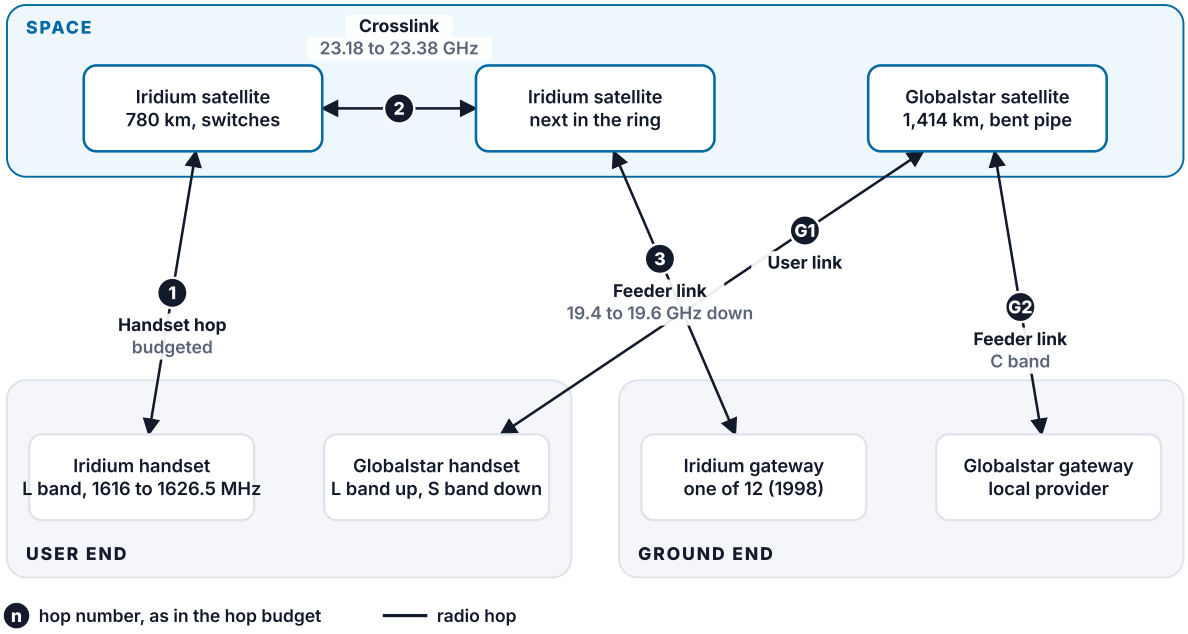
According to Iridium's filing, the space segment, including the initial deployment of the constellation, was completed in November 1998: 66 satellites in six planes at about 780 km, each circling the Earth in about 100 minutes (Iridium Form 10-K405 for 1998). Each satellite carried three kinds of antenna. Three phased arrays formed 48 beams that together covered a circle about 4,340 km across. Gateway link antennas reached the ground stations. Crosslink antennas reached the neighboring Iridium satellites at 23.18 to 23.38 GHz. The phones used 1616 to 1626.5 MHz, up and down in the same band by time division; the gateways used 29.1 to 29.3 GHz up and 19.4 to 19.6 GHz down.

Read as a division of labor, Iridium put most of the work in orbit. The satellite did not only amplify. It carried the call along the crosslinks, satellite to satellite, to the satellite above a suitable gateway, so the system needed few gateways: 12 in 1998, one of them owned by the US government. The handset stayed small and expensive: the filing gives a wholesale price of about 1,750 dollars and a retail price of at least 3,000 dollars. The ground end was a set of regional gateway companies, each with an exclusive territory.

The largest contract was for the space segment. The filing lists three supply contracts with Motorola: the space system, at about 3.435 billion dollars and substantially complete; five years of operations and maintenance, at about 2.89 billion dollars; and the gateway hardware and software, at about 356 million dollars. NASA's history, written before launch, called the total "well in excess of three billion dollars". Larger round totals in later press appear in no filing and are left out.

FIGURE 9.2

Iridium switched the call in orbit; Globalstar sent it straight down to a gateway in the same footprint



Two answers to one handset, late 1990s: Iridium's satellites pass a call along crosslinks to a gateway that may be far away; Globalstar's satellite returns it to a gateway that sees the same satellite. Only hop 1 is budgeted, in ledger LL-1998-01; the other hops are drawn for their place in the path.

Author's diagram based on Iridium Form 10-K405 for 1998 and Globalstar Form 10-K for 2001 (SEC EDGAR), checked 2026-11-23.

Globalstar as built: the switch stays on the ground

Globalstar, led by Loral and Qualcomm, gave the opposite answer. Its 48 satellites (52 launched) flew at 1,414 km in a design the company called "simple, traditional 'bent pipe'": each satellite amplified the signals it received and sent them straight back to Earth, with no links between satellites (Globalstar Form 10-K for 2001). The phones used code division access, Qualcomm's, at 1610 to 1621.35 MHz up and 2483.5 to 2500 MHz down; the gateways used 5091 to 5250 MHz up and 6875 to 7055 MHz down.

The division of labor follows. With no crosslinks, a call works only where the handset and a gateway see the same satellite, so the ground end carries the switching and the coverage. Globalstar had 38 gateways built and 25 in service at the end of 2001, owned and operated mainly by local service providers. The filing states the design's intent plainly: the system

"complements and extends, rather than bypasses, wireline and cellular network infrastructures". Coverage reached about 67 percent of the land and 18 percent of the water at the end of 2001. Northwestern Alaska, for example, was outside the coverage list.

The two designs share a band plan and a decade and divide the work in opposite ways. Iridium bought coverage of oceans and poles with switching and crosslinks in orbit. Globalstar bought a simpler satellite with many gateways and local partners on the ground. Neither choice decided the fate of either company, as the filings show below.

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.

ORBCOMM: messages, not voice

A third system in low orbit aimed lower. ORBCOMM carried short data messages, up to about 200 bytes, in the VHF band: 148.0 to 149.9 MHz up and 137.0 to 138.0 MHz down (ORBCOMM Global Form 10-K405 for 1999; ORBCOMM Inc. Form 10-K for 2006). Its first two satellites were launched in April 1995, full commercial service in the United States and Canada began in November 1998, and 35 satellites had been launched by the end of 1999. A satellite normally relayed a message from the subscriber's unit to a gateway earth station, which routed it to its destination; the satellites also had, in the filing's words, "a limited store-and-forward capability". The work was a small terminal at the user end, a simple satellite, and ten gateway earth stations in 1999. The system cost about 345 million dollars to build and launch, and about 21,000 units were active, according to its filing for 1999.

One satellite instead of a constellation

A handheld phone did not require low orbit. AMSC-1, launched on 7 April 1995, served vehicles across North America from geostationary orbit (NASA SP-4217, chapter 21). Thuraya went further. Its first satellite, launched in October 2000 on a Sea Launch rocket, carried a 12.25 m L band reflector that formed more than 200 spot beams and could handle 13,750 calls at once, according to its builder, Boeing (release of 18 June 2001). An on-board digital processor routed calls from one handset to another or toward the ground network. The handset worked on satellite and on GSM ground networks and included a GPS receiver. Boeing announced commercial service to more than 20 countries from July 2001, over a region of about 100 countries from North and Central Africa and Europe to the Middle East, the Indian subcontinent and Central Asia, with the primary gateway and network operations center in the United Arab Emirates.

This is a third division of labor. The satellite carries a very large antenna, which recovers much of the loss of a path about 46 times longer than Iridium's straight up (about 33 dB more at the same frequency, calculated), and one gateway serves the region. The cost is a delay of at least 238.7 ms from handset to gateway and 477.5 ms for a reply (calculated, propagation only, a lower bound with both ends below the satellite), no coverage of the poles, and one satellite as the whole space segment. Antenna size is not the whole budget: the handset's power, the satellite's receiver and the waveform also count, and none of them was read in a primary source. A peer-reviewed comparison of mobile payloads ("Performance analysis of satellite payload architectures for mobile services", IEEE Transactions on Aerospace and Electronic Systems, 2007) records that Thuraya used the GMR-1 family of radio specifications and that a similar regional system in Southeast Asia, ACeS, used GMR-2, a family closer to GSM. The operator's and regulator's records were not read, so the service page below rests on the builder's figures.

LINK LEDGER · LL-2000-03 · SERVICE LEDGER

2000 System: Thuraya handheld call through one geostationary satellite (first satellite) **Retired**

Class: service only

1 Requirement	A voice call from a dual-mode handset (satellite and GSM, with GPS) anywhere in one region of about 100 countries, from North Africa and Europe to Central Asia. Service announced for July 2001; dates are the manufacturer's.
2 Ends and path	A handset at one end; at the other, a second handset in the region, or a terrestrial network reached through the primary gateway in the United Arab Emirates. **Path:** Switched in orbit: an on-board digital processor routes a call between beams, handset to handset or toward the gateway. No crosslinks: one satellite.
3 Orbit and time	Geostationary; launched in October 2000 on a Sea Launch rocket. A 12.25 m L band reflector forms more than 200 spot beams. **Time:** 119.4 ms straight up; handset to gateway through the satellite at least 238.7 ms; a reply at least 477.5 ms (calculated, propagation only, both ends directly below the satellite).
4 Band and permission	**Handset to satellite, both directions.** L band; exact frequencies not in the sources read. Radio interface of the GMR-1 family of specifications (peer-reviewed paper, 2007) **Satellite to gateway.** Not stated in the sources read
5 Capacity	**Up.** 13,750 simultaneous calls across more than 200 spot beams (manufacturer, 2001). **Down.** As up. The per-call rate was not in the sources read.
6 Who owns each end	**Space segment.** Thuraya, a company whose shareholders were 18 telecommunications operators and investment houses (manufacturer, 2001) **Ground segment.** Thuraya: a primary gateway with a collocated network operations center in the United Arab Emirates **Customer relationship.** Not stated **The exit.** Not stated
7 Trust	Command arrangements are not published. Calls used the GMR-1 cipher, whose weaknesses published research used to recover a session key (survey, 2024; conditions not examined here).
8 How it fails, and how we would see it	One satellite carries the region: no second path in orbit, no service outside the beams. In the north the satellite sits low in the sky. **How we would see it:** Not published.
9 Cost shape	One satellite and one primary gateway instead of a constellation. Prices not in the sources read.
10 Evidence	12.25 m reflector; 13,750 calls operator claim Boeing release, 18 June 2001, 2026-11-23 Launch October 2000; service announced for July 2001 operator claim Boeing release, 18 June 2001, 2026-11-23 GMR-1 radio interface published history IEEE Trans. Aerospace and Electronic Systems, 2007, 2026-11-23 238.7 ms one way; 477.5 ms reply calculated Distance over the speed of light, 2026-11-23

Service only, no hop budget: no primary source read gives the handset's power, the satellite's G/T or the waveform's required Eb/N0.

Three verdicts, kept apart

The link. Each of these systems was built to carry calls or messages; the filings of Iridium, Globalstar and ORBCOMM record that they did, and Thuraya's builder announced its service for July 2001. The handset hop of Iridium is worked below as an illustrative model on representative values from an ITU recommendation: under its stated assumptions the modeled uplink has about 10 dB of margin in open sky at the edge of coverage, and inside a modern office building it misses by about 22 dB. The filing says the same in words: inside "buildings with steel construction and metal coated glass common in many urban high rise buildings ... no meaningful satellite voice service is available."

The service. The filings describe a service that worked and was hard to sell. Iridium's own account of its slow start names the initial distribution of phones (one maker could not ship significant quantities until early March 1999), a shortage of trained service providers and sales staff, and weak marketing coordination among Iridium, its gateways and its service providers. It also notes that its voice quality, signal strength and building penetration were below those of mature cellular systems, and that service providers, not Iridium, set retail prices.

The business. Iridium's bank facility required at least 27,000 satellite voice subscribers and 52,000 subscribers in all by 31 March 1999, rising to 173,000 and 454,000 by 30 September 1999. The company reported that it was "significantly below" its estimates and obtained a waiver. Iridium LLC operated under Chapter 11 from August 1999, and Motorola charged 2,069 million dollars to its Iridium reserves in 1999 (Motorola Form 10-K for 1999). ORBCOMM Global and seven subsidiaries filed on 15 September 2000 (Form 8-K). Globalstar filed on 15 February 2002 with about 66,000 commercial subscribers and 6.4 million dollars of revenue for 2001, after a 2.9 billion dollar impairment charge in 2000. Its filing names limited cash, debt in default, a growth rate "not sufficient to sustain Globalstar's cost of operations", and land-based networks "built more quickly than Globalstar anticipated".

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.

The scene above is set in the months between the start of service and the filing. The filing supports its terminal and its price: a handset at no less than 3,000 dollars, and service that ended at the door of a steel building. The filings give no per-minute price for 1999, so none is given.

The handset's hop, worked

The worked link below is shared with the first book of this series, which explains the method; it is reprinted here with its numbers unchanged. It is an illustrative model, in the sense of the Reader's Brief: representative values from an ITU recommendation, not Iridium's own filed budget, which was not read. For the history it shows one thing: on these assumptions the modeled uplink closes outdoors at the handset's highest listed power and does not close indoors; the model does not say what limited the service in its own years. One modeled hop does not cover the downlink, handover or call completion, and it cannot show what caused the bankruptcy; the filings name other causes.

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.

The ones that were not completed

Other systems of the decade stopped earlier. ICO, established in 1995 to build a system in medium orbit, filed for Chapter 11 on 27 August 1999; its first satellite was lost in a launch failure in March 2000, and one satellite, F2, was launched in June 2001 while ten more stayed in storage (ICO Form 10-K for 2006). TRW abandoned its Odyssey project in December 1997 and took a stake in ICO (SpaceDaily, trade press, 18 December 1997). Ellipso lost its FCC license in 2001 for missing a construction milestone (Satellite Today, trade press, 6 June 2001). Teledesic held an FCC license for a Ka band broadband system whose original plan was 840 satellites; it ordered two satellites in February 2002, suspended the work and surrendered the license by a letter of 27 June 2003 (Satellite News, trade press, July 2003). Chapter 14 returns to the Ka band idea, which others built two decades later.

Second owners

The satellites outlived the companies. On 11 December 2000 Iridium Satellite LLC acquired the satellite assets from Iridium LLC, then a debtor in possession (Iridium Communications Form 10-K for 2009). New owners took ORBCOMM's assets out of bankruptcy in April 2001 "for a fraction of their original cost", with 29 of 35 satellites still working (ORBCOMM prospectus, 2007). Thermo obtained operational control of Globalstar on 5 December 2003 and completed the purchase in 2004 (Globalstar, Inc. Form 10-K for 2006). No filing or court record available to this book gives the purchase prices, so none is printed.

The second owners kept the architecture and changed the customers and the balance sheet. The Globalstar filing of 2001 observes that the reorganizations of Iridium and ICO "allowed them to dramatically reduce or eliminate their debt". By the end of 2009 Iridium had about 369,000 subscribers, including machine-to-machine data users, and 23.6 percent of its revenue came from the US government; the Department of Defense owned and operated a dedicated gateway in Hawaii. By 2009 the constellation's customers included governments, ships, aircraft and machines as well as travelers.

FIGURE 9.3

Four handheld or small-terminal systems of one decade, four divisions of the work

	Iridium	Globalstar	ORBCOMM	Thuraya
Orbit	66 satellites, six planes, about 780 km	48 satellites (52 launched), 1,414 km	35 launched by 1999, about 740 to 825 km	One geostationary satellite (October 2000)
User band	L band, 1616 to 1626.5 MHz, both ways	L band up, S band down	VHF: 148.0 to 149.9 MHz up, 137.0 to 138.0 MHz down	L band
Path	Switched on board, crosslinks	Bent pipe, no crosslinks, CDMA	To a gateway; limited store and forward; about 200 byte messages	Routed on board between more than 200 beams
Gateways	12 (1998); one owned by the US government	25 in service, 38 built; owned mainly by local providers	10 gateway earth stations (1999)	A primary gateway in the United Arab Emirates
Service from	1 November 1998	Early 2000	November 1998 (full service)	July 2001 (announced)
Failure	Company: Chapter 11, August 1999	Company: Chapter 11, 15 February 2002	Company: Chapter 11, 15 September 2000	None found in a primary source
Second owner	Iridium Satellite LLC, 11 December 2000	Thermo, operational control 5 December 2003	New ORBCOMM, April 2001	Not in the sources read

Each cell is taken from the company's own filing or the manufacturer's release; a blank means the source read does not say.

Sources: Iridium Form 10-K405 for 1998 and Form 10-K for 2009; Motorola Form 10-K for 1999; Globalstar Form 10-K for 2001 and Globalstar, Inc. Form 10-K for 2006; ORBCOMM Global Form 10-K405 for 1999, Form 8-K of September 2000 and ORBCOMM Inc. prospectus of 2007 (all SEC EDGAR); Boeing release of 18 June 2001; IEEE Transactions on Aerospace and Electronic Systems, 2007 (Thuraya's L band). Checked 2026-11-23.

The replacements

A second owner still inherits satellites that age. By early 2007 Globalstar reported that the S band power amplifiers on its first generation satellites were degrading; it believed the cause might be radiation in orbit, and warned that by some time in 2008 substantially all satellites launched between 1998 and 2000 might no longer support two-way calls (Globalstar, Inc. Form 10-K for 2006). One-way data from small terminals, which used only the L band uplink, was not affected. Globalstar ordered 48 second generation satellites on 30 November 2006. Iridium announced its replacement, Iridium NEXT, in 2010; the last of 75 new satellites was launched on 11 January 2019 and the upgrade was declared complete on 5 February 2019, at a cost the company put at about 3 billion dollars (Iridium releases of 11 January and 6 February 2019). The architecture of 1998, crosslinks and switching in orbit, was rebuilt rather than replaced.

THE SYSTEM'S FAILURE

What failed: companies, not the links that were worked. Iridium LLC entered Chapter 11 in August 1999, nine months after service began, having missed the subscriber and revenue minimums of its bank facility (Form 10-K405 for 1998; Motorola Form 10-K for 1999). Globalstar filed on 15 February 2002 with about 66,000 subscribers and 6.4 million dollars of 2001 revenue (Form 10-K for 2001). The filings name debt, slow distribution, handset supply, service quality indoors and faster growth of ground networks; no single cause is named here. For contrast, a component failure that did not end a company: Globalstar's S band amplifiers, degrading by 2007, threatened two-way service until the satellites were replaced. **What the filings support:** a constellation is a long fixed cost carried by subscribers who arrive slowly, and a link that closes does not pay that cost.

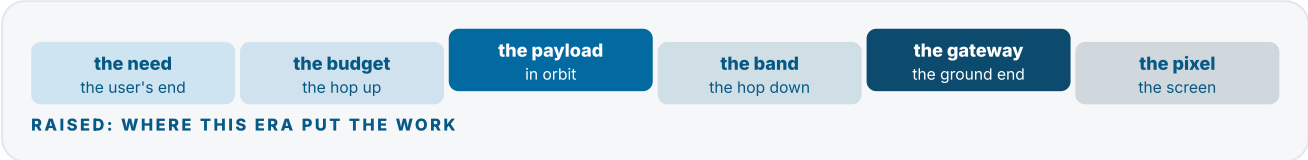
SECURITY NOTE

Who can interfere or command. Iridium was commanded from an operations center in Virginia, with a backup in Italy and control stations in Canada and Hawaii; Globalstar from two control centers in California (their filings). Where a call lands is a design and licensing choice: a crosslinked system can carry a call to a distant gateway, while a bent pipe lands it at a gateway in the same footprint, under that country's operator. Iridium describes its government traffic as routed across the constellation to the dedicated, secure Defense gateway, "thus reducing the vulnerability to electronic jamming and interception" (Form 10-K for 2009, an operator claim); neither design gives privacy or sovereignty by itself. Thuraya's calls relied on the GMR-1 cipher; a peer-reviewed survey ("A Survey on Satellite Communication System Security", Sensors, volume 24, 2024) reports published research that exploited weaknesses in that cipher to recover a call's session key. The conditions of the attack are in the original paper, which this book has not examined. **How it is seen.** Dropped calls and completion rates, which the filings name as measures of service. **How it is recovered.** In orbit, by spare satellites and by moving healthy ones, as Globalstar did from 2007. In ownership, by sale: the filings read do not say how command authority passed with the assets, so nothing more is claimed.

Monday rule: a link that closes is not a business that closes; ask for subscribers, price and debt next to the link budget.

CHAPTER TEN

1993 to 2015: Spot Beams and the Middle Orbit, the Broadband Answer Before the Constellations



On 12 September 1993 NASA launched ACTS, an experimental satellite that used the Ka band, 30 GHz up and 20 GHz down (NASA SP-4217, chapter 6). In the same decade the low orbit telephone systems of Chapter 9 were being built, and two of them would be in bankruptcy within a few years. The operators already in geostationary orbit took a different road to the demand for data: they kept their orbit and changed the satellite. This chapter asks how they answered that demand before the constellations of the 2020s, and what the answer cost on the ground.

The row for this chapter: 2010s to 2026, broadband, first half

Limit that ran out first	User end	Space	Ground end
Capacity per satellite and the cost of each bit delivered; also rain at higher bands and the delay of geostationary orbit	A dish on a house, a vehicle or a ship; a tracking antenna for medium orbit	Many spot beams on one geostationary satellite; a fleet in medium orbit	More gateways, each serving a group of beams

Meanwhile. The first low orbit wave failed as businesses and was bought by second owners (Chapter 9). The treaty organizations that had run the trunk and the maritime service became companies (this chapter). On the ground, cellular networks moved to data and phones became computers; Chapter 12 tells how the satellite came back to the phone.

