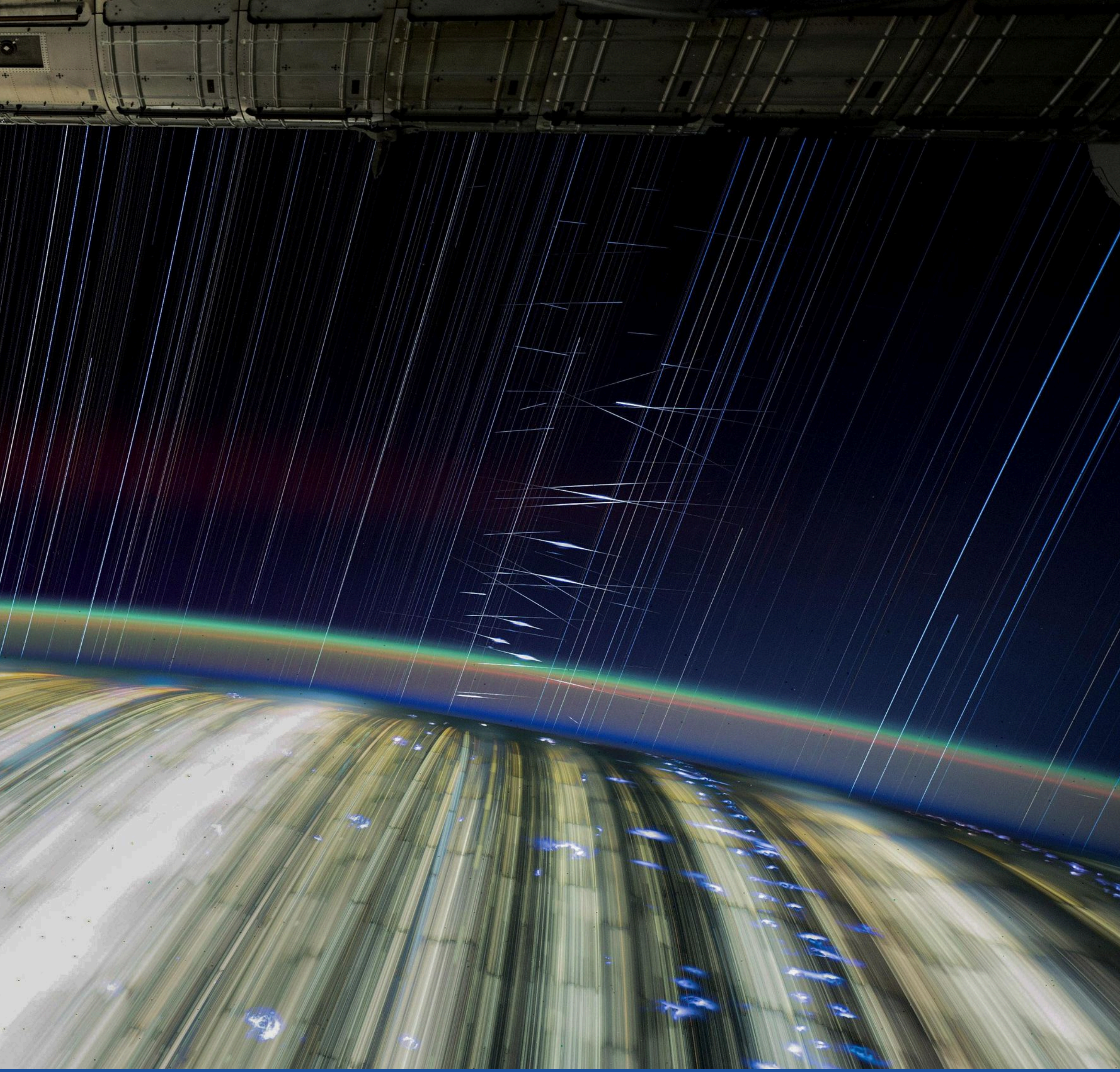

APOGEE VENTURES PAPER 2025-02 · DIRECT TO DEVICE

DIRECT TO DEVICE FROM LOW EARTH ORBIT

LINK BUDGETS, DOPPLER, AND THE SCS RULES FOR SERVING AN UNMODIFIED PHONE FROM 360 KM

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Scope and method

Published by Apogee Ventures LLC in a series on the rules governing satellite spectrum and orbit. Each paper states the regulatory requirement, reviews the published work bearing on it, reproduces the governing calculation, and sets out the consequences for design, licensing, and diligence. Calculations use the models published on the Tools page at apogee-ventures.com: an exponential atmosphere with a solar-activity scaling factor, a circular-orbit drag integrator, Hohmann transfer delta-v, free-space path loss, and ITU-R P.838 rain coefficients with the P.618 path reduction. They are sized for decisions; a filing uses the full recommendation and the applicant's own parameters.

