SPACEX V-BAND NON-GEOSTATIONARY SATELLITE SYSTEM

ATTACHMENT A
TECHNICAL INFORMATION TO SUPPLEMENT SCHEDULE S

A.1 SCOPE AND PURPOSE

This attachment contains the information required under Part 25 of the Commission's rules that cannot be fully captured by the associated Schedule S.

A.2 OVERALL DESCRIPTION

Orbital Parameters

The SpaceX V-band non-geostationary orbit ("NGSO") satellite system (the "SpaceX System") consists of two sub-constellations of space stations, as well as associated ground control facilities, gateway earth stations, and end user earth stations. The first, the "LEO Constellation," comprises the 4,425-satellite constellation (plus in-orbit spares)[1] described in SpaceX's application to operate a system in the Ku and Ka bands.[2] As described in that application, the LEO Constellation will be configured as shown in Table A.2-1 below:

[1] SpaceX intends to launch up to two extra spacecraft per plane to replenish the LEO Constellation in the event of on-orbit failures. If a spare is not immediately needed, it will remain dormant in the same orbit and will perform station-keeping and debris avoidance maneuvers along with the rest of the active constellation.

[2] *See* IBFS File No. SAT-LOA-20151115-00018, Attachment A, Technical Information to Supplement Schedule S ("Ku/Ka Technical Supplement").

Parameter	**Initial Deployment (1,600 satellites)**	**Final Deployment (2,825 satellites)**			
Orbital Planes	32	32	8	5	6
Satellites per Plane	50	50	50	75	75
Altitude	1,150 km	1,110 km	1,130 km	1,275 km	1,325 km
Inclination	53º	53.8º	74º	81º	70º

Table A.2-1: LEO Constellation Characteristics

The second component of the SpaceX V-band system, the "VLEO Constellation," comprises 7,518 satellites, each of which will occupy unique orbital planes in very low Earth orbit, as illustrated in the associated Schedule S and detailed in the database of technical parameters submitted herewith ("Technical Database").[3] The satellites are distributed approximately equally across three altitudes and inclinations, with the precise number in each chosen to maximize the spacing between satellites across the constellation and thereby preclude the risk of conjunction. Configuration of the VLEO Constellation can be summarized as shown in Table A.2-2 below:

Satellites per Altitude	2,547	2,478	2,493
Altitude	345.6 km	340.8 km	335.9 km
Inclination	53º	48º	42º

Table A.2-2: VLEO Constellation Characteristics

When combined into a single, coordinated system, these "LEO" and "VLEO" constellations will enable SpaceX to provide robust broadband services on a full and continuous global basis.

Technology and Operations

The SpaceX System will make use of advanced phased array beam-forming and digital processing technologies onboard each satellite payload in order to make highly efficient use of

[3] Because of limitations in the Schedule S software, SpaceX is submitting a sample of its orbital parameter data in the electronic version of Schedule S, and will deliver to the Commission a database with the complete orbital parameter information required on Schedule S for inclusion in the record of this application.

spectrum resources and share spectrum flexibly with other space-based and terrestrial licensed users. Phased array technologies will be employed on the system's user terminals to allow for highly directive, steered antenna beams that track the system's satellites. The same phased array technologies in gateway earth stations will generate high-gain steered beams to communicate with multiple satellites within the constellations from a single gateway site. The system will also employ optical inter-satellite links for seamless network management and continuity of service, while minimizing the spectrum footprint of the system overall and facilitating spectrum sharing with other space-based and terrestrial systems. The broadband services will be available for residential, commercial, institutional, governmental and professional users worldwide.

SpaceX has designed its V-band system to meet the dual requirements of the world's broadband demand – namely, connectivity for rural, remote and hard-to-reach end-users, as well as efficient, high-capacity connectivity at all locations. Figure A.2-1 below illustrates the comparative coverage of a LEO and a VLEO satellite footprint, as well as an individual beam from each.