The idea: reuse the same frequencies, beam by beam

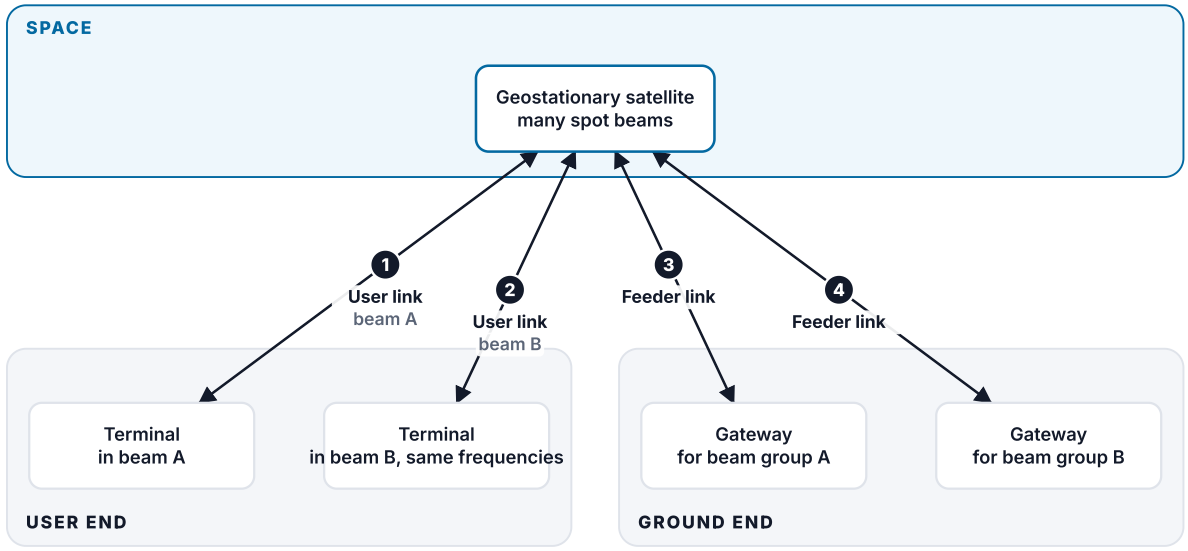
A satellite with one wide beam can use each frequency about once over its whole coverage, or twice with two polarizations. A satellite with many narrow spot beams can use the same frequencies again in beams far enough apart that the interference between them stays within a design limit. The capacity of one satellite can then grow with the number of times its

spectrum is reused, as far as its power, its feeder links and the traffic in each beam allow. At a given frequency a narrower beam needs a larger antenna on the satellite, so each beam also has more gain, and the user's dish can be smaller for the same rate. The first book of this series, *The Bit's Path*, explains the gain of an antenna and the cost of interference between beams; this chapter needs only the result.

The result moves work to the ground. Each beam's traffic has to leave the satellite somewhere, and on a transparent satellite it leaves through a feeder link to a gateway on the ground. A satellite with many beams therefore needs many gateways, or very wide feeder links, or both. Spot beams are a property of the antenna, not of one band: they can be built in Ku band or in Ka band. Ka band offers more spectrum and narrower beams for a given antenna; it also loses more in rain, as *The Bit's Path* works out in its chapter on bands and antennas.

FIGURE 10.1

Spot beams multiply what one satellite carries, and every beam's traffic must still land at a gateway



A transparent spot beam service: terminals in two beams that reuse the same frequencies, one satellite, and a gateway for each group of beams. The numbers of beams and gateways differ by system and are not drawn to scale.

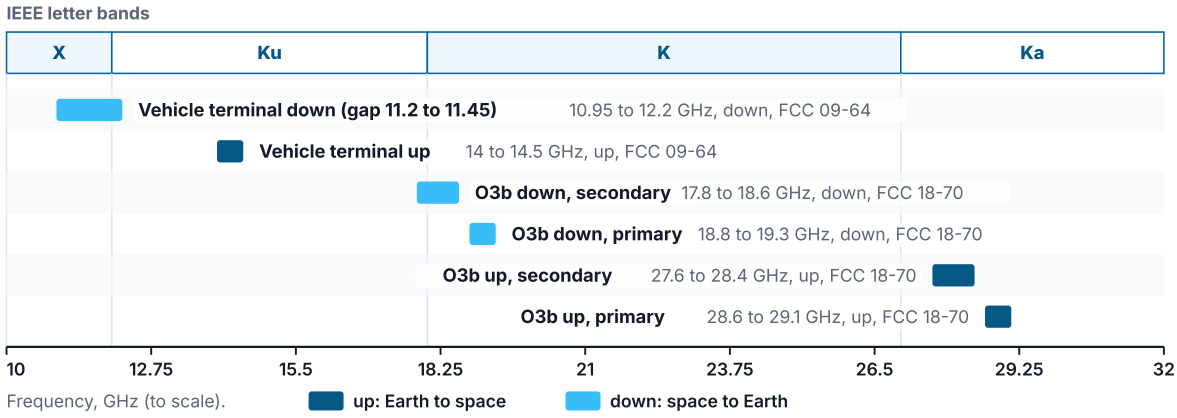
Author's diagram of the general spot beam arrangement; no hop of this figure is budgeted in this book.

Figure 10.2 places the links of this chapter on the frequency axis. The names need care. Regulators and operators speak of a Ku band of about 11 to 14.5 GHz and a Ka band of about 18 to 30 GHz, with the downlink in the lower part of each and the uplink in the upper part; the IEEE letter bands draw the boundaries elsewhere, so a downlink near 19 GHz that an

FCC order calls Ka band sits in the IEEE's K band. This book uses the regulator's names when it quotes a regulator. What the figure shows does not depend on the names: the vehicle terminal of 2009 worked near 12 and 14 GHz, while the experiment of 1993 and the medium orbit trunk of 2014 worked near 20 and 30 GHz, where more spectrum was available and rain costs more.

FIGURE 10.2

This chapter's links sat in two bands: Ku for the vehicle terminal, Ka for the medium orbit trunk



Bands as the sources give them: the US rules for vehicle-mounted terminals (2009) and O3b's grant in the United States (2018); ACTS (1993) used 30 GHz up and 20 GHz down. Regulators and operators call the 11 GHz downlinks Ku band and the 18 to 20 GHz downlinks Ka band; the IEEE letter bands on top draw the boundaries differently.

Sources: FCC 09-64 (2009); FCC 18-70 (2018); NASA SP-4217, chapter 6 (ACTS). Checked 2026-11-23.

The experiment

NASA's ACTS tested the Ka band for communication from 1993 (NASA SP-4217, chapter 6). Chapter 7 tells Japan's experiments of the same years in the same band. Chapter 13 tells how ACTS switched traffic on board, how it fought rain, and what its experiments showed. For this chapter it marks the band where the later broadband satellites went, and a choice each of them had to make: switch the traffic in orbit, as ACTS did, or keep each beam a transparent repeater and switch on the ground.

The commercial steps, 2005 to 2012

Between ACTS and the large Ka band satellites of 2011 the consumer service was built in steps, by operators that answered that choice in opposite ways. Launch and service entry are dates to keep apart, and the capacities in the table are the operators' own figures or trade

press, never a measurement. They are also not one measure: Hughes states gross transmission capacity, Viasat data throughput.

Spot beam broadband before the constellations, as the sources read describe it

System	Dated steps	What the satellite did	Source
IPSTAR (Thaicom 4), Shin Satellite	Launched 11 August 2005 on an Ariane 5	Internet access for business customers in Asia, Australia and New Zealand; bands and capacity not read in a primary source	Trade press
WildBlue, owned by Viasat from 15 December 2009	WildBlue-1 placed in service March 2007; service also carried on Telesat's Anik F2	"Unprocessed" Ka band spot beams	Viasat release and filings
Spaceway 3, Hughes	Launched August 2007; service in North America from April 2008	On-board packet switch; up to 112 uplink and 784 downlink spot beams; up to 10 Gbit/s gross	Hughes Form 10-K for 2008
KA-SAT, Eutelsat	Launched at the end of 2010; broadband service activated by 2 June 2011	82 spot beams connected to 10 ground stations; more than 70 Gbit/s	Viasat filing (launch); trade press (the rest)
ViaSat-1, Viasat	Launched October 2011; Exede service from January 2012	About 140 Gbit/s of data throughput	Viasat Form 10-K for fiscal 2012

According to the trade press (Satellite Today, 12 August 2005), an Ariane 5 put Shin Satellite's IPSTAR, "also known as Thaicom 4", into orbit on 11 August 2005 with a launch mass of 6,485 kg, to provide internet access across Asia, Australia and New Zealand. Its beams and capacity are often quoted, but no primary page giving them could be read, so none is printed. A Thai newspaper, The Nation, reported on 22 April 2026 that Thaicom 4 had exceeded its engineering life and that its customers would be moved for a time to a Korean satellite. No operator or regulator record of its later status was read, so the book gives none.

The two US operators took opposite sides of the choice that ACTS had posed. WildBlue, in Viasat's words when it agreed to buy the company on 1 October 2009, "pioneered the use of 'unprocessed' Ka-band spot beam technology to increase capacity and lower bandwidth

costs". Hughes launched Spaceway 3 in August 2007 with "an on-board fast packet switch and processor which enables direct user-to-user communication at broadband speeds" (Hughes Communications Form 10-K for 2008). The first keeps the satellite a repeater and puts the switching in the gateways; the second does in orbit what ACTS had tested, so two small terminals can reach each other in one pass through the satellite, with no gateway between them (one radio leg up, one down). NASA's history of 1997 already named Spaceway among the commercial systems that drew on ACTS (NASA SP-4217, chapter 6).

The consumer business sold speed to subscribers. Hughes reported about 432,800 consumer subscribers on 31 December 2008, sold with a hardware purchase and a long-term service plan. Viasat reported about 424,000 WildBlue subscribers on 2 April 2010 and about 409,000 on 1 April 2011, and priced the plans "based on maximum downstream/upstream data speeds" (Viasat Forms 10-K for fiscal 2010 and 2011). WildBlue brought about 209 million dollars of revenue in the twelve months to June 2009. The limit was the cost of capacity: Viasat said that ViaSat-1 would multiply WildBlue's total network capacity "by more than tenfold" and aimed nearly all of it at the areas where the cost of bandwidth held growth back. In Europe, the trade press reported in June 2011 that each Tooway package on KA-SAT came with a data allowance. The size of those allowances, the usage rules of the US services, and a cost per bit for any of these satellites appear in no primary record found, so the chapter prints none.

Viasat's figures for ViaSat-1 close the period: launched in October 2011 "with a data throughput of approximately 140 Gigabits per second", with commercial Exede service from January 2012 (Viasat Form 10-K for fiscal 2012). Hughes had given 10 Gbit/s of gross transmission capacity for Spaceway 3 four years earlier. The two figures are not the same measure, describe different designs and were not checked independently, so the book draws no growth ratio from them; the multiple it can quote is Viasat's own, for its network: "more than tenfold".

The division of labor changed less than the capacity did. The user end became a small dish and a modem in the home. The satellite became larger and more complex in its antennas; in WildBlue's design each beam stayed a transparent repeater, while Spaceway 3 switched packets in orbit. The ground end grew: more gateways, each connected to the terrestrial network, and a central system that manages the modems. That center is the part of this architecture an attacker reached in 2022, as Chapter 11 tells.

FIGURE 10.3

The broadband answer before the constellations: one experiment, two Ka band spot beam satellites, one medium orbit fleet

System	Orbit	Band	Launch	Service entry	What it changed	Source
ACTS (NASA)	Geostationary	Ka: 30 GHz up, 20 GHz down	12 September 1993	Experiment, no commercial service	Tested the Ka band for communication	NASA SP-4217, chapter 6
KA-SAT (Eutelsat)	Geostationary	Ka	End of 2010 (Viasat filing)	Activated by 2 June 2011 (trade press)	High-capacity Ka band service for Europe and parts of the Middle East and Africa	Viasat Forms 10-K for fiscal 2011 and 2012; Satellite Today, 2 June 2011 (trade press)
ViaSat-1 (Viasat)	Geostationary	Ka, spot beams	October 2011	January 2012 (Exede)	About 140 Gbit/s on one satellite (operator)	Viasat Form 10-K for fiscal 2012
O3b	Medium, equatorial, 8,062 km for the next satellites	Ka	Not verified in a primary source	September 2014 (commercial operations)	Trunks with a delay floor near a quarter of the geostationary one	FCC 18-70; FCC 20-13; SES results of 24 February 2017

Launch and service entry are kept apart; a cell reads 'not verified' where no primary source was read on the book's date, and a trade press date is labeled as such.

Sources as listed in the last column, checked 2026-11-23.

The middle orbit

One company moved the satellite closer instead of making it bigger. O3b operated satellites in medium Earth orbit under the authority of the United Kingdom. The FCC first granted it access to the US market on 25 September 2012, through individual earth stations working with eight satellites in medium orbit, and in January 2015 raised the count to twelve (FCC order 20-13, note 2). The FCC's 2018 order describes the next satellites of the system as flying in a circular equatorial orbit at 8,062 km, in Ka band (FCC 18-70, paragraph 18). SES, which acquired the remaining shares of O3b in August 2016, reported that O3b began commercial operations in September 2014 and had 52 customers and 109 million dollars of revenue in 2016 (SES results release, 24 February 2017). No primary record of the first launch date was found.

The orbit changes the delay. At 8,062 km a satellite is 26.9 ms away straight up; ground to ground through it takes 53.8 ms with both ends below the satellite and 73.1 ms with both at 20 degrees elevation, and a reply at least 107.6 ms, or 146.2 ms with both ends at 20 degrees (calculated, propagation only; the case with both ends below the satellite is a lower bound, not a real pair of sites). Through a geostationary satellite the same quantities are 238.7 ms ground to ground and 477.5 ms for a reply with both ends directly below it, and 263.9 ms

and 527.7 ms with both at 20 degrees (calculated). The price moves to the user end. A satellite at 8,062 km is not fixed in the sky (its period is about 4.8 hours, calculated from the altitude by Kepler's third law, T = 2 pi sqrt(r^3 / mu), with r the orbit's radius and mu the Earth's gravitational parameter), so the earth station needs antennas that track the satellites and hand over from one to the next. An equatorial orbit also limits where the service reaches: at this altitude no satellite is 20 degrees or more above the horizon beyond about 45.5 degrees of latitude, and none is above the horizon at all beyond about 63.8 degrees (calculated, spherical Earth), so the system serves the tropics and middle latitudes, not the poles.

The customers SES named were the ones a cable does not reach. In 2016 Digicel Pacific, Palau National Communications Corporation and others bought more O3b capacity; in January 2017 Palau Telecoms and Timor Telecom renewed and expanded their service, and SES stated that Timor Telecom "now receives more than one Gigabit per second (Gbps) of fibre-equivalent connectivity". These are operator claims. The service page below describes such a trunk.

LINK LEDGER · LL-2014-01 · SERVICE LEDGER

2014-09 System: O3b medium orbit trunk to an island operator

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

1 Requirement	Carry an island operator's internet trunk, fibre-equivalent in the operator's words, with less delay than a geostationary link.
2 Ends and path	An earth station at the island operator; at the other end, a gateway earth station connected to the internet. **Path:** Ground to satellite to ground, with no crosslinks named in the sources read; the payload type is not stated there.
3 Orbit and time	Medium orbit. The FCC's 2018 order gives a circular equatorial orbit at 8,062 km for the next satellites of the same system. The satellites move across the sky, so both ends track them and hand over. **Time:** 26.9 ms straight up; 53.8 ms ground to ground with both ends below the satellite, 73.1 ms with both at 20 degrees; a reply 107.6 ms with both below, 146.2 ms with both at 20 degrees (calculated, propagation only).
4 Band and permission	**Ka band.** 18.8 to 19.3 GHz and 28.6 to 29.1 GHz on a primary basis, 17.8 to 18.6 and 27.6 to 28.4 GHz secondary, in the US market access grant; the system operates under the authority of the United Kingdom
5 Capacity	**Up.** Not published per link in the sources read. **Down.** Timor Telecom: more than 1 Gbit/s (operator, February 2017).
6 Who owns each end	**Space segment.** O3b Limited; SES acquired the remaining shares in August 2016 **Ground segment.** O3b gateways; ownership not stated in the sources read **Customer relationship.** The island operator, for example Timor Telecom or Palau Telecoms **The exit.** Not stated in the sources read
7 Trust	Space operations are authorized by the United Kingdom under its Outer Space Act; US market access is conditioned on coordination with other systems. How commands are authenticated is not published.
8 How it fails, and how we would see it	Rain fades Ka band; a tracking antenna that loses a satellite during handover drops the trunk until it reacquires. **How we would see it:** Not published in the sources read.
9 Cost shape	Not published per customer. O3b's revenue was 109 million dollars in 2016, its second full year of commercial operations (operator).
10 Evidence	8,062 km, circular equatorial standard FCC 18-70 (2018), para. 18, 2026-11-23 Service from September 2014; 109 million dollars of 2016 revenue operator claim SES results, 24 February 2017, 2026-11-23 Timor Telecom more than 1 Gbit/s operator claim SES results, 24 February 2017, 2026-11-23 53.8 ms one way below, 73.1 at 20 degrees; reply 107.6 and 146.2 ms calculated Distance over the speed of light, 2026-11-23

Service only, no hop budget: no primary source read gives the terminal, satellite or gateway figures of a link.

Gated ledger, kept as a service page from regulator orders and the operator's results. The first generation's later status is not stated here; today's medium orbit service is a separate ledger later in this series.

Ownership: the treaty bodies become companies

In the same years the organizations that Chapters 4 and 8 described left their treaties. Inmarsat's privatization, from April 1999 to the end of 2003, is told in Chapter 8. On 18 July 2001 Intelsat transferred virtually all of its assets and liabilities to Intelsat, Ltd., a Bermuda company; COMSAT held 21.8 percent of it, and the former signatories together 86.1 percent. A US law, the ORBIT Act of March 2000, set conditions for that change (US Government Accountability Office, GAO-04-891). In both cases some public duties stayed with residual intergovernmental bodies, such as IMSO for maritime distress (Chapter 8). The commercial operator and the public duty were separated, and a treaty body was left to watch the duty.

A dish on a truck

Spot beams and household dishes are one side of the decade; the other is the terminal that goes where the network has failed. In 2009 the FCC adopted rules for vehicle-mounted earth stations: earth stations on a motorized vehicle, traveling mainly on land, that work with geostationary satellites in the conventional Ku band, 14.0 to 14.5 GHz up and 11.7 to 12.2 GHz down, and in parts of the extended Ku band (FCC 09-64, adopted 30 July 2009). The order lists emergency preparedness among the uses. That is a US rule for a class of service, not a single operator. The thread scene of 2012 below is a design example built on that class, not a reconstruction of a dated service: it names no operator, no terminal model and no price, and its only numbers are the ones any link of the class must meet.

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 example's delay is a floor set by physics: from a truck to a hub through a geostationary satellite the signal travels at least 238.7 ms, and at 30 degrees elevation at both ends 257.6 ms; a reply cannot arrive in less than about half a second from propagation alone, and network delay adds to that.

LINK LEDGER · LL-2012-01 · SERVICE LEDGER

2012

System: Ku band dish on a truck through a geostationary satellite (a design example on a class of service, no operator named)

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

1 Requirement	Send claim photographs from a disaster zone where the ground network is down, from a vehicle, the same day. The user must accept at least about half a second before any reply arrives.
2 Ends and path	A vehicle-mounted earth station at one end; at the other, the service provider's hub earth station, which connects to the internet and the company's offices. **Path:** Transparent: the satellite amplifies the signal and shifts its frequency; the hub does the networking.
3 Orbit and time	Geostationary, 35,786 km above the equator. **Time:** 119.4 ms straight up; 238.7 ms ground to ground with both ends below the satellite, 257.6 ms with both at 30 degrees elevation; a reply 477.5 ms with both below, 515.1 ms with both at 30 degrees (calculated, propagation only). Network and protocol delay add to this.
4 Band and permission	**Vehicle to satellite.** 14.0 to 14.5 GHz (conventional Ku band); FCC rules for vehicle-mounted earth stations, adopted 30 July 2009, United States **Satellite to vehicle.** 11.7 to 12.2 GHz (conventional Ku band), plus 10.95 to 11.2 and 11.45 to 11.7 GHz (extended Ku band); same rules
5 Capacity	**Up.** Set by the share of a leased transponder and by the dish; no 2012 service rate was read in a primary source. **Down.** As up.
6 Who owns each end	**Space segment.** A geostationary satellite operator that leases capacity **Ground segment.** The service provider's hub **Customer relationship.** The service provider **The exit.** Contract terms were not read
7 Trust	The licensee must stop transmitting within 100 ms if its off-axis power exceeds the values given to the satellite operator, for example after a pointing error. How the hub authenticates a terminal was not read.
8 How it fails, and how we would see it	A dish pointed off the satellite must stop transmitting; rain fades the Ku band signal; the hub is a single point for every truck it serves. **How we would see it:** At the truck, as loss of lock or lower signal quality; at the hub, as a terminal that drops out of the network.
9 Cost shape	No 2012 price was read. The shape: a dish and modem per vehicle, a share of a leased transponder, and the provider's hub.
10 Evidence	14.0 to 14.5 GHz up; 11.7 to 12.2 GHz down (standard) FCC 09-64 (2009), para. 1, note 1, 2026-11-23 Stop transmitting within 100 ms (standard) FCC 09-64 (2009), para. 101, 2026-11-23 238.7 ms one way below, 257.6 at 30 degrees; reply 477.5 and 515.1 ms (calculated) Distance over the speed of light, 2026-11-23

Service only, no hop budget: no dated 2012 service document giving the terminal and transponder figures was read; the requirement in this case turns on delay, which page 1 states.

A design example on the class of service authorized by the FCC's 2009 rules, not a dated service: no operator, terminal or price is named.

What stayed hard

Three limits survived the decade. The first is the delay of geostationary orbit, which no antenna can remove: about a quarter of a second one way and half a second for a reply, before any network delay. The medium orbit cut it to under a quarter of that with both ends below the satellite, and to a little over a quarter with both ends at 20 degrees elevation on both orbits (146.2 against 527.7 ms for a reply, calculated), and paid with tracking antennas and with coverage that stops short of the poles. The second is rain. A higher band brings more spectrum and narrower beams, and it loses more of the signal in heavy rain, so a service at Ka band is designed for an availability, not for every hour. The third is the ground. Each multiplication of capacity in orbit needed gateways, fiber to each gateway, and a management network that every terminal trusts. Chapter 11 shows the low orbit constellations taking the same three limits in a different order.

THE SYSTEM'S FAILURE

A trade-off, not a failure. None of the satellites or companies in this chapter has a failure on record in the documents read, so none is told, and the chapter gives no verdict on their service or their business. The documented trade-off is this: capacity in orbit was bought with work on the ground. Each beam of a transparent spot beam satellite lands at a gateway, and the modems are managed from the provider's network. A consumer service in geostationary orbit stayed at least 477.5 ms from a reply (calculated, propagation only), and medium orbit brought the floor for a reply down to 107.6 ms (146.2 ms at 20 degrees elevation) with tracking antennas at both ends. **What the record does show:** a jump in capacity in orbit is also a growth of the ground segment, and of the part of the system an attacker can reach.