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ABSTRACT

Direct-to-device service connects an unmodified phone to a satellite several hundred kilometers away using the phone's own antenna and power. The FCC's Supplemental Coverage from Space framework (March 2024), the first authorization under it (November 2024), and the out-of-band emission waiver that followed (March 2025) set the US rules; 3GPP Release 17 set the air interface. This paper works the link both ways with the models on this site: a 23 dBm handset with a -3 dBi antenna at 1.9 GHz from a 360 km orbit, the satellite receive gain needed to close it, the per-beam EIRP needed to reach the phone, the Doppler the waveform has to absorb, and what the rules require of the operator and the partner carrier. The conclusion is that the physics sets the service: narrowband messaging closes at most elevations, wideband data closes only at high elevation with large satellite apertures, and every improvement runs into the emission limits written to protect the adjacent terrestrial network.

PRINCIPAL RESULTS

- A 23 dBm handset with a -3 dBi antenna closes a 180 kHz channel to a satellite with 5 dB/K of G/T with 8 dB of margin at 30° elevation and 19 dB overhead; a 5 MHz channel closes only near zenith unless the satellite aperture doubles.
- On the downlink the handset's -35 dB/K receiver requires 16 to 36 dBW of per-beam EIRP depending on bandwidth and elevation. Power is not the constraint; the aggregate out-of-band emission limit across the constellation is.
- Doppler reaches about 45 kHz at 1.9 GHz from 360 km and sweeps through zero overhead; 3GPP Release 17 pre-compensates it on GNSS-equipped handsets.
- Under the SCS rules the spectrum belongs to the partner carrier, the emission limit is aggregate, and the operator inherits the 911 and device-certification regimes of a terrestrial network.

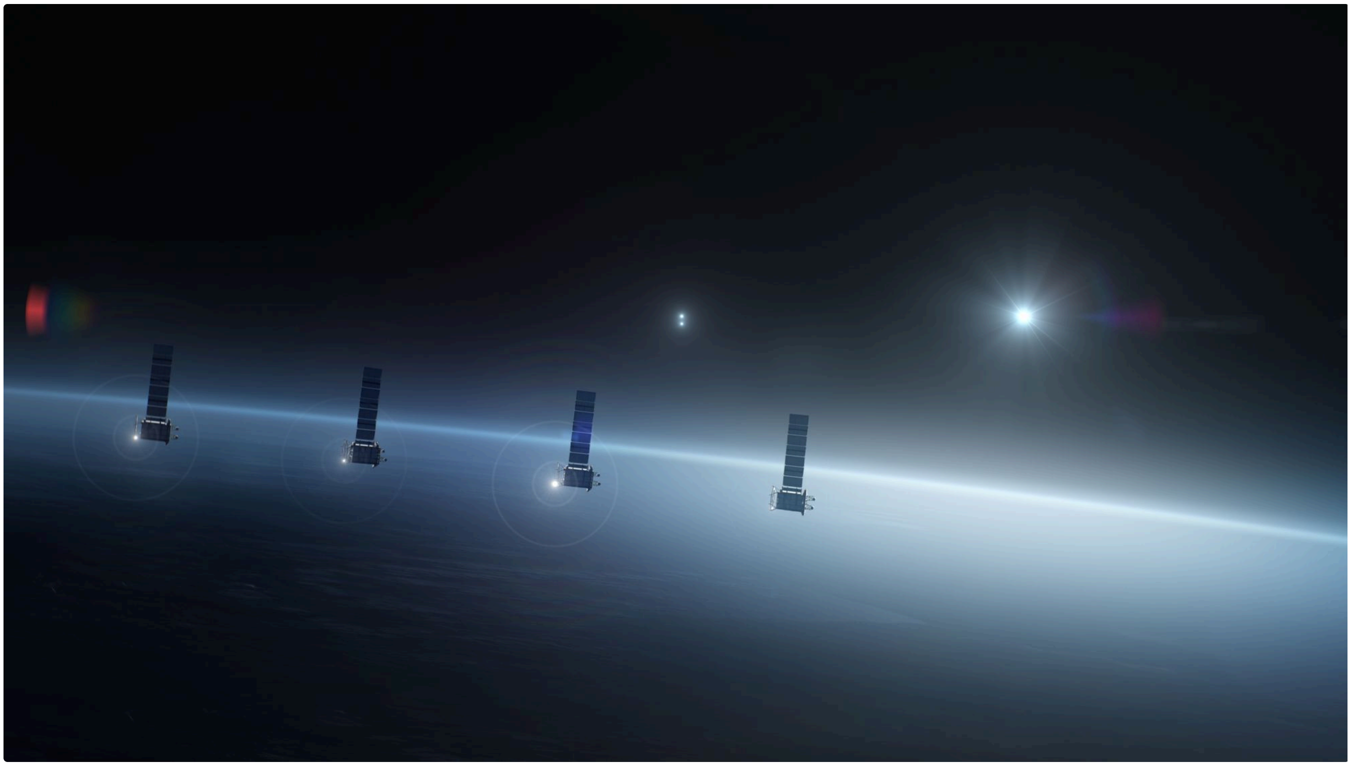

Figure 1. A plane of low Earth orbit satellites of the kind that now carries direct-to-device payloads. Stock illustration, licensed.

SECTION 1

Regulatory framework

The FCC adopted the Supplemental Coverage from Space (SCS) framework on March 14, 2024. It allows a satellite operator to use a terrestrial carrier's licensed mobile spectrum, under a lease, to serve that carrier's subscribers where the terrestrial network does not reach, by adding a secondary satellite allocation in specific bands and applying Part 25 rules to the space segment, with interim 911 routing requirements and equipment authorization for the handsets [1][2]. The first authorization came on November 26, 2024 for SpaceX and T-Mobile in the PCS G Block, conditioned on out-of-band emission limits and protection of neighboring licensees [3]. On March 7, 2025 the Space Bureau and Wireless Telecommunications Bureau conditionally waived the aggregate out-of-band emission limit in section 25.202(k)(1), after SpaceX explained that as the direct-to-cell constellation approached about 1,500 satellites it would otherwise have to reduce active beams or beam power to stay within the limit [4].

The air interface came from a different body. 3GPP's Release 17 added non-terrestrial network support to 5G NR and to the NB-IoT and LTE-M narrowband standards, with the timing, Doppler, and access adaptations a satellite link needs, following the study items documented in TR 38.821 [5][10]. Releases 18 and 19 continued the work. The first Starlink satellites with direct-to-cell payloads launched on January 2, 2024, and messaging tests with T-Mobile followed within the month [11].

SECTION 2

Link constraints

A conventional satellite terminal has a directional antenna, tens of watts of transmit power, and a receive chain designed for the link. A phone has none of those. A handset transmits at about 23 dBm through an antenna with roughly -3 dBi of gain in the direction of the sky, and its receiver has a noise figure near 7 dB behind that same antenna. Everything the terminal would normally contribute has to come from the satellite: a large phased array for gain, high per-beam EIRP, and a waveform that tolerates the Doppler and delay of a spacecraft moving at 7.7 km/s. The surveys of non-terrestrial networks describe these constraints in general terms [7][8][6]; the numbers below make them concrete for the SCS case.