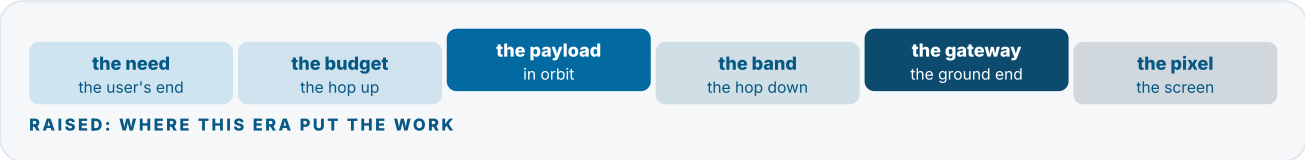
SECURITY NOTE

Who can interfere or command. The 2009 FCC rules for vehicle-mounted terminals show how interference from a moving dish is held in check: the licensee must keep its off-axis power within the values it gave the satellite operator and must stop transmitting within 100 milliseconds if it exceeds them, for example after a pointing error (FCC 09-64, section 25.226). The user's modem and the provider's network management are the attack surface of a consumer broadband system; Chapter 11 tells the 2022 case in which the satellite was untouched and the management network was the way in. O3b's US access required coordination with other systems in its bands and authorization of its space operations by the United Kingdom (FCC 18-70). A satellite that switches packets, as Spaceway 3 does, adds one more thing to guard: the routing it is told to apply in orbit. **How it is seen.** A terminal that leaves the network shows at the hub; interference shows as a drop in signal quality in a beam. **How it is recovered.** A mispointed terminal stops itself under the rules; a satellite operator can move a carrier or a beam; a lost gateway is replaced by another where the design provides one.

Monday rule: when capacity jumps, ask what was added on the ground to carry it.

CHAPTER ELEVEN

2015 to 2026: Thousands of Satellites



On 5 June 2026 the Federal Communications Commission waived a deadline for Amazon. Its license for the low orbit broadband system now called Amazon Leo required 1,616 of 3,232 satellites in operation by 30 July 2026; Amazon's own progress page, updated on 28 October 2026, counted "nearly 400" across 14 missions. The waiver came with conditions, among them the loss of the surety bond. On 15 November 2026 the same page reported that the first Vulcan mission for the system had lost its 40 satellites in a launch anomaly. A filing, a launch and a service are three different events, and this chapter keeps them apart. The question is the one chapter 9 left open: the idea of the 1990s, thousands of satellites in low orbit carrying broadband, returned after 2015 and was built at scale. What was different?

The row for this chapter

Era	Limit that ran out first	User end	Space	Ground end
2015 to 2026: broadband, second half	The cost of launch, of satellites built in volume, and of the user terminal; also spectrum, milestones and capital	A flat electronically steered antenna on a roof, a vehicle or a ship	Thousands of low orbit satellites, in two branches: transparent with many gateways, and crosslinked with routing in orbit	Gateways, points of presence, satellite factories, launch

Meanwhile. The geostationary incumbents build satellites of a terabit per second class (this chapter). The medium orbit trunk of chapter 10 grows into a fleet. Phones gain a satellite function (chapter 12). Processing moves on board for some workloads (chapter 13). The treaty organizations of the 1970s, Intelsat and Inmarsat, are now private companies, and both have been acquired (chapters 10 and 11).

What changed on the cost side

Chapter 9 told how Teledesic was licensed in the 1990s for a broadband constellation in low orbit and never completed. The physics of the 2020s systems is not different from the physics that faced it. A satellite at 550 km sees a small patch of the Earth, so the systems built for continuous broadband with capacity in the busy hour planned thousands of them, a number set by their coverage and capacity targets and not by the altitude alone; each passes overhead in minutes, and each user terminal must follow one satellite and hand over to the next. The usual explanation is that the cost of each part of that answer fell, and that money became available to pay for it.

That explanation names four costs: launch, the satellite, the terminal and capital. This book treats them as hypotheses, because no source read gives comparable figures for the 1990s and the 2020s on all four, and none ranks them. Against the records read, they come out as follows.

- **Launch: partly supported, by one company's account.** SpaceX's registration statement for its public listing, filed with the SEC on 20 May 2026, says that according to NASA the first Falcon 9 of 2010 cost about 2,700 dollars per kilogram to orbit, against a historical average of 18,500 dollars. The NASA study it cites could not be loaded on 23 November 2026, and a 2010 figure for one rocket says nothing about what each constellation paid. The same company builds the rockets that launch its own satellites and describes its "extensive vertical integration"; it expected its third version of broadband satellites to begin deploying on its own Starship in the second half of 2026. Other systems in this chapter depend on other launchers, and Amazon's lost Vulcan mission is one of them. Launch is the subject of the fifth book of this series, covered in depth later.
- **The satellite: scale shown, cost not.** No unit cost for a broadband satellite of either decade was read. What the records show is series production with planned replacement: Eutelsat had 669 replacement satellites on order for its OneWeb constellation in its quarter to September 2026, according to the trade press. Volume is consistent with a lower unit cost; it does not measure one.
- **The terminal: a fall within the 2020s, for one operator.** A user must track satellites that cross the sky in minutes. The answer was a flat phased array: an antenna whose beam is steered electronically, with no moving dish, sold with the service. SpaceX's filing reports a reduction of about 59 percent in the average cost of manufacturing its user kit from 2022 to 31 March 2026. That is the operator's own figure, and it starts in 2022, not in the 1990s.

- **Capital: a customer base shown, the cost of money not.** The same filing reports Starlink subscribers of 2.3 million at the end of 2023, 4.4 million at the end of 2024, 8.9 million at the end of 2025 and 10.3 million on 31 March 2026, and operating income for its connectivity business of 469 million dollars in 2023 and 4,423 million dollars in 2025. Globalstar had 66,000 subscribers at its 2002 filing (chapter 9). Whether that revenue made capital cheaper, and how replacement is financed, the sources read do not show.

Read this way, the records support scale and one operator's vertical integration better than they support a general fall in all four costs. The launch and terminal cases rest on that operator's own statements; the satellite and capital cases rest on scale alone.

The product changed as well. In the 1990s the handheld satellite phone competed with land based networks that, in Globalstar's own words in its filing, grew sooner than expected. The systems of this chapter sell broadband to a fixed or moving terminal, and the ground network is where their traffic ends up.

Three dates for every system

A system in this chapter has at least three dates: the announcement or filing, the first launch, and the first commercial service. They can be years apart, and a reader who treats the first as the third will be wrong about availability. This chapter gives each system a deployment status, one of four words, with the date it was checked: *operating*, *deployed before full service*, *deploying*, and *contracted or building*. "Has announced" and "has filed a schedule that requires" describe plans; neither describes a service.

The FCC's own record shows the gap for one operator. Its authorization of 2018 for SpaceX (FCC 18-38) listed the user uplink at 14.0 to 14.5 GHz; its order of April 2021 (FCC 21-48) authorized shells at 540 to 570 km, with user terminals and gateways at elevations of 25 degrees or more. Service came between and after those orders, satellite by satellite. In its quarterly report for the period to 30 September 2026, filed on 22 October 2026, the company counted more than 11,100 broadband and mobile satellites in low orbit. A count is the counter's, on the counter's date.

Two branches of architecture

The constellations of the 2020s divided the work in two ways, and figure 11.1 draws both on one canvas.

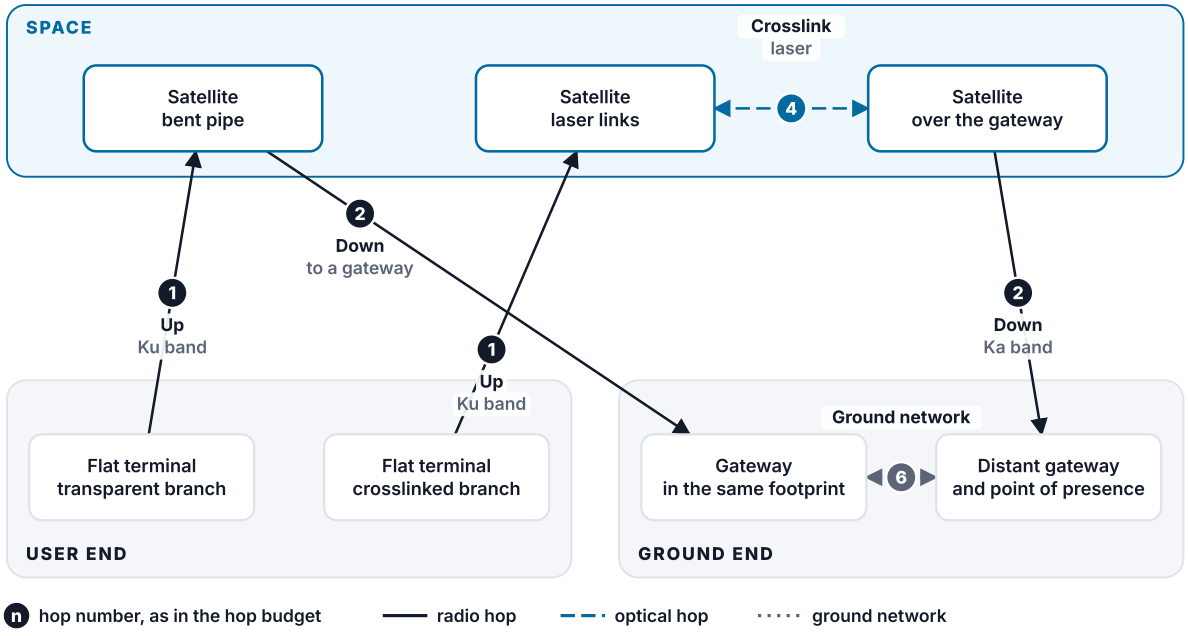
Transparent, with many gateways. The first phase of OneWeb was described in a 2023 survey in *IEEE Communications Surveys and Tutorials* as satellites in 18 polar planes at 1,200 km with "a transparent bent-pipe payload". A bent pipe repeats what it receives toward a gateway, so a terminal and a gateway must see the same satellite at the same time.

The work of the network sits on the ground: the satellites stay simple, and the operator builds and licenses gateways across the countries it serves. Chapter 9 showed what that costs when the gateways are not built: Globalstar's 2001 filing listed regions without a service provider and therefore without service.

Crosslinked, with routing in orbit. SpaceX's satellites can pass traffic to each other by laser. A measurement study of the network, published at the ACM Web Conference in 2024, describes the result as an "extended bent-pipe": the terminal's traffic goes up, may cross several satellites by laser, and comes down at a ground station that need not be near the user, then to a point of presence where it enters the internet. The same study notes that not all of the operator's satellites carry the laser links. Moving traffic through space reduces the number of gateways that coverage requires, especially over oceans, and moves a routing decision into orbit. It does not remove gateways: every bit still lands somewhere. What it changes is who decides where. The operator chooses the landing point, and the law of that country reaches the traffic there.

FIGURE 11.1

Two branches of low orbit broadband: a bent pipe that needs a gateway in view, and crosslinks that carry traffic through space



Left branch: a transparent satellite repeats the terminal's signal to a gateway under the same satellite. Right branch: laser links between satellites carry traffic to a gateway that may be far away; routing happens in orbit, and the point of presence decides where the traffic enters the internet. Hop numbers follow the series convention; this book budgets no hop of this figure.

Author's diagram based on Al-Hraishawi and others, IEEE Communications Surveys and Tutorials (2023), for the first OneWeb phase; Mohan and others, ACM Web Conference 2024, for the crosslinked branch; FCC 18-38 (2018) for the user band. Checked 2026-11-23.

Neither branch is an answer to every requirement. A transparent design keeps the satellite simple and the processing where it can be upgraded, at the price of a gateway in view of every satellite that serves users. A crosslinked design needs more on board and a routing plan that changes as the satellites move. The measurement study observed regular swings in delay and rate every 15 seconds, which its authors attribute to a globally synchronized reconfiguration of the satellite links.

The systems, by deployment status

Table 11.2 lists the systems this chapter treats, by deployment status on the book's date. Space goes by service history, not by country and not by equal shares.

FIGURE 11.2

The broadband systems by deployment status on 23 November 2026, each count with its date and who counted

System	Owner	Deployment status, 2026-11-23	Satellites in orbit (date, who counted)
Starlink	SpaceX	Operating	More than 11,100 (quarterly report to 2026-09-30, filed 2026-10-22; operator)
Eutelsat OneWeb	Eutelsat Group	Operating	More than 600 (2026-08-07; operator)
O3b mPOWER (medium orbit)	SES	Operating; the last 3 not yet in service (expected mid 2027)	10 of 13 launched by 2026-03-05, the last 3 on 2026-09-13 (operator)
ViaSat-3 (geostationary)	Viasat	Operating	3, all in service by 2026-09-21 (builder)
Amazon Leo (formerly Project Kuiper)	Amazon	Deployed before full service; enterprise preview from 2025-12-01	Nearly 400 (page updated 2026-10-28; operator)
Guowang	China Satellite Network Group (state)	Deploying	222 catalogued (October 2026; independent tracker)
Qianfan	Shanghai Spacecom	Deploying	233 working of 251 objects (October 2026; independent tracker)
Rassvet	Bureau 1440	Deploying; no service date found	About 31 (after 2026-07-19; trade press)
Telesat Lightspeed	Telesat	Contracted or building	0 (2026-10-29; operator)

System	Owner	Deployment status, 2026-11-23	Satellites in orbit (date, who counted)
IRIS2	European Union program; Eutelsat leads the low orbit part	Contracted or building; first launches announced from 2029	0 (2026-08-07; operator)

Deployment status: operating, deployed before full service, deploying, contracted or building. A count is the counter's, on the counter's date; Appendix D repeats each row with its source.

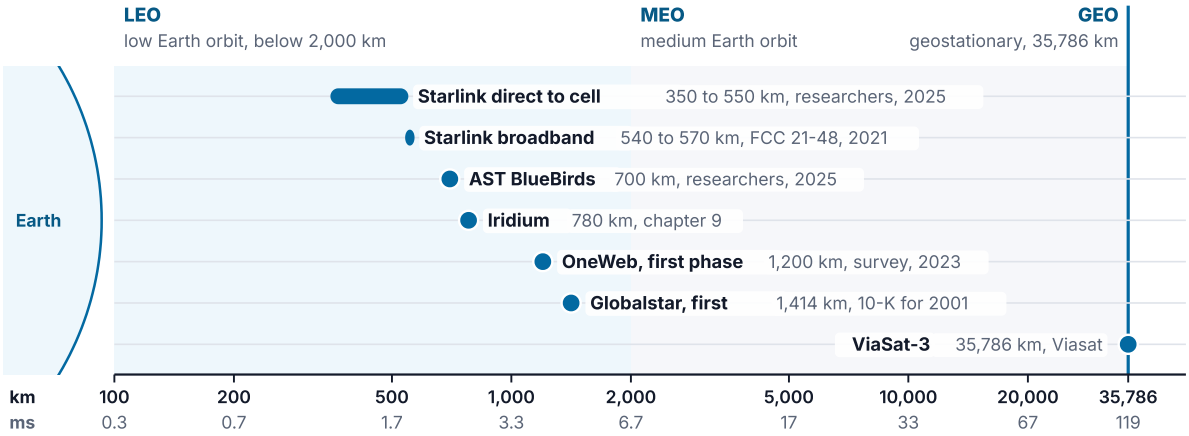
Source: SpaceX, Form 10-Q for the quarter to 2026-09-30; Eutelsat release, 2026-08-07; SES releases, 2026-03-05 and Q3 2026; Boeing, 2026-09-21; Amazon progress page and GSMA, 2025-12-01; KeepTrack, October 2026; RussianSpaceWeb, 2026-07; Telesat results, 2026-10-29. Read 2026-11-22 and 2026-11-23.

- **Operating.** SpaceX's Starlink, with 13.6 million consumer subscribers on 30 September 2026 by the company's quarterly report, and Eutelsat OneWeb, with more than 600 satellites in low orbit on 7 August 2026 by the operator's count. The trade press reported 26 Starlink satellites of the third version deployed from Starship on 28 September 2026.
- **Deployed before full service.** Amazon Leo, renamed from Project Kuiper on 13 November 2025. An enterprise preview began on 1 December 2025 with a terminal Amazon describes as delivering up to 1 Gbit/s down and 400 Mbit/s up; this book found no dated start of full commercial service.
- **Deploying.** China's two government-backed systems, Guowang and Qianfan, with 222 catalogued satellites and 233 working satellites respectively in October 2026, by the count of an independent tracker whose figures differ from others by tens of satellites; and Russia's Rassvet, by Bureau 1440, with about 31 production satellites after a launch of 19 July 2026, as reported by the trade press. No service date was found for any of the three.
- **Contracted or building.** Telesat Lightspeed, with no satellites in orbit on 29 October 2026 and a plan raised from 156 to 225 satellites, and Europe's IRIS2, whose low orbit part Eutelsat leads, with first launches announced from 2029.

The orbits differ more than the word "low" suggests. Figure 11.3 places them: SpaceX's broadband shells near 550 km, OneWeb's first phase at 1,200 km, and the older handheld systems of chapter 9 between them, against the geostationary arc where the incumbents of the next section fly.

FIGURE 11.3

Where the broadband and phone systems of this book fly



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

Low orbit shells from 350 to 1,414 km, against the geostationary arc; the second axis row is the one way light time straight up, calculated from the altitude.

Source: FCC 21-48 (2021); Garcia-Cabeza and others, arXiv 2506.00283 (2025); Al-Hraishawi and others, IEEE Communications Surveys and Tutorials (2023); Globalstar, Form 10-K for 2001; Viasat, ViaSat-3 page. Read 2026-11-22 and 2026-11-23.

The incumbents' answer

The operators already in geostationary and medium orbit did not leave the market. They built bigger satellites and merged. Viasat launched three ViaSat-3 satellites in Ka band between 1 May 2023 and 29 April 2026, describes the second and third as rated above 1 Tbit/s each, and its builder reported all three in service on 21 September 2026. SES completed its acquisition of Intelsat on 17 July 2025, with a fleet it put at about 120 satellites, about 90 of them geostationary and nearly 30 in medium orbit; it launched the last three of its O3b mPOWER medium orbit satellites on 13 September 2026 and expects them in service in mid 2027. In its results for the first nine months of 2026, SES also reported 229 million dollars of insurance collected on the first four mPOWER satellites.

The division of labor differs by orbit, and the geometry sets it. A geostationary satellite stays over one place and serves a fixed dish that never moves, at the cost in delay that chapter 5 describes. A low orbit satellite is close, so its path loss and delay are small, but it moves, so the terminal must steer and the network must hand users over. Which design meets a requirement depends on the requirement: delay, coverage of high latitudes, a terminal's size and price, the rate in the busy hour.

Rules that shape a schedule

A license in the United States comes with milestones. The FCC's rule, as applied to Amazon in its order DA 26-553, requires half of an authorized constellation in operation within six years and all of it within nine. For Amazon Leo's first generation that meant 1,616 of 3,232 satellites by 30 July 2026 and all of them by 30 July 2029. The waiver of 5 June 2026 kept the license but attached costs: satellites not operating by 30 July 2026 lose their priority in the processing round until half the system is deployed or until 30 March 2028, and the surety bond is forfeited. The same order records later grants for a second generation and a polar system, with milestones in 2032 and 2035. Other states and the International Telecommunication Union keep their own clocks; the law of spectrum and orbit is the subject of the fourth book of this series, covered in depth later.

Spectrum also became an asset in its own right. On 12 May 2026 the FCC approved EchoStar's sale of about 65 MHz to SpaceX and about 50 MHz to AT&T, and in the following months three EchoStar units entered chapter 11, as EchoStar's own filings with the SEC record. Dish DBS and Dish Wireless, with subsidiaries, filed prepackaged chapter 11 cases on 30 June 2026, and Dish DBS emerged on 1 October 2026; Hughes Satellite Systems and its United States subsidiaries filed on 2 August 2026, all in the Southern District of Texas. EchoStar reported 622,000 broadband subscribers on 30 June 2026. The spectrum that EchoStar sold is part of chapter 12's story.

What stayed hard

Three things stayed hard, whatever happened to the cost of the satellites, which the records read do not measure. The terminal still has to point a beam at a moving satellite, draw power to do it, and sit where it can see the sky. The ground still has to carry everything: gateways, points of presence and the fiber between them, each in some country, under that country's law. And spectrum is still shared: the user band of one system is the interference of another, and the filings that protect it take years. The measurement study of 2024 found that the round trip from the terminal to the point of presence was about 40 ms in most countries, and that the location of ground stations and points of presence explained much of the difference between countries. The radio part was fast; the ground decided the rest.

The service ledger at the end of this chapter is the one the first book of this series, *The Bit's Path*, prints for the same route. It is a composite profile of one operator, built from dated sources (an authorized geometry, measured round trips and public speed tests), not one measured route. Its two propagation figures are calculated here: through one satellite at 550 km, two legs straight up take 3.7 ms, and two legs at 25 degrees elevation take 7.5 ms, before any processing, queueing or ground network.

THE SYSTEM'S FAILURE

On 24 February 2022, about an hour before Russia launched its major invasion of Ukraine, a cyber attack disrupted a satellite broadband network that served users across central Europe. The United Kingdom's government stated on 10 May 2022 that its National Cyber Security Centre assessed it "almost certain" that Russia was responsible, that wind farms and internet users in central Europe were disrupted, and that, according to the operator Viasat, "tens of thousands of terminals have been damaged, made inoperable and cannot be repaired". A peer-reviewed survey of satellite security, published in *Sensors* in 2024, describes the malware as wiping data on the user modems of the KA-SAT service, and says the effect reached the remote monitoring of thousands of wind turbines. Neither source describes damage to the satellite. What failed was the service: the user terminals, the cheapest and most numerous end of the system, were reached from the ground and disabled in large numbers at once. The operator published its own overview of how the attacker got in; this book could not open it, so it prints no account of the route.

Shorter cases, each with its own record. A schedule failure: Amazon Leo did not reach its half-way milestone and received a conditional waiver (FCC DA 26-553). A launch failure: 40 satellites lost on 15 November 2026, per Amazon's own progress page; the launch provider's own statement could not be loaded on 23 November 2026. A company failure: three EchoStar units in chapter 11 in 2026, per EchoStar's filings, which describe a restructuring of debt while service continued.