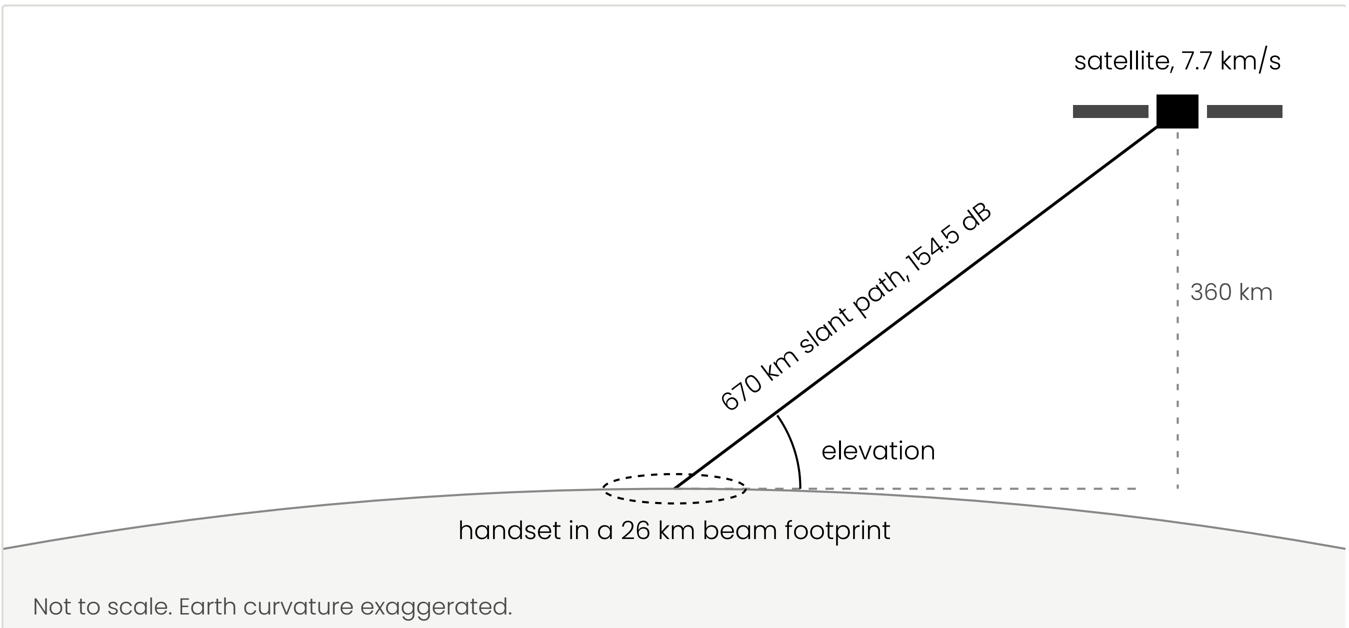

Figure 2. Link geometry for a direct-to-device pass. The satellite supplies the antenna gain the handset lacks; the beam footprint at 1.9 GHz from a 2.7 m aperture is about 26 km across at nadir.

Table 1. Slant range, free-space path loss at 1.9 GHz, and Doppler shift versus elevation angle for a 360 km circular orbit.

Elevation	Slant range	Path loss	Doppler shift
10°	1,331 km	160.5 dB	45.4 kHz
20°	897 km	157.1 dB	43.3 kHz
30°	670 km	154.5 dB	40.0 kHz
45°	496 km	151.9 dB	32.6 kHz
60°	412 km	150.3 dB	23.1 kHz
90°	360 km	149.2 dB	0 kHz

Path loss at 1.9 GHz is about 24 dB lower than at the 20 GHz of a Ka-band downlink over the same range, which is the only reason the link is possible at all. It is still 150 to 160 dB, and the handset contributes -10 dBW of EIRP on the uplink.

SECTION 3

Uplink budget

With a 23 dBm handset, a -3 dBi antenna, and 3 dB of body and polarization loss, the received carrier-to-noise density at a satellite with a G/T of 5 dB/K is about 61 dB-Hz at 30° elevation and 71 dB-Hz overhead. Figure 3 converts that into carrier-to-noise ratio for three channel bandwidths: the 180 kHz of an NB-IoT carrier, the 1.4 MHz of the narrowest LTE channel, and 5 MHz.

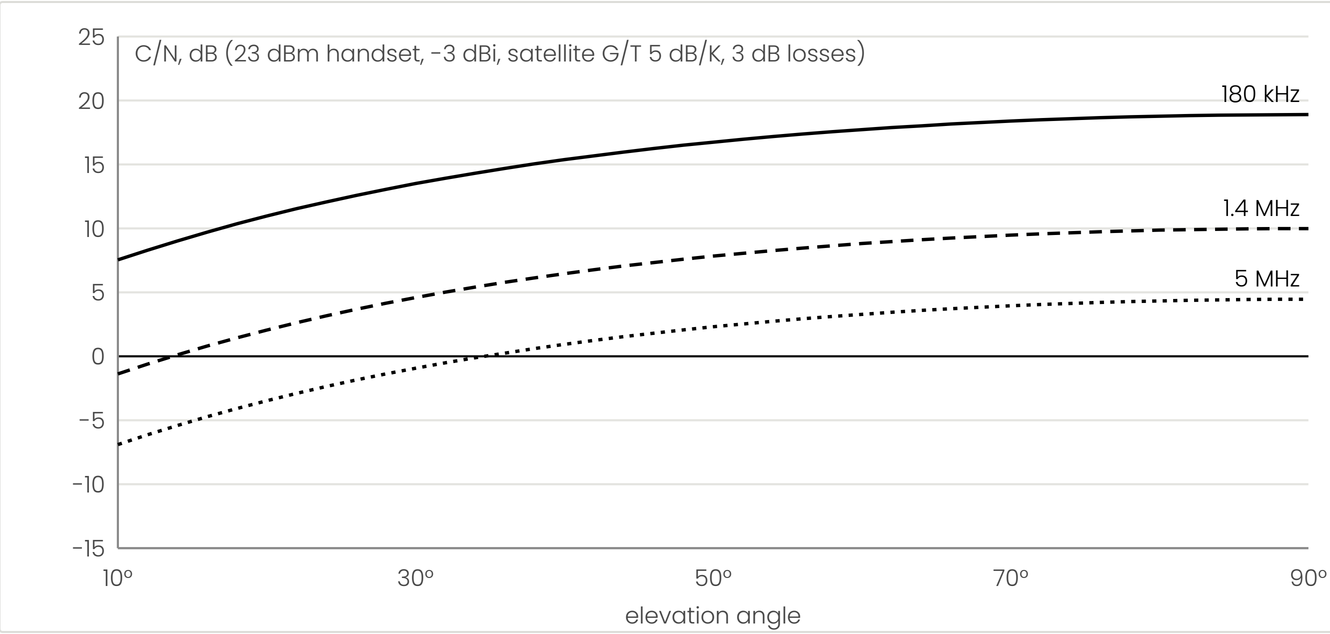

Figure 3. Uplink C/N versus elevation for three channel bandwidths, 1.9 GHz from 360 km, handset EIRP of -10 dBW, satellite G/T of 5 dB/K. The 0 dB line is where the link is at the edge of usability for the simplest modulations.

The result explains the service roadmap the operators announced: text first, then voice and data. A 180 kHz channel closes with 8 dB to spare at 30° and nearly 19 dB overhead. A 1.4 MHz channel is marginal below 30°. A 5 MHz channel closes only near zenith unless the satellite has 10 dB/K of G/T or more, which is the reason direct-to-device arrays are the largest antennas on their spacecraft. Doubling aperture area buys 3 dB; there is no equivalent lever on the phone. The narrowband LTE-M and NB-IoT adaptations for satellite that Ericsson's engineers documented exist for exactly this reason [9].

SECTION 4

Downlink budget

On the downlink the handset's receive G/T is about -35 dB/K, so the satellite's per-beam EIRP has to be large. Table 2 gives the EIRP required at the beam center to reach a 0 dB and a 5 dB carrier-to-noise ratio at the handset for the same three bandwidths, at 30° elevation and overhead, including 3 dB of losses.

Table 2. Per-beam EIRP required at the handset for a given C/N, 1.9 GHz from 360 km, handset G/T of -35 dB/K, 3 dB losses.

Channel	Elevation	EIRP for C/N 0 dB	EIRP for C/N 5 dB
180 kHz	30°	16 dBW (41 W)	21 dBW (129 W)
180 kHz	90°	11 dBW (12 W)	16 dBW (37 W)
1.4 MHz	30°	25 dBW (318 W)	30 dBW (1,007 W)
1.4 MHz	90°	20 dBW (92 W)	25 dBW (291 W)
5 MHz	30°	31 dBW (1,137 W)	36 dBW (3,597 W)
5 MHz	90°	25 dBW (328 W)	30 dBW (1,039 W)

EIRP is the product of transmitter power and antenna gain, so a 2.7 m array with roughly 32 dBi of gain reaches 30 dBW of EIRP with less than a watt of RF power per beam; the difficulty is not the power but the number of simultaneous beams, each a 26 km spot, needed to cover a service area, and the aggregate emission those beams produce outside the leased channel. That aggregate is what section 25.202(k)(1) limits and what the March 2025 waiver relaxed, on SpaceX's showing that the alternative was fewer or weaker beams as the constellation grew [4]. The emission limit, not the link budget, is the binding constraint on downlink capacity for a mature system.