SECURITY NOTE

Who can interfere or command. The operator commands the satellites and, through its ground management network, the user terminals; a terminal's software is updated by the operator, and the sources read describe no customer role in commanding the satellites or signing the terminal's software. The 2022 case shows what that management path is worth to an attacker: it can reach a large share of the terminals at once. Jamming of user terminals in a war zone appears only in the trade press, so no case is printed. **How it is seen.** A terminal that stops at once with thousands of others suggests the operator's network, though regional jamming or a fault in the space segment can look the same until telemetry separates them; a user sees only that the service is gone, and the operator's monitoring of its terminal fleet is not published. Keep your own record from your application's server: loss, round trip and throughput each minute. **How it is recovered.** In 2022 the recovery was new terminals, not a repair in orbit, per the operator as quoted by the UK government. Encrypt end to end so the operator's ground carries data it cannot read, and keep a second path through another operator or the ground network.

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'.

The ledger above is a composite profile of one operator, dated by its sources; the counts and owners of the other fleets are in Appendix D, each with its date.

Monday rule: for any count in orbit, write the number, its date and who counted; for any service, the country, the operator, the device and the date; for any plan, whether it is announced, filed, launched or in service.

CHAPTER TWELVE

2022 to 2026: The Phone That Cannot Grow



On 15 November 2022 Apple announced that Emergency SOS via satellite was available on the iPhone 14 lineup in the United States and Canada. A person outside cellular and Wi-Fi coverage could send a short emergency message, the answers to a few questions and a location, through satellites operated by Globalstar, the company that had filed for bankruptcy in 2002 (chapter 9). The phone had no dish and no separate satellite terminal, but it was not unchanged: the service needed that phone's hardware and software, and it worked only in the launch countries. This chapter asks what happens when the user end is a phone whose size and power will not grow, and where everything else goes. The decision it changes is how a reader checks a claim that a service is "available": by country, operator, device and date.

The row for this chapter

Era	Limit that ran out first	User end	Space	Ground end
2022 to 2026: direct to device	The phone cannot grow: about a fifth of a watt and a small antenna; also spectrum rights and device support	A phone with no external satellite terminal: built for mobile satellite spectrum, or a compatible phone on a carrier's own spectrum	Satellites with large receive arrays; in the standard, transparent first and regenerative next; one operator flew a base station on board from the start	The carrier's core network and spectrum, or the satellite operator's

Meanwhile. Broadband constellations pass ten thousand satellites (chapter 11). The geostationary incumbents merge (chapters 10 and 11). Satellite IoT standards reach small modules (this chapter). Processing in orbit becomes a product for some workloads (chapter 13). Spectrum changes hands faster than fleets do (chapter 11).

The lineage

2022 is not the birth of satellite service to a handheld. Iridium sold handsets from 1 November 1998, and Globalstar from early 2000; Thuraya and ACeS each served handsets from one geostationary satellite (chapter 9). Each of those needed its own handset, built around the satellite system. What changed after 2022 was the other direction: the satellite function moved inside a mass-market phone, or the satellite learned to talk to phones already in people's pockets.

The licenses came first. Lynk Global states that the FCC granted it on 16 September 2022 the first commercial license for satellite service direct to standard mobile phones, covering a satellite launched on 1 April 2022. That is the company's description of its own license; a license is not a service.

The limit in numbers

A handheld phone of 3GPP power class 3 transmits at a nominal maximum of 23 dBm, about 0.2 W, through an antenna small enough to fit in the case and partly covered by a hand. For an ordinary phone without an external terminal, nothing on the user's side can be made bigger. Distance is the first thing the rest of the system must pay for. At 2 GHz, a path of 550 km straight up to a low orbit satellite loses 153.3 dB in free space; a path of 5 km, a distance to a cell tower chosen for comparison, loses 112.4 dB. The satellite path starts 40.8 dB behind, a factor of about 12,000 in power (all calculated from the free-space formula; chapter 3 of the first book of this series, *The Bit's Path*, works the formula; the ledger at the end of this chapter, at the 1912.5 MHz of the carrier's block, finds 152.9 dB). At the edge of coverage the path is longer: at 25 degrees elevation the same satellite is 1,123 km away, which costs 6.2 dB more than the path straight up.

Measurements of one real service show what the difference looks like at the phone. Researchers at the Polytechnic University of Madrid and Weplan Analytics analyzed crowdsourced measurements from phones in the United States on SpaceX's direct to cell network, during its beta with T-Mobile from October 2024 to July 2025. They measured a median reference signal received power (RSRP, the LTE measure taken on the reference signals, not the power of the whole channel) of -121 dBm on the satellite network against -97 dBm on the carrier's terrestrial network, 24 dB lower, and a median signal to interference and noise ratio of 0 dB against 5 dB. The measured 24 dB must not be equated with the 40.8 dB free-space comparison above, nor subtracted from it to find what the satellite recovers: the 24 dB is a downlink measurement over real tower distances, not the 5 km of the comparison, and the satellite carries gain and power a tower does not. The study does not split the difference, and this book does not either. From the measured signal quality the researchers estimated about 3.1 Mbit/s per beam, shared by every phone in it.

Two device classes and two spectrum roads

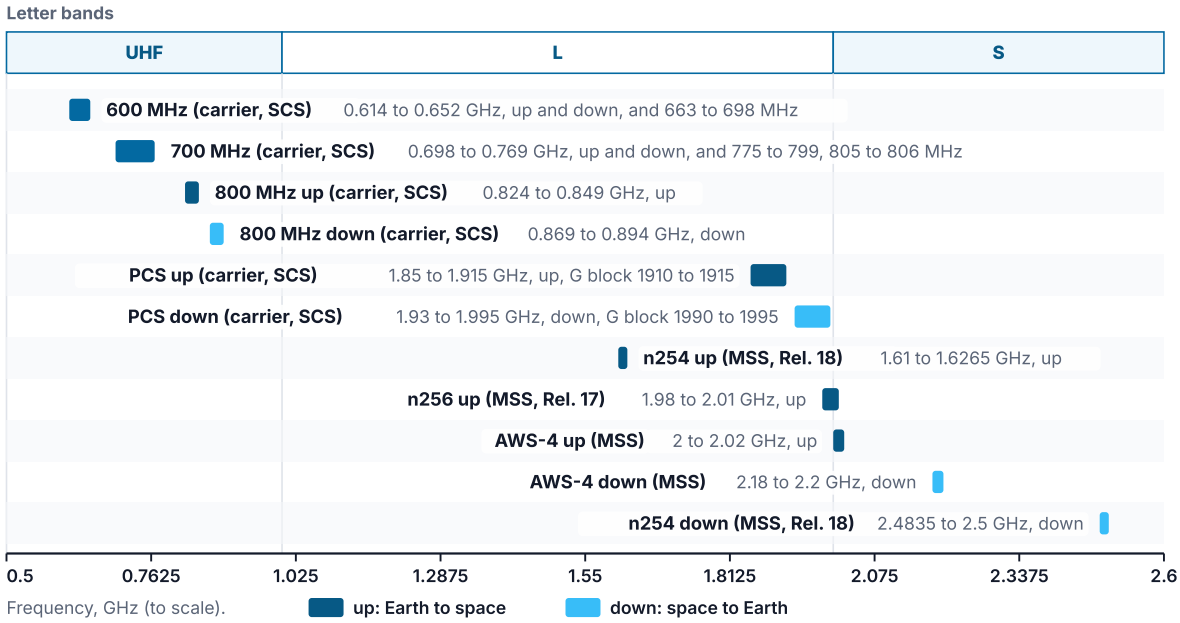
Two different things are called "direct to device", and they differ in the phone, the spectrum and who owns each end. Figure 12.1 places both roads on one frequency axis.

Phones built for mobile satellite spectrum. The phone carries a radio and software for bands allocated to the mobile satellite service, and the satellite operator holds the license. Apple's service of 2022 runs on Globalstar's licensed spectrum; Globalstar's filing of 7 September 2022 allocates 85 percent of its current and future network capacity to the service, with Apple paying 95 percent of the approved capital spending on new satellites. Skylo, which owns no satellites and uses the mobile satellite spectrum of partner geostationary operators, carries messaging for Verizon: emergency messaging from 2024, and from 19 March 2025 texting for the Galaxy S25 and Pixel 9 phones, per Skylo, which adds that its coverage comes from partners and is not complete worldwide. Iridium announced on 17 November 2026 the activation of Iridium NTN Direct, a 3GPP-based narrowband service on its existing low orbit satellites and its L band spectrum, with Nordic Semiconductor's nRF9151 as the first module approved for it. An earlier proprietary partnership between Iridium and a chip maker did not proceed, according to the trade press.

Compatible phones on a carrier's spectrum. The phone is an ordinary phone, with no satellite radio of its own, and the satellite transmits in the carrier's own terrestrial band. In the United States the FCC created a framework for this in March 2024, which it calls supplemental coverage from space (FCC 24-28, rules effective from 30 May 2024 for most sections, per the Federal Register). A satellite operator leases terrestrial spectrum from a carrier that holds all the licenses on a channel across a large enough area, the phones are licensed by rule, and interim routing of 911 calls and texts is required. The bands listed are 600, 700 and 800 MHz, Broadband PCS and the AWS H block. This is a United States case; other countries have their own rules. T-Mobile's service on Starlink satellites, T-Satellite, became available on 23 July 2025, according to T-Mobile's own release of that day; the trade press reported messaging first. During its beta it used the PCS G block, 1910 to 1915 MHz up and 1990 to 1995 MHz down, per the measurement study above. Its satellites do not simply repeat the signal: the same researchers describe conventional LTE base station (eNodeB) payloads integrated into the satellites, with traffic sent to a ground station or, when necessary, across the constellation by laser, and SpaceX's own filing, as quoted by the FCC in 2026, calls the design a "unique regenerative architecture" of "cell towers in space".

FIGURE 12.1

Two spectrum roads: a carrier's own bands lent to a satellite, or bands allocated to mobile satellite service



Dark: phone to satellite; light: satellite to phone; the 600 and 700 MHz rows show the first of their listed ranges, the rest in the note. Carrier bands as the FCC's 2024 rules list them for supplemental coverage from space; satellite bands as named in the 3GPP releases and the FCC's 2026 order, drawn only where their edges were read. A band on this axis is an allocation, not a permission.

Source: FCC Fact Sheet and draft Report and Order, Supplemental Coverage from Space (2024-02-22), band list checked against the final rule, Federal Register 89 FR 34148 (2024-04-30); 3GPP NTN overview; 3GPP TS 38.101-5 Table 5.2.2-1; FCC DA 26-471 (2026-05-12); Garcia-Cabeza and others (2025) for the G block. Read 2026-11-22 and 2026-11-23.

Spectrum then moved again. On 12 May 2026 the FCC consented to the assignment of EchoStar's AWS-4 band (2000 to 2020 and 2180 to 2200 MHz), its H block and unpaired AWS-3 licenses to SpaceX, with final closing expected about 30 November 2027 (FCC DA 26-471). The same order notes that SpaceX has a pending application for a direct to device system of up to 15,000 satellites at 226 to 435 km. A satellite operator that holds its own bands no longer depends on one carrier's lease.

The standard

3GPP, the body that writes the mobile standards, added satellite access in three steps. Release 17, frozen in June 2022, supports transparent payloads only, with new satellite bands n255 in L band and n256 in S band and phones that know their own position. Release 18 added band n254 and Ka bands, and network verification of the phone's location. Release

19 adds regenerative payloads, which carry base station functions on the satellite, and store and forward. A release is a standard, not a service: whether a phone supports it, whether an operator has spectrum for it, and whether a satellite runs it are separate questions.

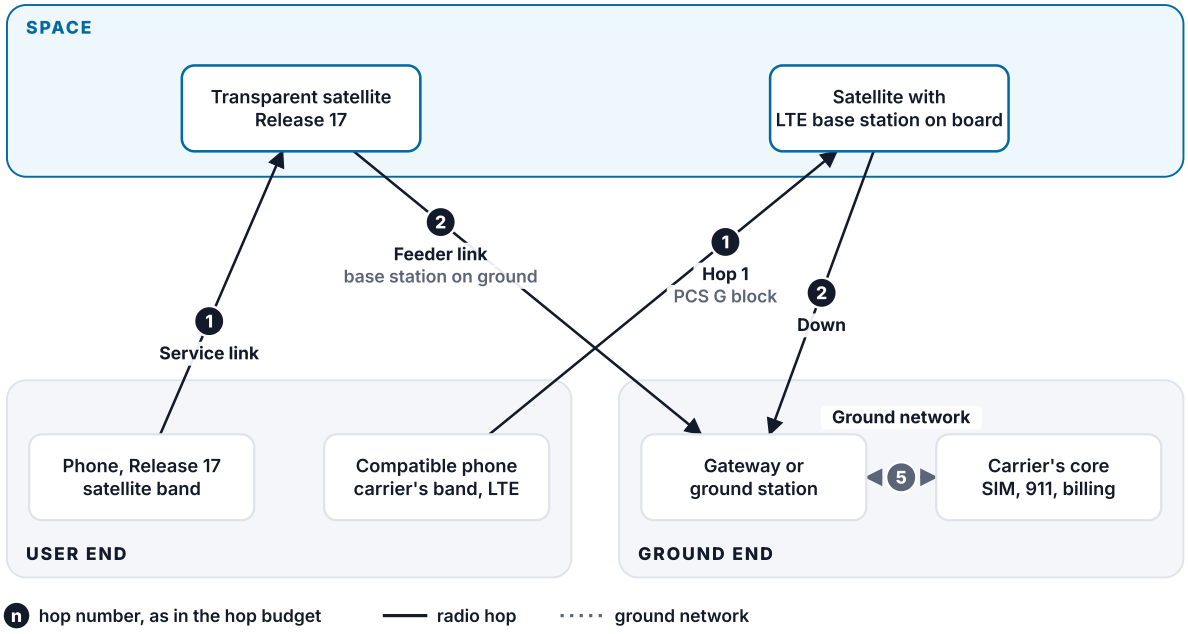
The very large array, and where the base station sits

If the phone cannot grow, the satellite must. AST SpaceMobile describes its second generation BlueBird satellites as carrying an array of about 2,400 square feet, about 223 m^2, against about 700 square feet for the first generation (its business update to the SEC, 9 November 2026). The company reported BlueBirds 1 to 6 and 8 to 13 unfolded and operating on that date and targets about 45 in orbit by mid 2027. That is one design. SpaceX's direct to cell satellites fly lower, mainly at about 550 km and some at about 350 km, according to the measurement study; AST's fly higher, at about 700 km by the same account. Flying lower saves path loss; a bigger array costs mass and launch volume. The documents read for this book do not publish either operator's antenna gain or noise temperature.

The illustrative uplink model at the end of this chapter (LL-2026-02) asks what a satellite would have to supply for one modest job: a text message at 16 kbit/s from a compatible phone, straight up from 550 km, on the carrier's PCS uplink. It is a model, not an archival budget: the receiver threshold is assumed, a standard's curve standing in for the LTE uplink, and every other line is taken from the series' model phone uplink, including its allowances for scintillation and shadowing, which are kept at zenith and so err toward a larger G/T. Under those assumptions the model reaches its 3 dB design margin only if the satellite's G/T toward the phone is at least -8.2 dB/K. Where the page prints "closes", it means only that this arithmetic reaches its margin; it does not qualify T-Satellite and says nothing measured about Starlink's satellites. With the model uplink assumptions of *The Bit's Path* (a system noise temperature of 350 to 800 K, 1 to 3 dB of scan, beam-edge and other receive losses added back to find the antenna's peak gain, and an aperture efficiency of 0.7 to 0.5), that is a physical array of about 0.2 to 1.0 m^2. In the model a text is cheap. At 25 degrees elevation the same satellite falls 3.2 dB short of zero margin, 6.2 dB short of the design margin. At 1 Mbit/s for one phone, a rate that still fits the 5 MHz block at this code, it falls 15.0 dB short of zero margin. For scale only, reaching the design margin at 1 Mbit/s straight up would need a G/T of 9.8 dB/K, or 12 to 60 m^2 under the same assumptions. No operator's design is implied: a real array serves many phones in many beams, at its own altitude.

FIGURE 12.2

Direct to device: the base station on the ground behind a transparent satellite, or on the satellite itself



Left: in 3GPP Release 17 a transparent satellite repeats the phone's signal to a gateway where the base station sits. Right: SpaceX's direct to cell satellites carry an LTE base station on board, before 3GPP standardized regenerative payloads in Release 19; hop 1 on the right is the hop of the illustrative uplink model LL-2026-02. In both, the carrier's core network authenticates the phone and delivers the message.

Author's diagram based on 3GPP, Non-Terrestrial Networks (NTN) overview; Garcia-Cabeza and others, arXiv 2506.00283 (2025), section II; FCC DA 26-471 (2026), quoting SpaceX's filing. Read 2026-11-22 and 2026-11-23.

Where the base station sits is the second design choice (figure 12.2). With a transparent satellite, which is what Release 17 supports, the phone's signal is repeated to a gateway, and the base station sits at or behind the gateway on the ground. With a regenerative satellite, which Release 19 standardizes, base station functions fly. SpaceX did not wait for the standard: its direct to cell satellites carry an LTE base station, per the sources above. Switching on board was older than either: NASA's ACTS tested it in 1993 and Iridium used it in commercial service from 1998 (chapter 13). In both, the carrier's core network, or the satellite operator's own, authenticates the phone and delivers the message.

Four separate things, and the names that returned

A claim that a phone "works with satellites" mixes four things that this book keeps apart: the standard (which release), device support (which phone, which software), spectrum rights (whose band, in which country) and the operator's own design (which satellites, which gateways). "In service" needs a country, an operator, a device class and a date. This book can name services launched in the United States, each with the newest record read, dated in Appendix D: T-Satellite on T-Mobile with SpaceX's satellites, Verizon's texting over Skylo on named Android phones, Apple's satellite features on iPhone 14 and later over Globalstar, and Iridium's new narrowband service for modules. For T-Satellite the newest primary record is the FCC's order of May 2026 (the carrier's release of July 2025 speaks only for the launch), and the carrier's current service page did not load, so its ledger prints the status on the book's date as not checked. AST SpaceMobile had announced that it expected intermittent nationwide service in the United States by the end of 2026; that is an expectation, not a service.

Two names from chapter 9 returned. Globalstar became the satellite operator for a phone maker's service, with up to 1.1 billion dollars of infrastructure prepayment from Apple agreed on 29 October 2024 (Globalstar's Form 8-K). On 14 April 2026 Amazon and Globalstar announced a definitive merger agreement under which Amazon will acquire Globalstar, expected to close in 2027 subject to regulatory approvals and Globalstar's replacement satellite milestones; Amazon says its Amazon Leo system will power Apple's satellite features and deploy its own direct to device system from 2028. Iridium launched a standards-based service on the satellites it had replaced, and on 28 June 2026 agreed to be acquired by Rocket Lab, a merger Iridium expected to complete in mid 2027 (both companies' Form 8-K filings). The satellites of the first wave outlived the owners that went bankrupt in chapter 9.

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.

The 2022 scene uses the service of this chapter's opening as it was on its first day: in the United States and Canada, on the iPhone 14 lineup, for emergencies only. The service page that follows is the one *The Bit's Path* prints for it.

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.

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 scene is fixed at the book's date, 23 November 2026, and in the United States: a compatible phone on T-Mobile's T-Satellite service, which T-Mobile's own release dates from 23 July 2025, and whose continued operation the FCC's order of May 2026 describes as supplemental coverage from space that "has brought" connectivity to dead zones, so far for text-based services. The carrier's current service page could not be loaded on 23 November 2026, so the scene rests on the newest record read, the FCC's order of May 2026.

THE SYSTEM'S FAILURE

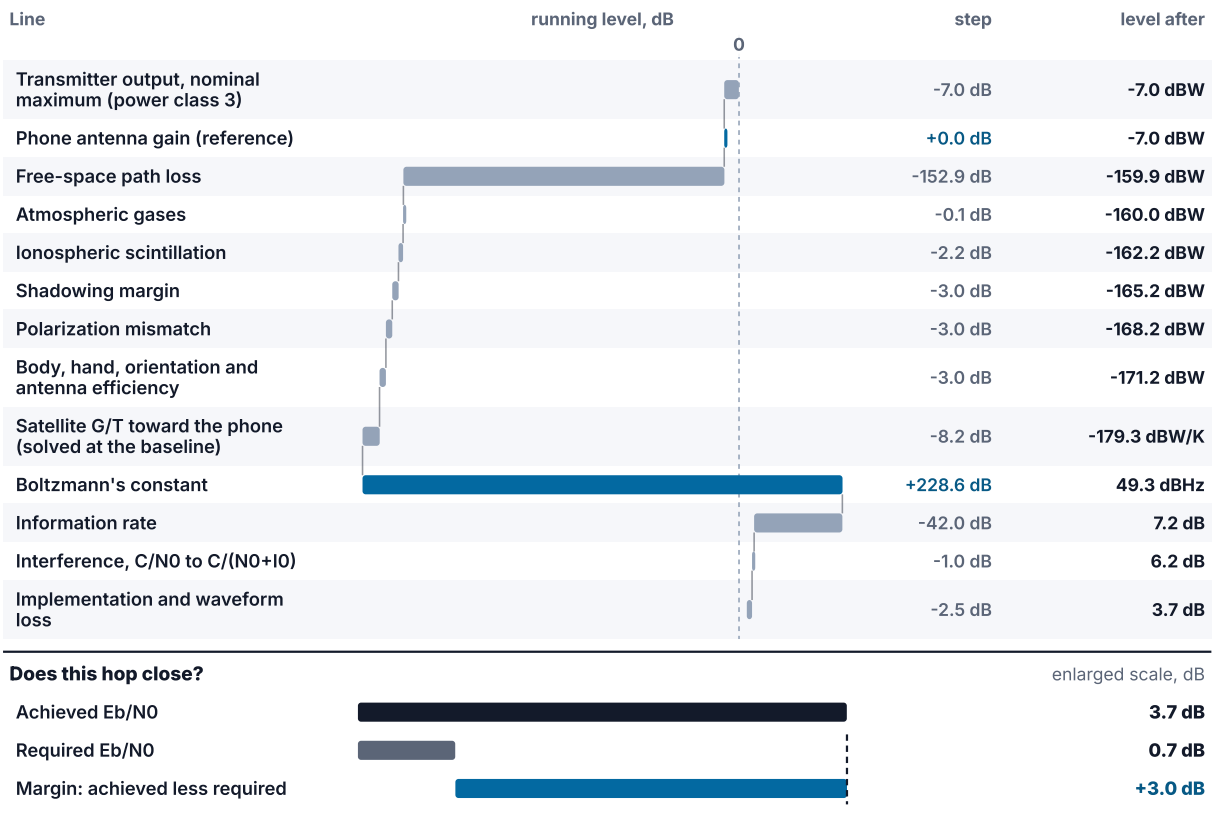
AST SpaceMobile's seventh BlueBird satellite was written off, according to the company's business update filed with the SEC on 9 November 2026. Trade press reported that the satellite was lost after a New Glenn upper stage left it in an orbit that was too low, in April 2026. This was a launch failure, not a failure of the satellite's design or of the service: the satellite never reached the orbit it was built for. For an operator with a dozen satellites in orbit, one lost satellite is a visible share of the fleet and of its coverage. The company reported that the other twelve were operating and kept its target of about 45 in orbit by mid 2027.

SECURITY NOTE

Who can interfere or command. The carrier's core network authenticates the phone's SIM, as it does on the ground, and the satellite operator commands the satellites; neither publishes how the space segment protects traffic in the documents read. A satellite beam covers a wide area, so the network must know where a phone is to apply the right country's rules: Release 18 adds network verification of the phone's reported location, to within about 5 to 10 km according to 3GPP's overview. Lawful access sits where the core sits, under that country's law. **How it is seen.** The user sees only whether the phone shows the satellite network and whether the text was delivered; the carrier sees delivery records in its core. Emergency traffic across borders depends on routing rules that each country sets: in the United States, the FCC requires interim routing of 911 calls and texts. **How it is recovered.** For an emergency message, the fallback is the next satellite pass or open sky. A user who depends on the service should know which country's rules and which operator's network apply where they are.

FIGURE 12.3

Illustrative uplink model: a text straight up to 550 km reaches its 3 dB design margin only if the satellite G/T toward the phone is -8.2 dB/K, against an assumed threshold



Line	step	level after
Transmitter output, nominal maximum (power class 3)	-7.0 dB	-7.0 dBW
Phone antenna gain (reference)	+0.0 dB	-7.0 dBW
Free-space path loss	-152.9 dB	-159.9 dBW
Atmospheric gases	-0.1 dB	-160.0 dBW
Ionospheric scintillation	-2.2 dB	-162.2 dBW
Shadowing margin	-3.0 dB	-165.2 dBW
Polarization mismatch	-3.0 dB	-168.2 dBW
Body, hand, orientation and antenna efficiency	-3.0 dB	-171.2 dBW
Satellite G/T toward the phone (solved at the baseline)	-8.2 dB	-179.3 dBW/K
Boltzmann's constant	+228.6 dB	49.3 dBHz
Information rate	-42.0 dB	7.2 dB
Interference, C/N0 to C/(N0+I0)	-1.0 dB	6.2 dB
Implementation and waveform loss	-2.5 dB	3.7 dB

Does this hop close?	enlarged scale, dB
Achieved Eb/N0	3.7 dB
Required Eb/N0	0.7 dB
Margin: achieved less required	+3.0 dB

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

Required for: quasi error free (packet error ratio 1e-7) on the standard's ideal curve, a stand-in for the LTE uplink. Dashed line: the design minimun
Operating point: 16 kbit/s while transmitting, phone to satellite, straight up, open sky, clear conditions, one phone; availability not assessed.
Source of the required value: Calculated from ETSI EN 302 307-1 V1.4.1 (2014-11), clause 6, Table 13: QPSK 1/4, spectral efficiency 0.490243, ideal Es/N0 -2.35 dB at quasi error free (packet error ratio 1e-7), AWGN, 64,800 bit frame. Eb/N0 = Es/N0 - 10 log10(0.490243). Its use for a 3GPP uplink is an assumption: a representative LDPC curve, not that uplink's validated threshold, 2026-11-23.

The waterfall of the model baseline: 23 dBm from the phone, 152.9 dB of free-space loss, the named losses, the solved satellite G/T and the rate of 16 kbit/s, against an assumed receiver threshold (a standard curve standing in for the LTE uplink). An illustrative model, not a qualification of the service.

Author's calculation; lines and sources on the hop budget page of LL-2026-02. Computed 2026-11-23.

LINK LEDGER · LL-2026-02 · SERVICE LEDGER

2026-11-23

System: A text from a compatible phone over a carrier's terrestrial spectrum: T-Mobile's T-Satellite on Starlink direct to cell satellites, United States (page 2: an illustrative model)

Status on the book's date: not checked **Class: full**

Budget: closes (baseline); stress cases B and C fail, as intended; case A closes

1 Requirement	A listed phone, outdoors with open sky and no tower in reach, sends a short text. The rate is not published; page 2 assumes one.
2 Ends and path	A listed phone that needs no satellite-band hardware; the carrier's core network, which delivers the text. **Path:** Regenerative: an LTE base station on each satellite; to a ground station, or across satellites by laser, then to the carrier's core (researchers, 2025; SpaceX's filing as quoted by the FCC, 2026).
3 Orbit and time	Low orbit, mainly about 550 km, some about 350 km (researchers, 2025); each satellite is in view for minutes. **Time:** Phone to satellite: 1.8 ms straight up, 3.7 ms at 25 degrees (calculated). Delivery time of a text is not published.
4 Band and permission	**Phone to satellite.** 1910 to 1915 MHz, PCS G block, T-Mobile's license; FCC 24-28 framework, the service's own grant not read; United States **Satellite to phone.** 1990 to 1995 MHz, the same block **Satellite to gateway.** Not read
5 Capacity	**Up.** A short text; rate not published. **Down.** About 3.1 Mbit/s per beam, shared by every phone in it (researchers' estimate, 2025). Beta median reference signal received power (RSRP, a signal level, not throughput): -121 dBm via satellite, -97 dBm via towers, 2024-10 to 2025-07.
6 Who owns each end	**Space segment.** SpaceX **Ground segment.** SpaceX's gateways; the carrier's core **Customer relationship.** T-Mobile **The exit.** Not checked: a contract question
7 Trust	The carrier authenticates the SIM in its own core. Satellite command and protection of traffic in space are not described.
8 How it fails, and how we would see it	No open sky, an unlisted phone or no satellite in view: the text waits or fails. **How we would see it:** Phone: shows the satellite network. Carrier: delivery records. Operator monitoring: not published.
9 Cost shape	Included in some plans, a monthly fee for others (trade press, 2025).
10 Evidence	Status: not checked *assumption* Newest record read: FCC DA 26-471 (2026-05-12); the carrier's page would settle it, 2026-11-23 Available from 2025-07-23 operator claim T-Mobile, "T-Satellite Now Available", newsroom release, 2025-07-23, 2026-11-23 PCS G block, 1910 to 1915 MHz up, 1990 to 1995 down **measured** Garcia-Cabeza and others, "Direct-to-Cell: A First Look into Starlink's Direct Satellite-to-Device Radio Access Network through Crowdsourced Measurements", arXiv 2506.00283v8 (preprint), 2026-11-23 RSRP -121 vs -97 dBm (550 km and some 350 km satellites) **measured** Same study, 2026-11-23 3.1 Mbit/s per beam (estimate) **calculated** Same study, 2026-11-23 1.8 ms up, 3.7 ms at 25 degrees **calculated** At 550 km, 2026-11-23

Page 2 is an illustrative uplink model, not a qualification of the service and not a property of Starlink.

LINK LEDGER · LL-2026-02 · HOP BUDGET · THE BASELINE

Baseline · Illustrative uplink model, baseline

Phone (power class 3) to Low orbit satellite, 550 km · 1912.5 MHz · 550 km, straight up · reference plane: the phone's antenna connector; the satellite's G/T toward this phone, scan and beam-edge loss inside it

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	assumption	Assumption, to verify: 23 dBm, the power class 3 maximum that 3GPP TS 38.101-5 V17.8.0 Table 6.2.1-1 gives for satellite bands n256 and n255 (read for Book 1 of this series). For an LTE phone in the PCS band the class is set in 3GPP TS 36.101, not read here, 2026-11-23
	Phone antenna gain (reference)	0 dBi	**+0.0** level -7.0 dBW	standard	3GPP TS 38.101-5 V17.8.0, clause 6.1: for a UE with an integral antenna a 0 dBi reference antenna is assumed (a test convention, not a phone's realized gain toward a satellite); 3GPP TR 38.821 V16.2.0 (2023-03), Table 6.1.1.1-3 (handheld: 0 dBi per element, an evaluation assumption). Every departure of a real phone from this reference is carried by the body, hand, orientation and efficiency line, 2026-11-23
LOSSES	Free-space path loss	550 km at 1912.5 MHz	**-152.9** level -159.9 dBW	calculated	20 log10(4 pi d f / c) at 1912.5 MHz, the center of the PCS G block uplink (1910 to 1915 MHz) that the beta used per Garcia-Cabeza and others, Direct-to-Cell: A First Look into Starlink's Direct Satellite-to-Device Radio Access Network through Crowdsourced Measurements, arXiv 2506.00283v8 (2025); distance from the altitude and elevation, Earth radius 6,371 km, 2026-11-23
	Atmospheric gases	0.1 dB	**-0.1** level -160.0 dBW	assumption	Assumption, to verify: 0.1 dB for gases at 1.9 GHz and 30 degrees. Settled by ITU-R P.676 at this frequency and elevation, or by 3GPP TR 38.811 equation 6.6-8 (the method TR 38.821 names), 2026-11-23
	Ionospheric scintillation	2.2 dB	**-2.2** level -162.2 dBW	standard	3GPP TR 38.821 V16.2.0 (2023-03), Table 6.1.3.2-1, parameters for link budget analysis (a 3GPP study evaluation assumption in an informative report, not a requirement): ionospheric loss 2.2 dB (P3 curve, 1 percent of time, scaled to S band); kept unchanged at zenith (an allowance, not recomputed for 90 degrees), 2026-11-23
	Shadowing margin	3 dB	**-3.0** level -165.2 dBW	standard	3GPP TR 38.821 V16.2.0 (2023-03), Table 6.1.3.2-1, parameters for link budget analysis (a 3GPP study evaluation assumption in an informative report, not a requirement): shadowing margin 3 dB for terminals other than VSAT; kept unchanged at zenith (an allowance, not recomputed for 90 degrees), 2026-11-23
	Polarization mismatch	3 dB	**-3.0** level -168.2 dBW	standard	3GPP TR 38.821 V16.2.0 (2023-03), clause 6.1.1.1: 3 dB depolarization loss for a linearly polarized handheld uplink into circular polarization at the satellite (configuration A); 0 dB if the satellite receives both polarizations per beam (configuration B)). An evaluation assumption of a 3GPP study, not a requirement, 2026-11-23

Part	Line	Value	dB, and the level after	Evidence	Source and date
	Body, hand, orientation and antenna efficiency	3 dB	**-3.0** level -171.2 dBW	assumption	Assumption, to verify: 3 dB for every departure of a real phone from the 0 dBi reference toward the satellite: head and hand, orientation and pattern nulls, antenna efficiency (percentile not yet set). Settled by over-the-air directional realized gain or EIRP patterns of the phone in the band, over representative grips and orientations, supported by total radiated power, or by a peer-reviewed measurement near 2 GHz, 2026-11-23
RECEIVE SENSITIVITY	Satellite G/T toward the phone (solved at the baseline)	-8.2 dB/K	**-8.2** level -179.3 dBW/K	calculated	Solved by this ledger: the directional G/T at which the baseline has exactly its 3 dB design margin; frozen at that value in the cases. No operator figure was read, 2026-11-23
	Boltzmann's constant	-228.6 dBW/K/Hz, subtracted	**+228.6** level 49.3 dBHz	standard	SI, 2019 redefinition: k = 1.380649e-23 J/K exactly (BIPM SI Brochure, 9th edition), 2026-11-23
BANDWIDTH	Information rate	16 kbit/s	**-42.0** level 7.2 dB	assumption	Assumption, to verify: a rate chosen for this model, a 140 byte text's payload alone takes about 70 ms at this rate, before framing, access and retries (a choice, not a fact). Settled by the carrier's or the operator's published uplink rate for the service, 2026-11-23
INTERFERENCE	Interference, C/N0 to C/(N0+I0)	I0/N0 = -6 dB	**-1.0** level 6.2 dB	assumption	Assumption, to verify: interference density 6 dB below the noise density (I0/N0 = -6 dB). Settled by the operator's co-channel analysis: other beams of the same satellite, other satellites, terrestrial cells in the footprint, 2026-11-23
CODING	Modulation and code	QPSK, LDPC rate 1/4 (DVB-S2 curve as a stand-in)		standard	Calculated from ETSI EN 302 307-1 V1.4.1 (2014-11), clause 6, Table 13: QPSK 1/4, spectral efficiency 0.490243, ideal Es/N0 -2.35 dB at quasi error free (packet error ratio 1e-7), AWGN, 64,800 bit frame. Eb/N0 = Es/N0 - 10 log10(0.490243). Its use for a 3GPP uplink is an assumption: a representative LDPC curve, not that uplink's validated threshold, 2026-11-23
	Implementation and waveform loss	2.5 dB	**-2.5** level 3.7 dB	assumption	Assumption, to verify, not necessarily conservative: 2.5 dB for the gap between the standard's ideal curve and a phone uplink (short code blocks, OFDM-based waveform, pilots, real channel estimation, Doppler residue). Settled by a link-level simulation or measurement of the 3GPP uplink at the chosen modulation, code rate and block error target, 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	Calculated from ETSI EN 302 307-1 V1.4.1 (2014-11), clause 6, Table 13: QPSK 1/4, spectral efficiency 0.490243, ideal Es/N0 -2.35 dB at quasi error free (packet error ratio 1e-7), AWGN, 64,800 bit frame. Eb/N0 = Es/N0 - 10 log10(0.490243). Its use for a 3GPP uplink is an assumption: a representative LDPC curve, not that uplink's validated threshold, 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, a stand-in for the LTE uplink		**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. 16 kbit/s while transmitting, phone to satellite, straight up, open sky, clear conditions, one phone; availability not assessed
Required Eb/N0, 0.7 dB: source. Calculated from ETSI EN 302 307-1 V1.4.1 (2014-11), clause 6, Table 13: QPSK 1/4, spectral efficiency 0.490243, ideal Es/N0 -2.35 dB at quasi error free (packet error ratio 1e-7), AWGN, 64,800 bit frame. Eb/N0 = Es/N0 - 10 log10(0.490243). Its use for a 3GPP uplink is an assumption: a representative LDPC curve, not that uplink's validated threshold, 2026-11-23

Assumptions. Illustrative model. The 16 kbit/s rate and the 3 dB design margin are assumptions, to verify: choices of this model, settled by the operator's own link design. The satellite G/T is solved, not known: no operator figure was read. The receiver threshold is assumed: a standard's ideal curve stands in for the LTE uplink. Every other line except the distance, the frequency and the rate is taken unchanged from the series' model ledger LL-2026-01. Not covered: the downlink, sharing in the beam, fast fading, power reduction, acquisition.

LINK LEDGER · LL-2026-02 · HOP BUDGET · CASE A OF THE BASELINE

Case A: distance only, the same receiver 5 km away (a counterfactual, not a cell budget)

Phone (power class 3) to The same receiver, moved to 5 km · 1912.5 MHz · 5 km · reference plane: the phone's antenna connector; the satellite's G/T toward this phone, scan and beam-edge loss inside it

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	Free-space path loss	5 km at 1912.5 MHz	**-112.1** level -119.1 dBW	calculated	20 log10(4 pi d f / c) at 1912.5 MHz, the center of the PCS G block uplink (1910 to 1915 MHz) that the beta used per Garcia-Cabeza and others, Direct-to-Cell: A First Look into Starlink's Direct Satellite-to-Device Radio Access Network through Crowdsourced Measurements, arXiv 2506.00283v8 (2025); distance from the altitude and elevation, Earth radius 6,371 km, 2026-11-23
RESULT	**Achieved Eb/N0: the sum of the lines above**		**44.6**	calculated by this ledger	
	Required Eb/N0 for quasi error free (packet error ratio 1e-7) on the standard's ideal curve, a stand-in for the LTE uplink		**0.7**	from the line above	
	Margin: achieved less required		**+43.8**	design minimum 3.0 dB	

Closes: margin +43.8 dB (design minimum 3.0 dB)

Operating point. as the baseline, at 5 km; G/T frozen at the baseline value
Required Eb/N0, 0.7 dB: source. Calculated from ETSI EN 302 307-1 V1.4.1 (2014-11), clause 6, Table 13: QPSK 1/4, spectral efficiency 0.490243, ideal Es/N0 -2.35 dB at quasi error free (packet error ratio 1e-7), AWGN, 64,800 bit frame. Eb/N0 = Es/N0 - 10 log10(0.490243). Its use for a 3GPP uplink is an assumption: a representative LDPC curve, not that uplink's validated threshold, 2026-11-23

LINK LEDGER · LL-2026-02 · HOP BUDGET · CASE B OF THE BASELINE

Case B: the phone at 25 degrees elevation

Phone (power class 3) to Low orbit satellite, 550 km · 1912.5 MHz · 1,123 km slant range · reference plane: the phone's antenna connector; the satellite's G/T toward this phone, scan and beam-edge loss inside it

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	Free-space path loss	1,123 km at 1912.5 MHz	**-159.1** level -166.1 dBW	calculated	20 log10(4 pi d f / c) at 1912.5 MHz, the center of the PCS G block uplink (1910 to 1915 MHz) that the beta used per Garcia-Cabeza and others, Direct-to-Cell: A First Look into Starlink's Direct Satellite-to-Device Radio Access Network through Crowdsourced Measurements, arXiv 2506.00283v8 (2025); distance from the altitude and elevation, Earth radius 6,371 km, 2026-11-23
RESULT	**Achieved Eb/N0: the sum of the lines above**		**-2.5**	calculated by this ledger	
	Required Eb/N0 for quasi error free (packet error ratio 1e-7) on the standard's ideal curve, a stand-in for the LTE uplink		**0.7**	from the line above	
	Margin: achieved less required		**-3.2**	design minimum 3.0 dB	

Does not close: short by 3.2 dB, and by 6.2 dB against the design minimum of 3.0 dB

Operating point. 16 kbit/s, phone to satellite, 25 degrees elevation, open sky; G/T frozen at the baseline value
Required Eb/N0, 0.7 dB: source. Calculated from ETSI EN 302 307-1 V1.4.1 (2014-11), clause 6, Table 13: QPSK 1/4, spectral efficiency 0.490243, ideal Es/N0 -2.35 dB at quasi error free (packet error ratio 1e-7), AWGN, 64,800 bit frame. Eb/N0 = Es/N0 - 10 log10(0.490243). Its use for a 3GPP uplink is an assumption: a representative LDPC curve, not that uplink's validated threshold, 2026-11-23
Line that fails. Free-space path loss: 1,123 km instead of 550 km costs 6.2 dB, so the hop ends 3.2 dB below zero margin and 6.2 dB below the 3 dB design margin

LINK LEDGER · LL-2026-02 · HOP BUDGET · CASE C OF THE BASELINE

Case C: a data rate of 1 Mbit/s, inside the 5 MHz block

Phone (power class 3) to Low orbit satellite, 550 km · 1912.5 MHz · 550 km, straight up · reference plane: the phone's antenna connector; the satellite's G/T toward this phone, scan and beam-edge loss inside it

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.					
BANDWIDTH	Information rate	1 Mbit/s	**-60.0** level -10.7 dB	*assumption*	A stated data rate of 1 Mbit/s for one phone, for comparison only (a choice); about 2.0 Mbaud at this code, inside the 5 MHz G block, 2026-11-23
RESULT	**Achieved Eb/N0: the sum of the lines above**		**-14.2**	calculated by this ledger	
	Required Eb/N0 for quasi error free (packet error ratio 1e-7) on the standard's ideal curve, a stand-in for the LTE uplink		**0.7**	from the line above	
	Margin: achieved less required		**-15.0**	design minimum 3.0 dB	

Does not close: short by 15.0 dB, and by 18.0 dB against the design minimum of 3.0 dB

Operating point. 1 Mbit/s, phone to satellite, straight up, open sky; G/T frozen at the baseline value
Required Eb/N0, 0.7 dB: source. Calculated from ETSI EN 302 307-1 V1.4.1 (2014-11), clause 6, Table 13: QPSK 1/4, spectral efficiency 0.490243, ideal Es/N0 -2.35 dB at quasi error free (packet error ratio 1e-7), AWGN, 64,800 bit frame. Eb/N0 = Es/N0 - 10 log10(0.490243). Its use for a 3GPP uplink is an assumption: a representative LDPC curve, not that uplink's validated threshold, 2026-11-23
Line that fails. Information rate: 1 Mbit/s costs 18.0 dB against 16 kbit/s, so the hop ends 15.0 dB below zero margin and 18.0 dB below the design margin

Monday rule: "in service" needs four words, a country, an operator, a device and a date; a claim that every phone works, or that the phone is unchanged, fails that test.

CHAPTER THIRTEEN

Processing Moves On Board, 1993 to 2026



In September 2020 a CubeSat called Phi-sat-1 went to orbit carrying a small processor that ran a neural network on its own images. Its job was narrow: recognize images covered by cloud and throw them away before the downlink. Intel, which made the chip, said this saved about 30 percent of bandwidth; that is the chip maker's claim, not a published measurement. Chapter 1 defined processing as anything a satellite does to a signal beyond filtering it, amplifying it and shifting its frequency, and noted that a simple bent pipe, with fixed connections, carries a zero there by design. This chapter asks when it has paid to process the bit in orbit instead of sending it down, and when it has not.

The row for this chapter

Era	Limit that ran out first	User end	Space	Ground end
Processing in orbit, 1993 to 2026	Downlink, energy, heat, radiation and cost, workload by workload	An application interface or a data product	Switching first, then sensor filtering, then hosted computing	Less downlink to carry; more control to keep

Three different things

"Processing in orbit" names three jobs with different histories and different trades. Keeping them apart is the first step in judging any claim about them.

- **Communication switching.** The satellite demodulates the signal, decides where each piece goes, and modulates it again. 3GPP calls a satellite that does this regenerative, and one that only shifts, filters and amplifies transparent. A transparent payload can still switch whole channels between beams without recovering the bits, as the ACTS switch matrix below did; this book counts that as processing too, and keeps the word regenerative for recovering the bits. Iridium switched calls on board from its service start on 1 November 1998 and passed them between satellites over crosslinks (chapter 9).

NASA's experimental ACTS, launched on 12 September 1993, tested switching on board in the Ka band before either; the next section tells how. For phones, 3GPP Release 19 adds regenerative payloads that carry base station functions (chapter 12).