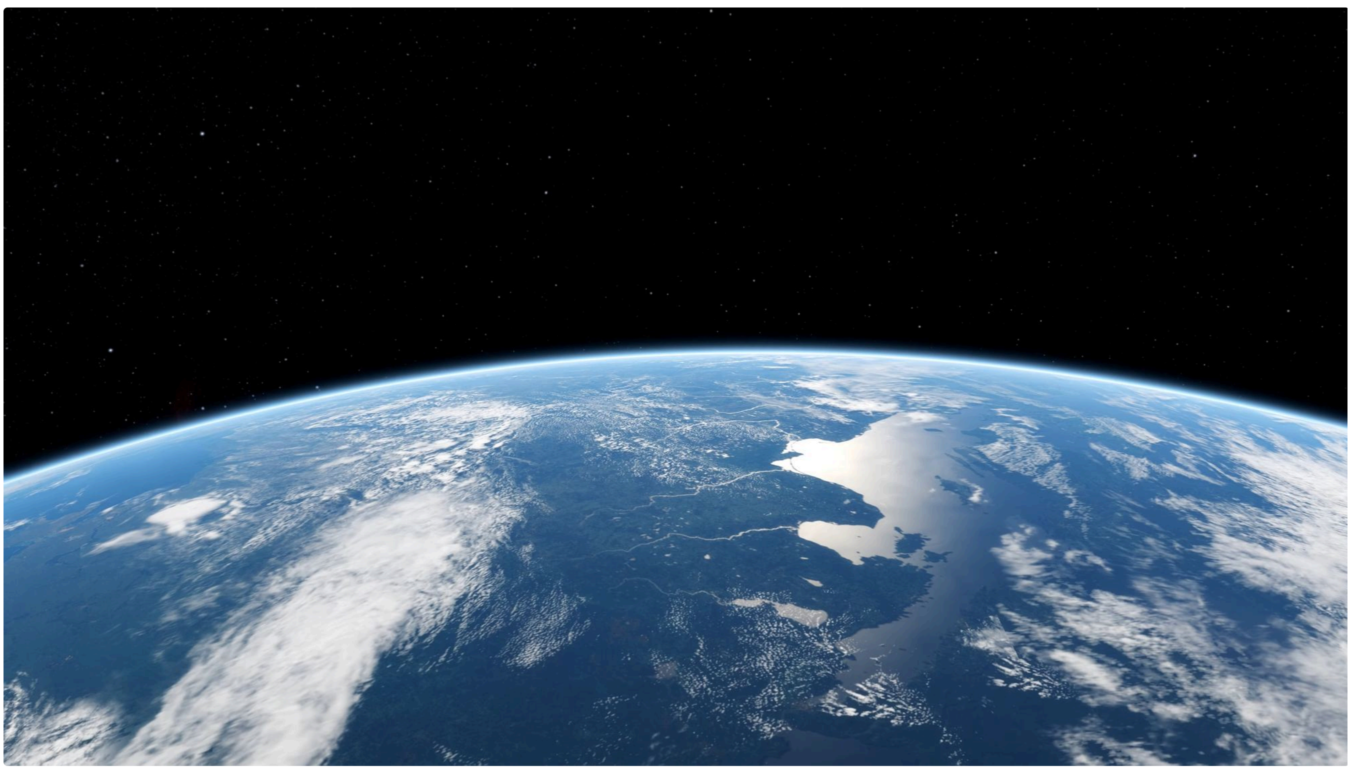

Figure 4. The ground the beams have to cover: from 360 km each 26 km spot sweeps across it at 7 km/s, and dozens of beams have to be steered and re-pointed as the satellite passes. Stock illustration, licensed.

SECTION 5

Doppler and timing

At 1.9 GHz a satellite at 360 km produces a Doppler shift of up to about 45 kHz at low elevation, sweeping through zero as the satellite passes overhead, with a rate of change of hundreds of hertz per second near zenith. Terrestrial LTE and NR were designed for Doppler of a few hundred hertz. Release 17 solved this on the network side for a GNSS-equipped handset: the satellite broadcasts its ephemeris, the phone estimates its own position, and the phone pre-compensates timing and frequency before it transmits, so the base station on the satellite sees a signal within the terrestrial tolerances [5][10]. Round-trip delay of a few milliseconds and the geometry of a beam moving across the ground at 7 km/s are handled with extended timing advance and scheduling offsets. The consequence for an operator is that the service works only with handsets whose software implements these procedures, or with a satellite that compensates on its own for legacy devices at a cost in capacity.