- **Sensor filtering.** An observation satellite decides on board which of its data are worth sending down, as Phi-sat-1 did with cloudy images.
- **Hosted general-purpose computing.** A computer in orbit runs software that its owner did not write, for customers who rent time on it.

The first is part of the link: it changes who carries the processing in the division of labor. Its commercial cases are told in chapters 9, 10 and 12; its test bed, ACTS, is told here. The second and third change the data before it reaches the link, and they take the rest of the chapter.

The switch in orbit: ACTS, 1993 to 2000

NASA's official history calls the Advanced Communications Technology Satellite a "switchboard in the sky": its payload combined steerable spot beam antennas with onboard switching "that allows signals to be routed aboard the spacecraft", in the Ka band, 30 GHz up and 20 GHz down (NASA SP-4217, chapter 6). It went up on the Space Shuttle, mission STS-51, in September 1993. Its own engineers listed the parts that mattered as "a fast hopping multibeam antenna, an on-board baseband processor, a wide-band microwave switch matrix, adaptive rain fade compensation, and 900 MHz transponders operating at Ka-band frequencies" (Acosta and others, IEEE Journal on Selected Areas in Communications, 1999). Each part answers a limit of the user end.

- **Hopping spot beams.** The antennas made spot beams about 0.3 degrees wide (Regier, NASA, 1992). A beam that narrow has high gain, so the ground terminal can be small; it also covers little ground, so the beams hopped, or scanned, from one place to another. How long it dwelt on each spot is given in the full reports, which could not be read for this chapter.
- **The baseband processor.** Built by Motorola (NASA SP-4217), it served the hopping beams. NASA's propagation program described the scheme as time division access with "microwave baseband switching, onboard regeneration" (Chakraborty and Davarian, NASA, 1991). In the 3GPP terms above that is a regenerative payload: the satellite recovered the bits from each burst, sent each piece to the beam where it belonged, and transmitted it again. The processor's designer wrote of "dynamic reconfiguration of message routing" (Moat, 1986). The result for the user, as two program engineers put it before launch, was that "each individual voice or data circuit can be separately routed", so that 1.544 Mbit/s services could run "with only a single hop" between small terminals (Gedney and Schertler, IEEE, 1989).

- **The microwave switch matrix.** The other path through the satellite connected whole 900 MHz channels between beams at radio frequency, without recovering the bits: the transparent side of the same payload. The satellite could be run in either mode (Gargione, IEEE, 1993).
- **Rain fade compensation.** At 20 and 30 GHz a heavy shower can take away much of a link's margin. ACTS met it terminal by terminal. Its small ground stations detected the fade and compensated "by burst rate reduction and forward error correction" (Johnson and others, NASA, 2000): the faded terminal sent more slowly and with more coding. The processor could apply that coding to each terminal on its own, "to overcome localized rain fading" (Moat, 1986). The decibels recovered are in the full reports, which were not read.

The satellite was used as a test bed, not a service. The experiments program began in December 1993 and "consisted of 103 different experiments" (Bauer and Derwae, NASA, 2000). After five years as a geostationary satellite, its north to south stationkeeping was stopped in August 1998, and it went on working in an inclined orbit; NASA planned to end its operations in June 2000, after 81 months (Bauer, NASA TM-2000-209639). The official history of 1997 counted two years without failures and more than 100 experiments and tests by then, and named its commercial heirs: Motorola was putting onboard switching into Iridium, and Hughes was working on Spaceway (NASA SP-4217, chapter 6).

What ACTS showed, on this record, is that switching in orbit worked in the Ka band and let small terminals reach each other in one hop, with the satellite deciding where each burst went and each terminal fighting its own rain. What it did not settle was the business. Chapter 10 shows the market splitting on exactly this point: Hughes flew an on-board packet switch on Spaceway 3 in 2007, while WildBlue built its service on "unprocessed" spot beams and left the switching to the ground. The error rates measured on orbit, the dwell of the beams and the margin bought back from rain were reported in NASA's full technical reports; this chapter read only their summaries and prints none of those values.

The trade, workload by workload

Processing on board costs something on every line of a satellite's budget, and pays only on some.

- **Downlink.** What processing can save. An image that is discarded in orbit costs no downlink time. A result that replaces raw data, a count of ships instead of a picture of a harbor, can be much smaller. How much is saved depends on the workload: about 30 percent of bandwidth for Phi-sat-1's cloud screening, by its chip maker's claim.
- **Energy.** Every watt the processor draws comes from the solar arrays and the battery, and on a small satellite the processor competes with the radio and the instrument for it.

- **Heat.** Nearly every watt a processor draws becomes heat that must be radiated away; in vacuum there is no air to carry it.
- **Radiation.** Particles flip bits and wear out parts. A processor either tolerates radiation by design, which usually costs performance, or is protected by redundancy and checks, which cost mass and power.
- **Mass, cost and repair.** On a free-flying satellite that nobody services, the computer cannot be replaced; its software can be updated, if the update path is secure.

No rule says one of these is always scarcer than another. A satellite that sees a cloudy planet and has little ground station time gains from filtering; a satellite whose users want every raw pixel gains nothing. Figure 13.1 sets the three kinds of processing against the trade.

FIGURE 13.1

Three kinds of processing in orbit, and what each trades

Kind	What is done on board	What it saves	What it costs	Example, with date and status
Communication switching	Demodulate, switch or route, modulate again	With crosslinks, fewer gateways in view; a hop through the ground	Power and heat for the processor; a payload fixed to its waveform unless it can be updated	Iridium, in service from 1 November 1998 (chapter 9); 3GPP Release 19 regenerative payloads (a standard)
Sensor filtering	Discard or compress data before the downlink	About 30 percent of bandwidth on one 2020 CubeSat (its chip maker's claim)	A processor that survives radiation; the risk of discarding what a user wanted	Phi-sat-1, launched September 2020, discards cloudy images (flown)
Hosted general computing	Run a customer's software on a shared computer in orbit	Time from collection to answer; downlink of raw data	Energy, heat rejection, radiation, repair; who may load code	Kepler cluster, about 40 processors on 10 satellites, 18 customers (April 2026, trade press); two Axiom nodes launched 2026-01-11 (operator)

Each row trades downlink against energy, heat, radiation, mass and cost; none is right for every workload. Status words follow the sources.

Source: 3GPP NTN overview; Intel Newsroom, Intel Powers First Satellite with AI on Board (2020); TechCrunch (trade press), 2026-04-13; Axiom Space, Orbital Data Centers page. Read 2026-11-22.

Where the processors stand

One program shows how long a new flight processor takes from contract to qualification. NASA awarded Microchip a contract of 50 million dollars on 15 August 2022 to design and deliver a new spaceflight processor, the High Performance Spaceflight Computing processor (HPSC), with a target of at least 100 times the computational capacity of current spaceflight computers. According to NASA's project page, the design passed its critical design review in 2024 and was taped out in mid 2025, and the first processors were produced later in 2025. As of March 2026, the latest status on that page, the processor was still in power, performance, reliability and radiation testing and had not been declared space qualified.

Commercial processors fly anyway, on missions that accept the risk. Phi-sat-1 used an Intel Movidius Myriad 2 vision processor. Its launch date differs by a day between sources, because of the time zone: Intel says 2 September 2020, and other sources give 3 September. ESA described the experiment in 2019 as an artificial intelligence chip on one of two FSSCat CubeSats, there to filter out cloudy images before the downlink.

Orbital computing, labeled as announced or flown

An orbital data center, in this book, is a shared computing platform in orbit, scheduled remotely and sold as a service to customers who load their own software. Several companies used the phrase by 2026, for things at very different stages. Each item below carries its date and its status as its own source gives it.

- **Flown and offered.** Kepler's cluster: about 40 Nvidia Orin processors on 10 satellites, with 18 customers, on 13 April 2026, as reported by trade press. Axiom Space states that its first two orbital data center nodes launched on 11 January 2026 with Kepler's first satellites, and that they support software and model updates over the air. Spire sells "Software in Space" for a flat monthly fee, and Loft Orbital offers on-orbit artificial intelligence; neither publishes a price.
- **Flown as an experiment.** Starcloud's first satellite launched in November 2025 with an Nvidia H100 processor, as reported by trade press.
- **Announced.** Google announced Project Suncatcher, a research design for computing in orbit with its own tensor processors, on 4 November 2025, with two prototype satellites with Planet planned by early 2027. Google reported that the processors showed no hard failure up to a total ionizing dose of 15 krad in its tests; a dose test is not a qualification, and it does not cover single-event effects or years in orbit.

None of this is a general verdict on computing in orbit. What has flown shows that a commercial processor can run a customer's workload in low orbit for some time; what is announced shows where companies are putting money. Heat rejection at scale, radiation

over years, and repair remain open problems, stated as open. The seventh book of this series covers on-board computing in depth.

THE SYSTEM'S FAILURE

The systems in this chapter have no failure on record in the documents read, so an open problem stands in its place: as of March 2026, NASA's own new flight processor, under contract since August 2022, had not been declared space qualified, according to NASA's project page. On that status, dated March 2026 and still the page's when read on 23 November 2026, a mission that needed a qualified processor could not yet choose this one (a later qualification was not checked); a mission that flies a commercial one accepts a risk the qualification would have measured. The lesson is specific: a processor's announcement date, its first silicon and its qualification are three different dates, like the filing, the launch and the service of chapter 11.

SECURITY NOTE

Who can interfere or command. A computer that accepts new software in orbit has an upload path, and whoever controls that path controls the computer. For a hosted platform there are at least two parties: the platform's operator, who may command the satellite, and the customer, who may load a workload but should not reach the platform or another customer's code. Axiom describes over-the-air updates; how they are authenticated and how customers are kept apart is exactly what its page leaves out, and what a buyer has to ask. ACTS shows the older form of the same question: a satellite that routes traffic itself holds a routing plan that someone on the ground loads. **How it is seen.** Ask the operator for a log of every upload and its signature check, and for what a failed check does. **How it is recovered.** A platform needs a way back to known software that a bad upload cannot remove, and a command path that is not the one the customers use. Ask how both work before loading anything.

Monday rule: before asking for a faster downlink, ask what fraction of the data is worth sending down, and whether processing it on board costs less in mass, power and risk than sending it.

CHAPTER FOURTEEN

What Returned, What Did Not, and Where the Frame Stops



On 4 October 1960 the US Army launched Courier 1B, a sphere of 500 pounds with five tape recorders inside. Each time it passed over Puerto Rico or New Jersey, the Signal Corps loaded it with teletype traffic, and the satellite played the traffic back to the next station, according to the Army's own history. Thirty-eight years later ORBCOMM opened full commercial service in the United States and Canada with satellites that stored and forwarded short messages, according to its filing for 1999. The idea had come back. What came back with it, and what did not, is the subject of this chapter, together with the cases the book's frame cannot explain.

What returned

Several answers of the early decades came back once their constraints moved. None came back unchanged. Table 14.1 sets six of them side by side, each with what it was the first time, what it returned as, and what did not carry over.

FIGURE 14.1

What returned, and what did not carry over

Idea	An early appearance	Returned as	What did not carry over
Store and forward	Courier 1B, 1960: five tape recorders, loaded and unloaded as it passed a station (US Army)	ORBCOMM short messages of about 200 bytes, full US and Canada service from November 1998 (filings); store and forward in 3GPP Release 19 for satellite IoT; Sentinel-1 storing 1,410 Gbit for later download	Tape and a few military stations; the user became a device or a sensor that can wait
Many satellites in a middle orbit	AT&T's plan of 1962: 50 to 120 satellites about 7,000 miles high, not built (NASA SP-4217)	Medium orbit broadband: SES had launched 10 of 13 O3b mPOWER satellites by 5 March 2026 (operator)	One telephone company owning satellites, stations and the traffic; chapter 10 tells the return
Switching in orbit	ACTS, 1993: switching on board in Ka band, an experiment (NASA SP-4217); Iridium, 1998: commercial service with links between satellites at 23 GHz and switching on board (filing)	Regenerative payloads for phones in 3GPP Release 19	A proprietary handset and network; the payload is now described by an open standard

Idea	An early appearance	Returned as	What did not carry over
Thousands of satellites for broadband	Teledesic's licensed plan of 840 satellites in Ka band; license surrendered by letter of 27 June 2003 (trade press)	Low orbit broadband constellations in service in the 2020s (chapter 11)	The old cost assumptions: chapter 11 finds scale and one operator's integration documented, a general fall in the four costs not shown
A large antenna in orbit	ATS-6, 1974: a 9.14 m reflector so village antennas of 3 m could receive television (NASA SP-4217)	Arrays of about 2,400 square feet built for phones (operator filing, November 2026)	A fixed antenna on a village roof; the user end is now a phone's built-in antenna
Shared reception, then one dish per house	SITE, 1975 to 1976: about 5,000 television sets in villages, on a borrowed satellite (NASA SP-4217)	Hermes to a 60 cm dish in May 1978 (NASA SP-4217), then direct to home television (chapter 7)	A set shared by a village; reception became private and the box in the home became the point of control

Six early answers that came back when their constraints moved, each changed on the way; the second column gives an early appearance, not a claim of the first.

Sources: US Army, Early Signal Corps satellite programs remembered; ORBCOMM Forms 10-K405 for 1999 and 10-K for 2006; 3GPP, NTN overview; Copernicus SentiWiki, S1 Mission; NASA SP-4217, chapters 6, 14 and 16; SES news, 5 March 2026; Iridium Form 10-K405 for 1998; Satellite Today (trade press), 14 July 2003; AST SpaceMobile Form 8-K exhibit 99.2, November 2026. Checked 2026-11-23.

Two patterns run through the table. First, an idea returns when the limit that stopped it moves, not when it is remembered: the medium orbit plan of 1962 (chapter 4) came back for broadband half a century later, under different owners and with different terminals. Second, the old answer usually returns with the work divided differently. Store and forward in 1960 meant tape and a few military stations; in 2026 it means a satellite holding bits for devices that each send a few hundred bytes, described by a standard (3GPP Release 19, by 3GPP's own overview). Read across the rows, and in this book's reading, the user end changed most: from a village set or a station to a sensor, a home dish or a phone, and each change moved work back into orbit.

Some ideas did not return at all. Nothing in this book's record shows the passive reflector of 1960 (chapter 2) coming back for communication. Echo 2 followed on 25 January 1964, but by NASA's history its investigations concerned less communication than the dynamics of large spacecraft, and after it NASA abandoned passive systems for active satellites (NASA SP-4217, chapter 6). A satellite that adds no power leaves all of it to the ground, and no user end in this book's record supplied that.

Where the frame stops

The frame of this book, five things divided among three places under the constraints of the time, describes how a satellite service splits its work. It is not limited to two-way links: broadcast is one way and fits it well. It is weak, or silent, in six places, and the book has met each of them.

- **Navigation.** The mission is position and time, not a message between two ends. The satellite does not know its users exist. There is no user uplink, no subscription and no gateway in the user's path, though the receiver is real engineering and the system still has a ground segment that loads the satellites.
- **Earth observation.** The "user" is a data product, far from the link. The satellite collects on board and unloads to a few stations. Sentinel-1, Europe's radar satellite, sends payload data down by X band at 520 Mbit/s, or by an optical link through a relay satellite, and stores 1,410 Gbit on board, according to the Copernicus mission page. The grid can describe that downlink; it cannot say what the images are worth.
- **Spectrum and law.** Often worth more than the satellites. The Act of 1962 shaped the 1960s, and in May 2026 the FCC consented to the sale of spectrum licenses to a satellite operator for service to phones (chapter 12). The frame records who holds a permission; it cannot price it.
- **Military need.** Protection against jamming and independence from others can justify designs no commercial constraint would. The book states such reasons only where an official source states them.
- **Demand, debt and competition.** Iridium and Globalstar delivered their links and failed as businesses, in 1999 and 2002.
- **Prestige and industrial policy.** A national satellite may be bought to build an industry or a nation as much as to carry circuits. Chapter 6 states those aims from sources and without judgment.

Transit: a case that does not fit, worked on purpose

Transit, formally the Navy Navigation Satellite System, was designed by the Johns Hopkins Applied Physics Laboratory for the Navy's ballistic missile submarines. The account used here is the laboratory's own, written in 1998 by its former program manager for Transit. In the spring of 1958 the laboratory wrote a 50 page proposal in about 17 days. The first operational satellite, Transit 5BN-2, was launched on 5 December 1963, and submarines and aircraft carriers used the system from the start of its operation in 1964.

The requirement explains the design. The Navy wanted fixes several times a day, each within 0.1 nautical mile, and the users were to have passive receivers, which never transmit. So the work went elsewhere. The satellite broadcast two coherent carriers, at 150 and 400 MHz; the ionosphere delays them differently, and comparing the two removes most of its error. The receiver measured how the frequency shifted as the satellite passed, the Doppler shift, and computed its position from that and from the orbit the satellite broadcast. The ground tracked the satellites, predicted their orbits and loaded each navigation message into satellite memory, a technique tested on Transit 3B in 1961.

Read against the grid, the division is plain. The power that made the signal sat in orbit, and the orbit prediction on the ground; the user supplied a receiver, an antenna and the computation of the fix. Processing sat in the receiver and in the ground's orbit computations; the satellite stored and repeated. Cost sat with the Navy. A civil user paid only for a receiver. Vice President Humphrey released the system for public and commercial use in 1967, and once receivers fell to about 1,000 dollars, in the years after the oil crisis of 1974 by the laboratory's account (it gives no exact year), pleasure boats began to use it. Its service ended on 31 December 1996.

What does not fit is the user end. Field 5 of its form, capacity, has nothing to say about the way up, because there is none, and nothing about contention, because a receiver takes nothing from any other receiver. Field 6 has no customer relationship. The frame can describe Transit, but its central question, who carries the load of the user's link, has an unusual answer: the satellite carries the whole link, one signal sent to everyone, and the user carries reception, the Doppler measurement and the computation of the fix, with no uplink at all.

LINK LEDGER · LL-1964-01 · SERVICE LEDGER

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

Class: service only

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

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

Transit's successors carry the same shape. The Department of Defense launched its first GPS satellite in 1978, according to NASA's history; the satellites fly about 20,200 km high, according to the government's GPS site. The Soviet Union placed its first GLONASS satellites in orbit on 12 October 1982, according to NASA's laser ranging service; Europe's Galileo declared its initial services in 2016, according to ESA; China's BeiDou and the regional systems of Japan and India complete the list. Each broadcasts its navigation signal one way to the user. Navigation is covered in depth later in this series.

THE SYSTEM'S FAILURE

Transit's early operational satellites failed in orbit for reasons that had nothing to do with the frame's five things and everything to do with how they were built. The plan was for the Naval Avionics Facility at Indianapolis to build the operational satellites, called Oscars. It built five; four reached orbit, and in the laboratory's words "the fabrication of the satellites did not meet specifications, and those that achieved orbit operated only a few weeks". After Oscars 1 and 2 failed to operate more than a few days, the Navy had the laboratory refurbish the next five, which worked for 7 to 11 months. The failures of Oscars 4, 6, 8 and 9 were considered workmanship-related; on Oscar 10, solar cell connections failed as the satellite passed in and out of sunlight. From Oscar 12 the satellites averaged more than 14 years in orbit, and two passed 20. The paper also records that a high-altitude nuclear test in 1962 caused satellite failures, and that the later Transit satellites were hardened against that kind of radiation. The lesson the source supports: a design that divides the work well still fails if the parts are not built to it, and the fix was in who built them and how, first refurbishment at the laboratory and then a production contractor, not in the architecture.

The frame's own limit

The division of labor describes how a system was built. It cannot see a market. Applied in November 1998, it would have recorded Iridium's switch in orbit (chapter 9) and would not have predicted the filing of August 1999. Applied to Globalstar in 2000, it would have recorded the opposite division (chapter 9) and would not have predicted the 2002 filing, whose own reasons include land networks that grew sooner than expected.

That is not a defect to hide. It is the reason this book keeps three verdicts apart. The frame answers the first question, whether the link was divided sensibly for its constraints. The second and third, whether the service and the business worked, need subscribers, prices, debt and competitors, which come from filings and not from the grid.

The test, restated

The systems of this book reduce to a short procedure for the next one.

1. **Name the constraints** the designers face, each with a source: launch, power, terminal, spectrum, money, permission.
2. **Draw the division:** who carries the power, the antenna, the processing, the cost and the risk, at the user end, in orbit and on the ground.
3. **Name the owners** of each end, and who gave permission.
4. **Keep three verdicts apart:** the link, the service, the business. A link that works proves nothing about the other two, and a bankruptcy proves nothing about the link.
5. **Say where the frame stops:** if the case turns on permission, demand or mission, ask that question directly instead.

> **SECURITY NOTE**
>
> **Who can interfere or command.** For Transit, only the Navy's ground system loaded and commanded the satellites; the later satellites could be switched through either of two redundant command receivers, according to the laboratory. The user had no way to send anything to the satellite, so there was no user to authenticate. A one-way broadcast can carry its own authentication, as some modern navigation signals do; the laboratory's accounts describe none for Transit. Such a signal can in principle be drowned by a stronger one or imitated, and those accounts record no case of either. **How it is seen.** On the ground, in tracking and telemetry; at sea, as a pass that never comes or a fix that disagrees with dead reckoning. **How it is recovered.** By the operator reloading or replacing a satellite; for the navigator, by falling back on other means. The modern navigation systems face the same questions at a far larger scale; they are covered in depth later in this series.

Monday rule: when the frame does not fit a system, say which question you are asking instead, permission, demand or mission, and find a source that answers that one.

Epilogue: Reading the Next Announcement



Some time next year a company will announce a satellite system. The release will give a number of satellites, a capacity, a date and a list of partners. This book cannot say whether that system will succeed. It can say how to read the release, because the same questions have been asked of every system in this book, and the record shows which answers mattered.

Announcement status: four words

Before anything else, give the announcement its announcement status, one of four words. They are different facts, and a release often blurs them. (They are not the deployment status of chapter 11 and Appendix D, which describes a fleet: operating, deployed before full service, deploying, contracted or building.)

Announcement status, and what proves each

Status	It means	What would show it
Announced	A company has said it intends to build or offer something	The company's own release, dated
Filed	An application is with a regulator. A grant, if one follows, is a separate event with its own date and conditions	The filing or the order, with its number
Launched	Satellites are in orbit; it says nothing about service	A count, its date and who counted
In service	Users can buy it: a named country, operator, device class and date	The operator's terms or a regulator's record

The history gives each word its weight. Teledesic held a license for a constellation of 840 satellites and surrendered it in 2003, according to the trade press of the time, without a commercial service. ICO filed for Chapter 11 in August 1999, lost its first satellite in a launch

failure in March 2000 and put one satellite in orbit in June 2001, by its own later filing. In June 2026 the FCC granted one broadband constellation a conditional waiver of its half-way deployment milestone, by the regulator's own order: a filing with dates is not a fleet. "Will launch in" and "is expected to" are not states. Write "has announced" or "has filed a schedule that requires".

The six questions, applied

1. **What must be delivered, and by when?** Find the requirement the system is built for, in the operator's words: rate, delay, coverage, availability, terminal. A release that states only a total capacity has not stated a requirement. In 1984, by NASA's history, complaints about delayed voice on one carrier's satellite trunks rose sharply (chapter 5): a link can meet its error rate and still fail its users.
2. **How is the work divided between user, space and ground?** Draw the grid of chapter 1: who carries the power, the antenna, the processing, the cost and the risk. Then ask which limit the design assumes has moved since the last system that tried it.
3. **Does each hop close, with what margin, under which assumptions?** Ask for the operating point. If the operator publishes no waveform and no figures, write "not published" and say which number would settle it.
4. **Who owns each end, and who gave permission?** The satellites, the gateways, the spectrum filing, the customer relationship and the exit. Iridium's satellites, Globalstar's and ORBCOMM's all outlived their first owners (chapters 9 and 14).
5. **How does it fail, who can interfere, and what would show us?** Name what failed in the record of similar systems: the launch, the satellite, the service or the company. Telstar's repeater kept working in 1962 while its command decoder failed (chapter 3).
6. **What can I use or rent before I build?** Most readers will buy a service, not a satellite. Ask what can be tested on a contract of months before a commitment of years.

   Then keep the three verdicts apart when the results come in. If the link works, write that the link works. Wait for subscribers, prices and debt before writing anything about the business.

OUR VIEW, AS OF NOVEMBER 2026

These are the constraints that, in our reading of the record, are likeliest to bind next. They are an opinion, not a forecast of winners.

- **Spectrum.** Services to ordinary phones depend on who may transmit on which frequencies over which country, and that is decided by regulators and by license sales as much as by engineering.
- **Orbital space and debris.** Thousands of satellites in low orbit make the rules on disposal and coordination part of every design.
- **Terminal cost.** The terminal limited the handheld phones of 1998 and the broadband dishes after them; a flat array that tracks satellites is still a costly part.
- **Energy and heat in orbit.** Very large arrays and processing on board both need power that must be generated and heat that must be rejected, with no one to repair the satellite.

Where the series goes next

This book stopped at the division of labor. Later books of this series cover in depth today's constellations and phone services, with operators chosen by stated criteria; the permissions, treaties and debris rules a plan must meet; and computing in orbit, as a trade study. The question stays the same in each: who carries the load, and does it work, as a link, as a service and as a business?

APPENDICES

APPENDIX A

The Link Ledger: Blank Pages and This Book's Worked Ledgers

The two blank pages of the form, a short guide to filling them for a system of the past, and the index of every worked example in this book. The form is the one the first book of this series, *The Bit's Path*, uses for systems of today; a history fills it from older records and says so on every line.

Filling it for a system of the past

- **Date.** Write the date the page describes, not the date the sources were read, and fill each field from what builders and operators recorded at the time.
- **Requirement.** In the builders' terms: one television channel, 240 telephone circuits, a telex from a ship. A requirement written later in today's terms is labeled so.
- **Owners.** Many systems in this book changed hands; write the owners of the page's date.
- **Trust and failure.** "Not stated in the sources read" is an honest entry. A failure names what failed: the launch, the satellite, the service or the company.
- **Page 2.** Say which of the two kinds it is, in the system line: an **archival budget**, where every line that decides the result comes from a builder's report, a filing, a standard or a peer-reviewed paper, with any recalculation shown; or an **illustrative model**, built from representative, solved or assumed values, each labeled. Sign each line in decibels with its class, source and date, and write the operating point before the margin. A model's "closes" means only that the model closes under its stated assumptions; it never qualifies a real service. A budget that does not close names the line that fails. Without readable hop numbers the example stays one page and says why.

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 labeled historical scholarship reports it; the work and the page are named

The blank pages

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.

Index of the worked examples

Each id names one link across the whole series, so a system the first book also treats keeps that book's id and numbers, and this book prints only the page it needs. The system column says whether a page 2 is an archival budget or an illustrative model; a service ledger has no budget. The PDF page column gives the pages where each worked ledger is printed.

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.	39, 41 to 42
LL-1964-01	1964	Transit (Navy Navigation Satellite System): a position fix at sea	service only	Retired	service only	Positions for ballistic missile submarines several times a day, 0.1 nautical mile per fix, from passive receivers. Later: a usable pass on average within 4 hours anywhere on Earth.	172
LL-1965-01	1965-06-28	Early Bird (Intelsat I): a transatlantic telephone circuit through one geostationary transparent satellite	service only	Retired	service only	Carry telephone circuits, and at times one television channel, between North America and Western Europe at every hour, on a satellite its owner treated as both experimental and commercial. The unit sold was a voice circuit leased to a carrier.	48

Id	Date	System	Class	Status	Budget	Requirement	PDF page
LL-1965-02	1965-04-23	Molniya 1: television and telephone across the Soviet Union through a satellite in a 12 hour elliptical orbit	service only	Retired	service only	Relay television and telephone calls between the western and eastern ends of the Soviet Union, including high latitudes; inferred from the service recorded at the time.	51
LL-1975-01	1 August 1975 to 31 July 1976	SITE: village television through NASA's ATS-6 (India)	service only	Retired	service only	Six hours a day of educational television in four languages, for 365 days, to villages without terrestrial television and often without electricity.	71
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.	93
LL-1978-01	1978	Hermes (CTS) to a 60 cm dish: direct to home television, Lima, May 1978	service only	Retired	service only	One television program, a Canadian hockey game, received on a 60 cm dish at the home of a Canadian embassy official in Lima, Peru, during a reception in May 1978. The objective was experimental: to show direct reception with very small, low-cost antennas.	82

Id	Date	System	Class	Status	Budget	Requirement	PDF page
LL-1984-01	1983 to 1988	MCI domestic telephone trunk on purchased transponders (Galaxy II and III)	service only	Retired	service only	Long distance voice circuits for MCI's national network, built quickly and cheaply after 1982, plus redundancy against a partial network failure. Two executives objected before the purchase that delay and echo would irritate customers.	63
LL-1986-01	1 February 1986 to 8 July 1989	DFH-2: China's domestic C band trunk and television satellite	service only	Retired	service only	Long distance telephone, telegraph, facsimile, data and television for the whole country, including remote regions, frontier stations and islands.	73
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.	113 to 115
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.	108
LL-2000-03	2000	Thuraya handheld call through one geostationary satellite (first satellite)	service only	Retired	service only	A voice call from a dual-mode handset (satellite and GSM, with GPS) anywhere in one region of about 100 countries, from North Africa and Europe to Central Asia. Service announced for July 2001; dates are the manufacturer's.	110

Id	Date	System	Class	Status	Budget	Requirement	PDF page
LL-2012-01	2012	Ku band dish on a truck through a geostationary satellite (a design example on a class of service, no operator named)	service only	Not checked	service only	Send claim photographs from a disaster zone where the ground network is down, from a vehicle, the same day. The user must accept at least about half a second before any reply arrives.	129
LL-2014-01	2014-09	O3b medium orbit trunk to an island operator	service only	Not checked	service only	Carry an island operator's internet trunk, fibre-equivalent in the operator's words, with less delay than a geostationary link.	127
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.	151
LL-2026-02	2026-11-23	A text from a compatible phone over a carrier's terrestrial spectrum: T-Mobile's T-Satellite on Starlink direct to cell satellites, United States (page 2: an illustrative model)	full	Not checked	closes (baseline); stress cases B and C fail, as intended; case A closes	A listed phone, outdoors with open sky and no tower in reach, sends a short text. The rate is not published; page 2 assumes one.	155 to 156, 158 to 159
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.	142

APPENDIX B

Timeline, 1945 to 2026

Every entry below was read in the source named in its last column, and dates are given as precisely as that source gives them. Where two sources disagree, the entry says so or gives the less precise date. "First" appears only in quotation marks or with the source that claims it. Facts the chapters leave undated, because no primary record was read, are listed at the end as open entries rather than guessed. The status of systems in service today is in Appendix D, dated November 2026.

Source key. SP4217 = NASA SP-4217, *Beyond the Ionosphere* (1997), with the chapter number. NASA-CS = NASA History, "Communications Satellites: Making the Global Village Possible". NSSDCA = NASA Space Science Data Coordinated Archive. BSTJ = Bell System Technical Journal, July 1963. 10-K = an annual report filed with the US Securities and Exchange Commission. TP = trade press, labeled as such. Full titles are in Appendix E.

1945 to 1964: store, reflect, repeat

Date	System or event	Country or owner	Orbit, band	Source
Oct 1945	Clarke, "Extra-Terrestrial Relays": three stations in a 24 hour orbit	United Kingdom (article)	Orbit of 42,000 km radius; 3,000 Mc/s	Wireless World, pp. 305 to 308
1955	Pierce compares satellite repeaters with TAT-1 (about 36 circuits, about 35 million dollars)	AT&T Bell Laboratories		SP4217 ch. 9
1956	TAT-1, transatlantic telephone cable	AT&T and partners	Cable	SP4217 ch. 9
4 Oct 1957	Sputnik 1	Soviet Union	Low orbit, about 98 minutes	NASA History
31 Jan 1958	Explorer 1; its data reveal the radiation belts	United States	Low orbit	NASA History

Date	System or event	Country or owner	Orbit, band	Source
18 Dec 1958	SCORE launched, carrying a recorded presidential Christmas message	United States (ARPA, Army)	Low orbit; store and forward	US Army
13 Apr 1960	Transit 1B, the first Transit in orbit	United States (Navy)	Low orbit; navigation	JHU APL Technical Digest
12 Aug 1960	Echo 1, a 30.48 m balloon; Goldstone to Holmdel	United States (NASA)	Low orbit; passive reflector	NSSDCA; NASA
4 Oct 1960	Courier 1B; communication system fails after 17 days	United States (Army)	Low orbit; delayed repeater	US Army
10 Jul 1962	Telstar 1: 6390 MHz up, 4170 MHz down, about 2 W	AT&T (reimbursed NASA for launch)	Elliptical, 952 by 5,651 km (BSTJ)	NASA History; BSTJ
31 Aug 1962	Communications Satellite Act (Public Law 87-624)	United States		US GPO
13 Dec 1962	Relay 1	NASA (built by RCA)	Medium altitude	NSSDCA; SP4217 ch. 6
1 Feb 1963	COMSAT incorporated	United States		SP4217 ch. 9
14 Feb 1963	Syncom 1, silent when its apogee motor fires	NASA (built by Hughes)	Intended 24 hour orbit	SP4217 ch. 6

Date	System or event	Country or owner	Orbit, band	Source
26 Jul 1963	Syncom 2: one two-way telephone channel	NASA (built by Hughes)	Geosynchronous, inclined 33 degrees; 7360 MHz up, 1815 MHz down	NSSDCA
5 Dec 1963	Transit 5BN-2, operational navigation satellite; system in use from 1964	United States (Navy)	Low orbit; 150 and 400 MHz	JHU APL Technical Digest
19 Aug 1964	Syncom 3; television of the Tokyo Olympics	NASA (built by Hughes)	Geostationary, 180 degrees	NSSDCA
20 Aug 1964	Intelsat interim arrangements opened for signature; COMSAT 61 percent	Intelsat (consortium)		SP4217 ch. 13

1965 to 1989: the geostationary trunk and the national programs

Date	System or event	Country or owner	Orbit, band	Source
6 Apr 1965	Early Bird (Intelsat I): 240 circuits or one TV channel, about 7 million dollars with launch	COMSAT for Intelsat	Geostationary	SP4217 ch. 9
23 Apr 1965	Molniya 1 launched into a 12 hour, highly eccentric orbit (US tracking records)	Soviet Union	Highly elliptical, apogee near 40,000 km	NORAD weekly intelligence report 44/65

Date	System or event	Country or owner	Orbit, band	Source
Jun 1965	Commercial service on Early Bird begins; the sources give 1, 27 and 28 June, and an emergency start after a cable failure	Intelsat	Geostationary	SP4217 ch. 9; ESA
29 Nov 1965	Color television experiments between the Soviet Union and France through a Molniya satellite	Soviet Union, France	Highly elliptical	SP4217 ch. 13
16 Jun 1966	First seven IDCSP satellites launched	US Department of Defense	Near-synchronous; X band	SP4217 ch. 7
Jun 1967	France and Germany agree on Symphonie	France, Germany		DLR
13 Jun 1968	Last group of eight IDCSP satellites launched	US Department of Defense	Near-synchronous; X band	SP4217 ch. 7
5 Aug 1968	Intersputnik draft submitted to the United Nations; one state, one vote	Soviet Union and seven states		SP4217 ch. 13
Jul 1969	Intelsat III completes Indian Ocean coverage, days before 20 July	Intelsat	Geostationary	NASA-CS

Date	System or event	Country or owner	Orbit, band	Source
1 Sep 1969	Telesat Canada created, half government, half private	Canada		SP4217 ch. 14
1970	TAT-5: 720 circuits for 79 million dollars	Cable owners	Cable	SP4217 ch. 9, note 12
20 Aug 1971	Definitive Intelsat agreement signed (in force 12 Feb 1973)	Intelsat		GAO-04-891
2 Nov 1971	First DSCS II pair launched	US Department of Defense	Geostationary; X band	SP4217 ch. 7
15 Nov 1971	Intersputnik agreement	Intersputnik		Intersputnik
Nov 1972	Anik A1; service from 1973	Telesat Canada	Geostationary; C band	SP4217 ch. 14
13 Apr 1974	Westar I, described as the first US domestic communications satellite	Western Union	Geostationary	NASA-CS
30 May 1974	ATS-6, a 9.14 m reflector	NASA	Geostationary	SP4217 ch. 6
Dec 1974; 27 Aug 1975	Symphonie A and B (in service to December 1984)	France, Germany	Geostationary; 4 and 6 GHz	DLR
1 Aug 1975 to 31 Jul 1976	SITE: village television in India through ATS-6	India, NASA	Geostationary; 6 GHz up, 860 MHz down	SP4217 ch. 6, 16
Dec 1975	RCA Satcom F-1	RCA	Geostationary	NASA-CS

Date	System or event	Country or owner	Orbit, band	Source
17 Jan 1976	Hermes (CTS); 60 cm dish reception in Lima, May 1978	Canada, NASA	Geostationary; 12 and 14 GHz	SP4217 ch. 14
Early 1976	First Comstar	AT&T, COMSAT	Geostationary	NASA-CS
Feb 1976; service summer 1976	Marisat: shore stations at Southbury and Santa Paula	COMSAT	Geostationary; C band to shore, L band to ships	NASA-CS; SP4217 ch. 21
1976	Palapa 1; NASA's histories call Indonesia the third country with a domestic satellite	Indonesia	Geostationary	SP4217 ch. 17
3 Sep 1976	Inmarsat convention adopted (in force 16 Jul 1979)	Inmarsat		IMO
End 1976	120 transponders over the US, each 1,500 telephone channels or one TV channel	US carriers	Geostationary	NASA-CS
1976	LES-8 and LES-9 launched: EHF links, crosslinks, on-board processing	MIT Lincoln Laboratory for the US Air Force	Geosynchronous ; EHF	SP4217 ch. 8
1978	OTS flies	ESA	Geostationary	SP4217 ch. 10
15 Dec 1978	Anik B, C and Ku band	Telesat Canada	Geostationary	SP4217 ch. 14

Date	System or event	Country or owner	Orbit, band	Source
May 1979	ESA to pay up to 60 percent of EUTELSAT's operating costs	Europe		SP4217 ch. 10
1981	Milstar program started, replacing STRATSAT	US Air Force	Geostationary; EHF	SP4217 ch. 7; GAO-03-825R
1 Feb 1982	Inmarsat global operations, on leased Marisat satellites	Inmarsat	Geostationary	SP4217 ch. 21
30 Oct 1982	First DSCS III launched	US Department of Defense	Geostationary; X band	SP4217 ch. 7
Feb 1983	MCI buys 24 transponders, 48,000 circuits, on Galaxy II and III	MCI; Hughes	Geostationary	SP4217 ch. 22
4 Feb 1983	Sakura 2a	Japan	Geostationary; Ka band per NASA	SP4217 ch. 6
4 Apr 1983	TDRS-1 on STS-6; reaches its orbit after months of maneuvers	NASA	Geostationary; relay	NASA STS-6
1983	First ECS; three more in 1984, 1987, 1988, on Ariane	ESA, EUTELSAT	Geostationary	SP4217 ch. 10
30 Aug 1983	INSAT-1B: 4,375 two-way circuits	India	Geostationary, 74 E	ISRO

Date	System or event	Country or owner	Orbit, band	Source
Mar 1984	MCI's Washington to New York single-mode fiber operational	MCI	Cable	SP4217 ch. 22
8 Apr 1984	China's first geosynchronous experimental communication satellite	China	Geostationary, 125 E	SP4217 ch. 15
17 Jun 1985	STS-51G launched; it deployed Morelos-A, ARABSAT-A and Telstar-3D during the mission	Mexico; Arab Satellite Communications Organization; AT&T	Geostationary (final orbit)	NASA STS-51G
1 Feb 1986	DFH-2: two transponders, 1,000 telephone channels	China	Geostationary, 103 E; 6 and 4 GHz	SP4217 ch. 15
4 Dec 1986	FLTSAT-7 launched with the first FLTSAT EHF package	US Navy	Geostationary; UHF and EHF	SP4217 ch. 8
7 Mar 1988	DFH-2A: four transponders, 3,000 telephone channels	China	Geostationary, 87.5 E; C band	SP4217 ch. 15
1988	TAT-8, NASA's "first fiber-optic trans-atlantic telephone cable"	Cable owners	Cable	NASA-CS
19 Feb 1988	Sakura 3a	Japan	Geostationary	SP4217 ch. 6

Date	System or event	Country or owner	Orbit, band	Source
Dec 1988	SES launches Astra 1A, 16 transponders	SES (Luxembourg)	Geostationary, 19.2 E; Ku band	SES prospectus, 2020
10 Dec 1988	First Skynet 4 launched	United Kingdom (MOD)	Geostationary	SP4217 ch. 8
Feb 1989	Astra 1A begins transmitting	SES	Geostationary, 19.2 E	SES prospectus, 2020

1990 to 2014: handhelds, second owners, privatization

Date	System or event	Country or owner	Orbit, band	Source
1990	Motorola announces Iridium	Motorola	Low orbit	SP4217 ch. 21
Oct 1990	Inmarsat's own first satellite, Inmarsat II F-1	Inmarsat	Geostationary	NASA-CS
1991 to 1994	Astra 1B, 1C and 1D co-located with 1A at 19.2 E	SES	Geostationary, 19.2 E	SES prospectus, 2020
19 Jul 1993	Five-satellite DSCS III constellation complete	US Department of Defense	Geostationary; X band	SP4217 ch. 7
12 Sep 1993	ACTS	NASA	Geostationary; 30 GHz up, 20 GHz down	SP4217 ch. 6
Dec 1993	DBS-1 launched (DIRECTV and USSB)	Hughes; USSB	Geostationary; Ku band	USSB 10-K (fiscal 1996)
Dec 1993	ACTS experiments program begins (103 experiments in all)	NASA	Geostationary; Ka band	Bauer and Derwae, NASA 2000 (abstract)

Date	System or event	Country or owner	Orbit, band	Source
7 Feb 1994	First Milstar launched	US Air Force	Geostationary; EHF	SP4217 ch. 7
Jun 1994	DIRECTV service begins in the United States, 18 inch dish	Hughes	Geostationary; Ku band	Hughes 10-K (2002)
30 Nov 1994	DFH-3 launched; never operational after thruster leaks	China	Quasi-geosynchronous	SP4217 ch. 15
31 Jan 1995	FCC authorizes Iridium: 66 satellites and 12 spares	Motorola (US license)	Low orbit; 1621.35 to 1626.5 MHz	FCC DA 96-1789
Apr 1995	First two ORBCOMM satellites	ORBCOMM	Low orbit; VHF	ORBCOMM 10-K405 (1999)
7 Apr 1995	AMSC-1, mobile service for North America	AMSC	Geostationary; L band	SP4217 ch. 21
Dec 1995	EchoStar I launched	EchoStar	Geostationary; Ku band	EchoStar prospectus, 1997
1996	Inmarsat-3 deployment begins (February, by SP-4217; no launch record read)	Inmarsat	Geostationary	SP4217 ch. 21
Mar 1996	DISH Network service begins	EchoStar	Geostationary; Ku band	EchoStar prospectus, 1997
Aug 1997	DVB-S standard EN 300 421 V1.1.2 issued	ETSI	Digital satellite television	ETSI EN 300 421

Date	System or event	Country or owner	Orbit, band	Source
Aug 1998	ACTS north-south stationkeeping stopped; inclined-orbit operations	NASA	Geosynchronous, inclined	NASA TM-2000-209639 (abstract)
1 Nov 1998	Iridium commercial service; 12 gateways	Iridium LLC	Low orbit, about 780 km; crosslinks 23.18 to 23.38 GHz	Iridium 10-K405 (1998)
Nov 1998	ORBCOMM full commercial service in the US and Canada	ORBCOMM	Low orbit; 137 to 150 MHz	ORBCOMM 10-K405 (1999)
Apr 1999	Inmarsat privatized (completed by the end of 2003)	Inmarsat		IMO
Aug 1999	Iridium LLC in Chapter 11	Iridium LLC		Motorola 10-K (1999)
27 Aug 1999	ICO files for Chapter 11	ICO	Medium orbit (planned)	ICO 10-K (2006)
Early 2000	Globalstar commercial service	Globalstar	Low orbit, 1,414 km; bent pipe	Globalstar 10-K (2001)
Jun 2000	ACTS operations planned to end after 81 months	NASA		NASA TM-2000-209639 (abstract)
15 Sep 2000	ORBCOMM Global files for Chapter 11	ORBCOMM		ORBCOMM 8-K