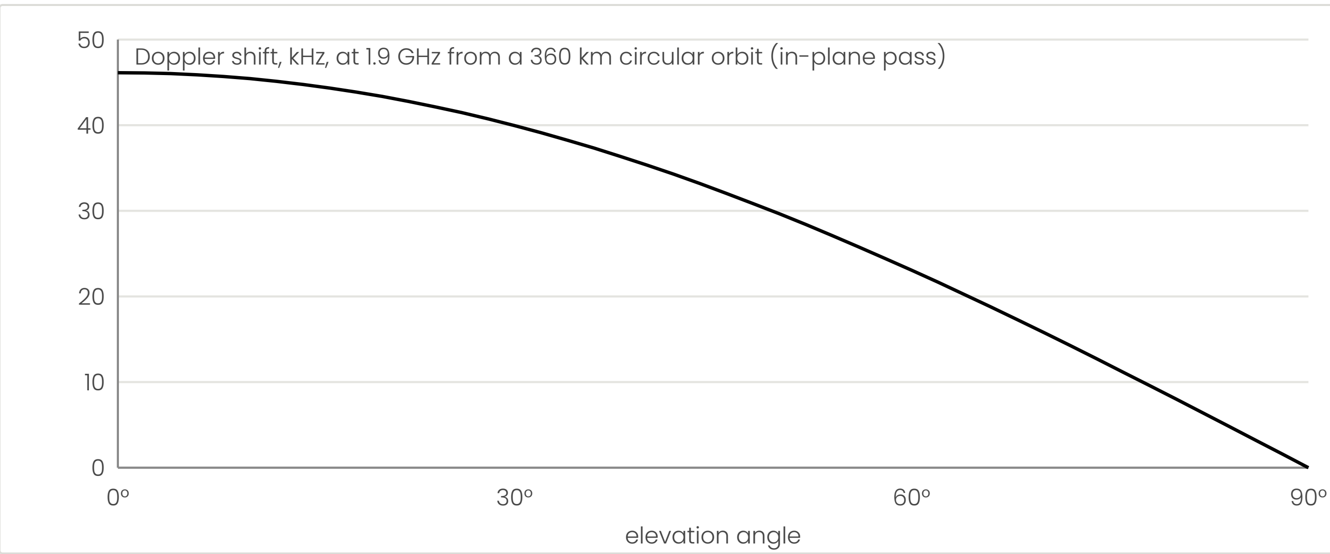

Figure 5. Doppler shift versus elevation angle for an in-plane pass at 1.9 GHz from a 360 km circular orbit. The phone or the satellite has to remove nearly all of it before the signal reaches the modem.

SECTION 6

Operator obligations under the SCS rules

Three features of the SCS framework shape the business as much as the link. First, the spectrum belongs to the terrestrial partner, not the satellite operator; the satellite operator files a Part 25 modification and the partner files a lease, and the partner must hold all co-channel licenses across a geographically independent area, which limits the arrangement to carriers with contiguous nationwide or regional holdings [2]. Second, the out-of-band emission limit is aggregate across the constellation, so capacity added by launching more satellites is capped unless the operator demonstrates, as SpaceX did, that the limit overprotects adjacent networks [4]. Third, the 911 routing and equipment authorization requirements put the satellite operator inside the public safety and device certification regimes of a terrestrial carrier for the first time [1].

For a new entrant the design questions follow from the link budget. Which service, messaging or data, does the aperture actually support at the elevation angles a real orbit delivers? Which carrier partner holds contiguous spectrum in the target market, and in which band, since path loss and antenna gain both scale with frequency? Will the handsets in that market implement Release 17 NTN procedures, or will the satellite have to compensate for them? And what emission budget is left once the neighbors' protection is accounted for? None of these are answered by a coverage map.

> **Direct-to-device service is a link budget with the terminal removed. The phone supplies -10 dBW and a -35 dB/K receiver, and every other decibel has to come from the spacecraft.**

SECTION 7

Conclusion

Direct-to-device service is a link budget with the terminal removed. The phone supplies -10 dBW and a -35 dB/K receiver, and every other decibel has to come from a spacecraft that also absorbs 45 kHz of Doppler and the emission limits of the terrestrial band it borrows. Narrowband messaging closes with margin across most of a pass; wideband data closes only at high elevation with the largest apertures now flying. The SCS framework makes the service legal in the United States and defines who holds the spectrum, who routes the emergency calls, and how much the constellation may emit in aggregate. An operator planning a direct-to-device payload should size the array to the service it intends to sell, choose the partner by spectrum holdings and handset population, and treat the emission limit as the constraint it will spend the most time negotiating.

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