Date	System or event	Country or owner	Orbit, band	Source
Oct 2000	Thuraya's first satellite launched on Sea Launch; 12.25 m L band reflector, more than 200 spot beams	Thuraya	Geostationary; L band	Boeing release, 18 Jun 2001
11 Dec 2000	Iridium Satellite LLC acquires the Iridium assets	Iridium Satellite LLC		Iridium 10-K (2009)
Jun 2001	ICO F2 launched (one satellite)	ICO	Medium orbit	ICO 10-K (2006)
Jul 2001	Thuraya commercial service to more than 20 countries announced for July (manufacturer's release of June)	Thuraya	Geostationary; L band	Boeing release, 18 Jun 2001
18 Jul 2001	Intelsat transfers its assets to Intelsat, Ltd.; COMSAT 21.8 percent	Intelsat		GAO-04-891
15 Feb 2002	Globalstar files for Chapter 11	Globalstar		Globalstar 10-K (2001)
6 Sep 2002	DIRECTV sues NDS, its conditional access supplier	DIRECTV		Hughes 10-K (2002)
2003	Skynet 5 private finance contract awarded	United Kingdom (MOD)	Geostationary; X band and UHF	UK government, SKYNET 6

Date	System or event	Country or owner	Orbit, band	Source
Apr 2003	Last Milstar launched	US Air Force	Geostationary; EHF	GAO-03-825R
27 Jun 2003	Teledesic surrenders its license	Teledesic	Ka band (planned)	TP: Satellite Today
5 Dec 2003	Thermo takes operating control of Globalstar	Globalstar		Globalstar 10-K (2006)
11 Aug 2005	IPSTAR (Thaicom 4) launched on Ariane 5	Shin Satellite (Thailand)	Geostationary	TP: Satellite Today
Mar 2007	Skynet 5A launched	United Kingdom (MOD)	Geostationary	MOD release, 20 Dec 2012
Mar 2007	WildBlue-1 placed into service	WildBlue	Geostationary; Ka band spot beams	Viasat 10-K (fiscal 2012)
Aug 2007	Spaceway 3 launched, with an on-board packet switch	Hughes	Geostationary; Ka band	Hughes 10-K (2008)
Oct 2007	First WGS launched	US Department of Defense	Geostationary; X and Ka band	GAO-08-467SP
Nov 2007	United States and Australia sign a memorandum on WGS	US and Australia		GAO-08-467SP
Apr 2008	Hughes service on Spaceway in North America	Hughes	Geostationary; Ka band	Hughes 10-K (2008)
15 Dec 2009	Viasat completes its acquisition of WildBlue	Viasat		Viasat 10-K (fiscal 2012)

Date	System or event	Country or owner	Orbit, band	Source
End 2010	KA-SAT launched	Eutelsat	Geostationary; Ka band	Viasat 10-K (fiscal 2011)
2 Jun 2011	KA-SAT broadband service activation announced	Eutelsat	Geostationary; Ka band	TP: Satellite Today
Oct 2011	ViaSat-1 launched, about 140 Gbit/s (operator)	Viasat	Geostationary; Ka band spot beams	Viasat 10-K (fiscal 2012)
Jan 2012	Exede broadband service on ViaSat-1 begins	Viasat	Geostationary; Ka band	Viasat 10-K (fiscal 2012)
Dec 2012	Skynet 5D, the fourth Skynet 5, launched	United Kingdom (MOD)	Geostationary	MOD release, 20 Dec 2012
3 Apr 2014	Sentinel-1A; payload data at 520 Mbit/s by X band, and also by an optical link through EDRS	European Union (Copernicus)	Low orbit; radar at 5.405 GHz	Copernicus SentiWiki
Sep 2014	O3b begins commercial operations	O3b (SES from Aug 2016)	Medium orbit, equatorial; Ka band	SES results release, 24 Feb 2017

2015 to 2026: constellations and the phone

Date	System or event	Country or owner	Orbit, band	Source
11 Jan 2019	Last Iridium NEXT launch: 75 satellites in eight launches	Iridium	Low orbit	Iridium release
Jun 2022	3GPP Release 17 frozen: satellite access, transparent payloads only	3GPP	L and S band (n255, n256)	3GPP
15 Nov 2022	Emergency SOS via satellite on iPhone 14, US and Canada	Apple with Globalstar	Low orbit; mobile satellite spectrum	Apple Newsroom
1 Mar 2024	New Skynet service contract begins	United Kingdom (MOD)		UK government, SKYNET 6
17 Jul 2025	SES completes its acquisition of Intelsat	SES	Geostationary and medium orbit	SES
23 Jul 2025	T-Satellite commercial launch on Starlink	T-Mobile, SpaceX	Low orbit; terrestrial PCS spectrum	T-Mobile release
13 Nov 2025	Project Kuiper renamed Amazon Leo	Amazon	Low orbit; Ka band	Amazon
14 Apr 2026	Amazon agrees to acquire Globalstar	Amazon, Globalstar		Amazon 8-K
20 May 2026	SpaceX files its registration statement (Form S-1)	SpaceX		SEC EDGAR

Date	System or event	Country or owner	Orbit, band	Source
5 Jun 2026	FCC grants Amazon Leo a conditional waiver of its 50 percent milestone	Amazon (US license)	Low orbit	FCC DA 26-553
28 Jun 2026	Rocket Lab agrees to acquire Iridium	Rocket Lab, Iridium		Rocket Lab 8-K
30 Jun 2026	Dish DBS and Dish Wireless file prepackaged chapter 11 cases	EchoStar		EchoStar 10-Q (Q2 2026)
2 Aug 2026	Hughes Satellite Systems files chapter 11	EchoStar		EchoStar 8-K
14 Aug 2026	Lynk and Omnispace complete their merger as Elveo Mobile	Elveo Mobile	Low and medium orbit; S band	TP: Light Reading
13 Sep 2026	SES launches the last three O3b mPOWER satellites	SES	Medium orbit	SES
1 Oct 2026	Dish DBS emerges from chapter 11	EchoStar		EchoStar 8-K
15 Nov 2026	A Vulcan launch loses 40 Amazon Leo satellites	Amazon	Low orbit	Amazon progress page
17 Nov 2026	Iridium activates NTN Direct, a standards-based NB-IoT service	Iridium	Low orbit; L band	Iridium release

Open entries

These facts are named or implied in the chapters, but no primary record of them was read for this book. They are listed so a reader can see each gap, and they will be dated only when a source is read.

- The Soviet geostationary series Raduga, Ekran and Gorizont: first launch dates. Orbita: the date the receiving network began service (Molniya 1's launch is dated above, from US tracking records).
- Japan: the launch of the first experimental Sakura and of the first broadcast satellite, Yuri (Sakura 2a and 3a are dated above).
- Brasilsat A1, Aussat, Turksat, Koreasat and Yamal: first launch dates; Arabsat: its founding date.
- ACeS: launch and service dates. Thuraya: the operator's and regulator's own record of its dates (the dates above are the manufacturer's).
- O3b: the first launch (commercial operations are dated above). WildBlue: the start of its 2005 service on leased capacity. IPSTAR and KA-SAT: service dates in the operators' own records (the dates above rest on trade press and on a competitor's filing).
- FLTSATCOM, UHF Follow-On and AEHF: actual first launch dates; WGS launches after the first. Skynet 1: launch date.

APPENDIX C

Glossary

The terms the chapters use, in plain words. The number in brackets is the chapter where a term is introduced or worked; R is the Reader's Brief and A the appendix of the ledger. The radio theory behind several terms is worked in the first book of this series, *The Bit's Path*.

Term	Meaning
3GPP	The partnership of standards bodies that writes the mobile network standards, in numbered releases; satellite access was added from Release 17 [12]
Bent pipe	A transparent satellite: it receives a signal, shifts its frequency, filters and amplifies it, and sends it down, without decoding it; a transparent payload may still switch whole channels between beams [1, 9, 11, 13]
Community reception	One antenna serving a village or a building, which redistributes the signal; the step between a national station and a dish on each house [6, 7]
Crosslink	A radio or laser link between two satellites, which lets traffic cross space before it comes down [9, 11]
Delayed repeater	A satellite that records a message and sends it later, when the receiving station is in view; another name for store and forward [2]
Direct to device	Satellite service to a phone or small module with no external satellite terminal; it covers two spectrum roads and two device classes [12]
Division of labor	How a system shares five things, power, antenna, processing, cost and risk, among the user end, the satellite and the ground end [R, 1]
Eb/N0	The energy of one bit against the noise density; a coded link needs a stated minimum of it for a stated error rate [A]

Term	Meaning
EIRP	Equivalent isotropically radiated power: transmitter power less feeder loss plus antenna gain, in decibels [A]
Feeder link	The link between a satellite and its gateway; in 3GPP terms, between the gateway and the payload [11, 12]
Free-space loss	The loss of a radio path between two ideal antennas, which grows with the square of distance and of frequency [12]
G/T	A receiver's figure of merit: antenna gain in dBi minus 10 log10 of the system noise temperature in kelvin, written in dB/K; higher is better; a ledger can solve for the G/T a hop needs [12]
Gateway	The earth station where a satellite's traffic meets the ground network [9, 11]
Geostationary orbit	A circular orbit 35,786 km above the equator in which a satellite turns with the Earth and stays over one point; a reply takes about half a second from propagation alone [3, 5]
Half circuit	One end of an international telephone circuit, owned by one country's carrier; the unit in which early satellite capacity was counted [4, 5]
Highly elliptical orbit	An orbit that dwells for hours over high latitudes near its highest point, used by Molniya [4]
Hop	One radio or optical link between two antennas; a hop budget adds its gains and losses [A]
Hosted computing	A computer in orbit that runs software its owner did not write, for customers who rent time on it [13]
Link Ledger	The series form: page 1 the service in ten fields, page 2 one hop budget per hop [R, A]
Low orbit	Orbits below about 2,000 km; satellites pass overhead in minutes, so a service needs many of them [9, 11]

Term	Meaning
Margin	Achieved signal quality less the required value, at a stated operating point [A]
Medium orbit	Orbits between low orbit and geostationary; a fleet there needs fewer satellites than in low orbit and has less delay than geostationary [10, 11]
Milestone	A licensing deadline by which a share of an authorized constellation must be in operation; in the United States, for a constellation in non-geostationary orbit, half in six years and all in nine, as the FCC applied it in order DA 26-553 [11]
Mobile satellite service	Bands allocated by regulation to satellites serving moving users, such as L and S band; one of the two spectrum roads of direct to device [8, 12]
Operating point	The conditions at which a budget is stated: rate, direction, elevation, weather, availability; a margin without one means nothing [A]
Phased array	An antenna of many elements whose beam is steered electronically, with no moving parts; the flat terminal of low orbit broadband [11]
Point of presence	The site where an operator's network hands traffic to the internet; it may be in another country than the gateway [11]
Power class 3	The 3GPP class of a handheld phone: a nominal maximum output power of 23 dBm, about 0.2 W, met within the tolerance the 3GPP specification sets for each band [12]
Processing	Anything a satellite does to a signal beyond filtering it, amplifying it and shifting its frequency: switching channels between beams, demodulating, routing, storing, computing. Switching can act on the radio signal, in a transparent payload, or on the recovered bits, in a regenerative one [1, 13]

Term	Meaning
Propagation delay	The time a signal takes to travel a path at the speed of light, before any processing or queueing [3, 5, 11]
Regenerative payload	A satellite that demodulates and decodes, may switch or route, and modulates again; in 3GPP terms, one that carries base station functions [9, 12, 13]
Service link	The link between the satellite and the user's terminal or phone [12]
Spot beam	A narrow beam covering a small area; many spot beams reuse the same frequencies in different places [10]
Store and forward	Receiving a message, keeping it, and sending it when the destination is in view [2, 9, 13]
Supplemental coverage from space	The FCC's 2024 framework under which a satellite operator uses a carrier's terrestrial band to reach ordinary phones in the United States [12]
Three verdicts	The link, the service and the business, judged separately: a link can close while the business fails [R, 9]
Transponder	One channel of a transparent payload: a receiver, a filter, a frequency shift and an amplifier for a slice of the band [5, 7]
Transparent payload	See bent pipe; 3GPP Release 17 supports only this kind [12]
VSAT	Very small aperture terminal: a small dish in a network with a central hub on the ground [7]

APPENDIX D

Dated Register: Fleets, Owners and Service Status as of November 2026

A history ends on a date. The facts below describe the systems of the whole book on the date each source gives: today's fleets, owners and services first, then, at the end, the systems of chapters 2 to 10 at their last dated record, and they will change soon after this book is read: how many satellites a fleet has, who owns whom, and what is in service where. The chapters use them 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 a row, read its source again. No row is a price.

How to read a row

- **As of** is the date the fact describes.
- **Kind** is the class of the fact or, for a count by others, the kind of source: an operator claim is what a company or agency says about itself; trade press and independent trackers are labeled as such; a measurement names who measured.
- **Status** is deployment status, in chapter 11's four words: operating, deployed before full service, deploying, contracted or building. "Announced" describes a plan.
- Every source was read on 22 or 23 November 2026. A row is refreshed by reading its source again.

Fleets and status

Fact	As of	Source	Kind	Ch
Starlink: more than 11,100 satellites in low orbit; 13.6 million consumer subscribers; operating	2026-09-30	SpaceX, Form 10-Q for the quarter to 2026-09-30 (filed 2026-10-22)	operator claim	11
Starlink subscribers 2.3 million (2023), 4.4 million (2024), 8.9 million (2025), 10.3 million (2026-03-31); kit manufacturing cost about 59 percent lower since 2022	2026-03-31	SpaceX, Form S-1 (2026-05-20)	operator claim	11

Fact	As of	Source	Kind	Ch
Eutelsat OneWeb: more than 600 low orbit satellites; operating; 669 replacement satellites on order (2026-10-30)	2026-08-07	Eutelsat release; Via Satellite	operator claim; trade press	11
Amazon Leo (formerly Project Kuiper, renamed 2025-11-13): nearly 400 satellites over 14 missions; deployed before full service; enterprise preview from 2025-12-01	page updated 2026-10-28	Amazon, Amazon Leo mission updates; GSMA	operator claim	11
Amazon Leo: Vulcan mission LV-01 lost 40 satellites in a launch anomaly	2026-11-15	Amazon, Amazon Leo mission updates	operator claim	11
Amazon Leo: half-way milestone of 1,616 satellites by 2026-07-30 waived with conditions	2026-06-05	FCC, Order DA 26-553	standard (regulator order)	11
Guowang: 222 catalogued satellites; Qianfan: 233 working of 251 objects; both deploying	October 2026	KeepTrack, How many Chinese satellites are in orbit	independent tracker	11
Rassvet (Bureau 1440): about 31 production satellites; deploying; no service date found	2026-07-19	RussianSpaceWeb	trade press	11
Telesat Lightspeed: no satellites in orbit; plan raised from 156 to 225; contracted or building	2026-10-29	Telesat, results for the nine months to 2026-09-30	operator claim	11
IRIS2: Eutelsat leads the low orbit part (264 plus 66 satellites); first launches announced from 2029	2026-08-07	Eutelsat release	operator claim	11
ViaSat-3: three geostationary Ka band satellites, all in service	2026-09-21	Boeing, ViaSat-3 satellites enter service; Viasat, ViaSat-3	operator claim (builder; operator page)	11
O3b mPOWER: last three satellites launched; in service expected mid 2027	2026-09-13	SES, results for the nine months of 2026	operator claim	11

Fact	As of	Source	Kind	Ch
AST SpaceMobile: BlueBirds 1 to 6 and 8 to 13 operating; BlueBird 7 written off; about 45 targeted by mid 2027	2026-11-09	AST SpaceMobile, Form 8-K exhibits 99.1 and 99.2	operator claim	12

Owners

Fact	As of	Source	Kind	Ch
SES completed its acquisition of Intelsat; fleet of about 120 satellites	2025-07-17	SES, SES Completes Acquisition of Intelsat	operator claim	11
Amazon agreed to acquire Globalstar; closing expected in 2027, subject to approvals and replacement satellite milestones	2026-04-14	Amazon, Form 8-K exhibit 99.1	operator claim	12
Rocket Lab agreed to acquire Iridium (agreement of 2026-06-28); completion expected in mid 2027	2026-09-18	Rocket Lab, Form 8-K; Iridium, Form 8-K	operator claim	12
FCC approved EchoStar's spectrum sales to SpaceX (about 65 MHz) and AT&T (about 50 MHz); SpaceX closing expected about 2027-11-30	2026-05-12	FCC, DOC-421651 and DA 26-471	standard (regulator order)	11, 12
Dish DBS and Dish Wireless filed prepackaged chapter 11 cases (2026-06-30); Hughes Satellite Systems filed on 2026-08-02; Dish DBS emerged on 2026-10-01; EchoStar broadband subscribers 622,000 (2026-06-30)	2026-10-01	EchoStar, Forms 10-Q (Q2 2026) and 8-K (2026-08-03, 2026-10-02)	operator claim (filings)	11
Lynk Global and Omnispace merged as Elveo Mobile	2026-08-14	Light Reading	trade press	12

Services to phones in the United States

Fact	As of	Source	Kind	Ch
Emergency SOS via satellite, iPhone 14 lineup, United States and Canada, on Globalstar	2022-11-15	Apple Newsroom	operator claim	12
T-Satellite (T-Mobile with SpaceX) available, messaging first (trade press)	2025-07-23	T-Mobile, "T-Satellite Now Available" (newsroom release); Broadband Breakfast for messaging first	operator claim	12
T-Satellite: coverage from space "has brought" connectivity, text-based services; the newest primary record read. Status on 2026-11-23 not checked (LL-2026-02)	2026-05-12	FCC, Order DA 26-471	standard (regulator order)	12
Verizon satellite texting over Skylo on Galaxy S25 and Pixel 9 phones	2025-03-19	Skylo newsroom	operator claim	12
Iridium NTN Direct, a 3GPP-based narrowband service in Iridium's L band, activated	2026-11-17	Iridium release	operator claim	12
AST SpaceMobile expects intermittent nationwide service in the United States by the end of 2026 (announced, not in service)	2026-11-09	AST SpaceMobile, Form 8-K exhibit 99.1	operator claim	12

Processing in orbit

Fact	As of	Source	Kind	Ch
NASA's HPSC processor in testing, not declared space qualified	March 2026	NASA, High Performance Spaceflight Computing	operator claim	13
Kepler: about 40 Nvidia Orin processors on 10 satellites, 18 customers	2026-04-13	TechCrunch	trade press	13
Axiom Space: two orbital data center nodes launched	2026-01-11	Axiom Space, Orbital Data Centers	operator claim	13
Google Project Suncatcher announced; two prototypes with Planet planned by early 2027	2025-11-04	Google Research blog	operator claim	13

Systems of chapters 2 to 10: owners and status at their last dated record

Most systems of the early chapters are retired; a row gives the last dated fact the chapter prints about owner or status. Launch and service dates are in Appendix B.

Fact	As of	Source	Kind	Ch
Echo 1, the passive reflector, re-entered; Echo 2 (1964) followed, after which NASA abandoned passive systems for active satellites	1968-05-24	NASA NSSDCA, Echo 1; NASA SP-4217, ch. 6	published history	2
Early Bird outlived its planned 18 month life by two years	1965 to 1969	ESA, 28 June	published history	4
Definitive Intelsat agreement in force (signed 1971-08-20)	1973-02-12	GAO-04-891	published history	4
Intelsat privatized: assets transferred to Intelsat, Ltd.; COMSAT held 21.8 percent	2001-07-18	GAO-04-891	published history	4
MCI out of the satellite business as far as it could be, after buying SBS (completed March 1986)	after 1988	NASA SP-4217, ch. 22	published history	5
SITE ended; ATS-6 moved away by NASA	1976-07-31	NASA SP-4217, ch. 16	published history	6

Fact	As of	Source	Kind	Ch
Symphonie A and B ended operations	1984-12-12 and 1984-12-19	German Aerospace Center (DLR), Symphonie A+B	published history	6
Iridium: satellite assets acquired from the debtor by Iridium Satellite LLC	2000-12-11	Iridium Communications, Form 10-K for 2009	operator claim	9
Iridium: about 369,000 subscribers; 23.6 percent of revenue from the US government; Defense gateway in Hawaii	2009-12-31	Iridium Communications, Form 10-K for 2009	operator claim	9
ORBCOMM: assets bought out of bankruptcy by new owners; 29 of 35 satellites operational	2001-04	ORBCOMM Inc., prospectus, 2007	operator claim	9
Globalstar: Thermo took operating control (purchase completed in 2004)	2003-12-05	Globalstar, Inc., Form 10-K for 2006	operator claim	9
ICO: one satellite (F2) launched; ten more in storage	2001-06	ICO Global Communications, Form 10-K for 2006	operator claim	9
Thuraya: commercial service to more than 20 countries on its first satellite, announced for July 2001	2001-07	Boeing release, 2001-06-18	operator claim (manufacturer)	9
ViaSat-1 Exede service begins; about 140 Gbit/s on one satellite	2012-01	Viasat, Form 10-K for fiscal 2012	operator claim	10
O3b in commercial operations; SES owns all of it from August 2016	2014-09; 2016-08	SES results release, 2017-02-24	operator claim	10
Astra 1A reaches over 16 million cable and direct-to-home households	end 1990	SES prospectus, 2020	operator claim	7
DSS conditional access operated by News Corporation (News Datacom); DIRECTV responsible for security	1996-09	USSB, Form 10-K for fiscal 1996	operator claim	7

Fact	As of	Source	Kind	Ch
DISH Network: about 1.9 million subscribers; EchoStar owns 50 percent of NagraStar	1998-12-31	EchoStar, Form 10-K for 1998	operator claim	7
DIRECTV: about 11.2 million subscribers in the United States	2002-12-31	Hughes Electronics, Form 10-K for 2002	operator claim	7
Skynet: four Skynet 5 satellites give X band and UHF services; Skynet 6A scheduled for launch in 2027	2025-08-04	UK government, SKYNET 6	operator claim	8
Hughes: about 432,800 consumer broadband subscribers in North America	2008-12-31	Hughes Communications, Form 10-K for 2008	operator claim	10
WildBlue: about 409,000 subscribers (424,000 a year earlier); owned by Viasat since 2009-12-15	2011-04-01	Viasat, Forms 10-K for fiscal 2010 and 2011	operator claim	10
Thaicom 4 (IPSTAR) past its engineering life; customers to move for a time to a Korean satellite; later status not read	2026-04-22	The Nation Thailand	trade press	10

APPENDIX E

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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 357 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.

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