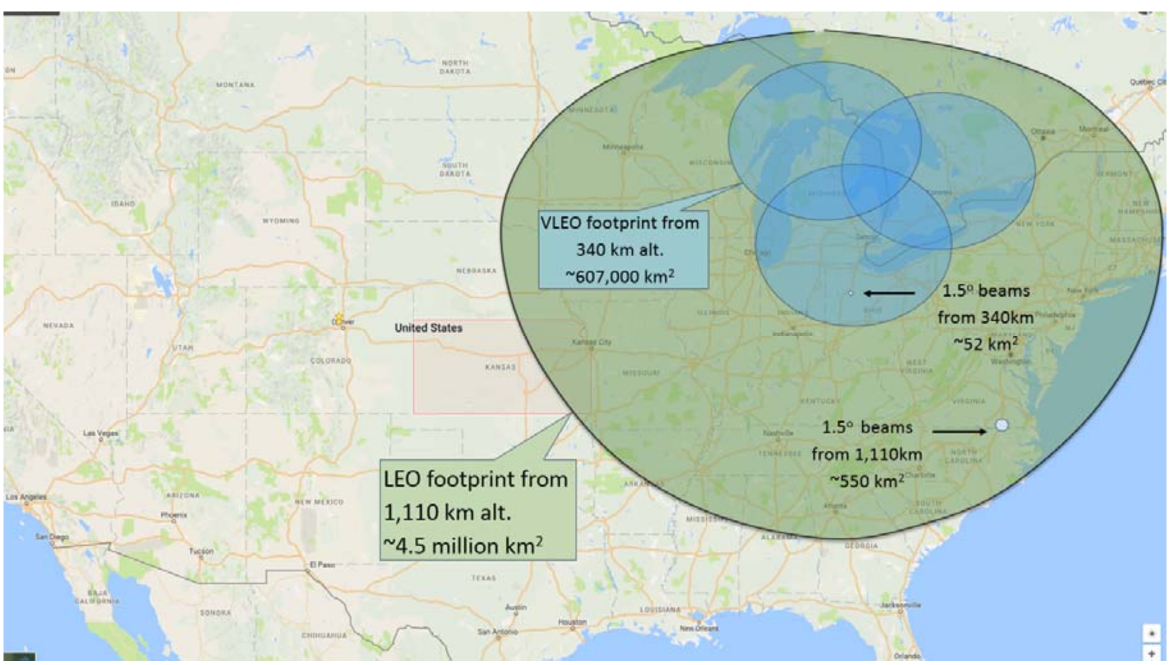

Figure A.2-1: Comparative Illustration of LEO and VLEO Coverage

Operating at an altitude of 1,110 km or more at inclinations ranging from 53 to 70 degrees, satellites in the LEO Constellation will have a relatively larger footprint, featuring narrow spot beams covering a relatively broad service area of approximately 4.5 million square kilometers. Because the VLEO Constellation operates at approximately one-third the altitude of the LEO Constellation, its satellites operate with spot beams that will cover less than one-tenth the area of the LEO Constellation's beams, but will map to the same grid. While more VLEO satellites must be deployed in this case, the result is substantially greater ability to reuse spectrum, enabling the VLEO Constellation to deliver more bandwidth to customers, more satellite diversity options,[4] or a combination of the two. In areas of denser population, the VLEO satellite may concentrate its bandwidth where needed to meet high demand, while the LEO Constellation continues to provide widespread coverage to all users within a broader area. In this way, the two constellations can work cooperatively to provide both dense and comprehensive coverage.

The advanced technology in each SpaceX satellite enables the two constellations to optimize coverage in a coordinated fashion when interoperating. Figure A.2-2 provides a simplified example where two LEO satellites and two VLEO satellites interoperate with overlapping coverage areas. The black dashed lines indicate the coverage footprint of each satellite, with a large number of narrow spot beams steerable within that area. Because all satellites are operating in the same V-band spectrum, they must avoid transmitting to a user location using the same frequency if the satellites appear to be "in line" from the user's point of view. For purposes of this illustration, we use 10 degrees to define the angular separation within which two

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[4] As explained by the Commission, "[w]ith satellite diversity, NGSO FSS systems can avoid an in-line interference event by selecting another visible satellite within their system constellation (performing a hand-over process) whenever the current satellite approaches the in-line event with a satellite operating in another NGSO FSS system constellation." *Establishment of Policies and Service Rules for the Non-Geostationary Satellite Orbit, Fixed Satellite Service in the Ka-Band*, 18 FCC Rcd. 14708, ¶ 44 (2003).

satellites cannot both provide service to the same user with the same frequency. Applying this principle, users in the areas denoted by the red and blue lines could not receive co-frequency signals from the S2H satellite and the S1L or S2L satellites, respectively.

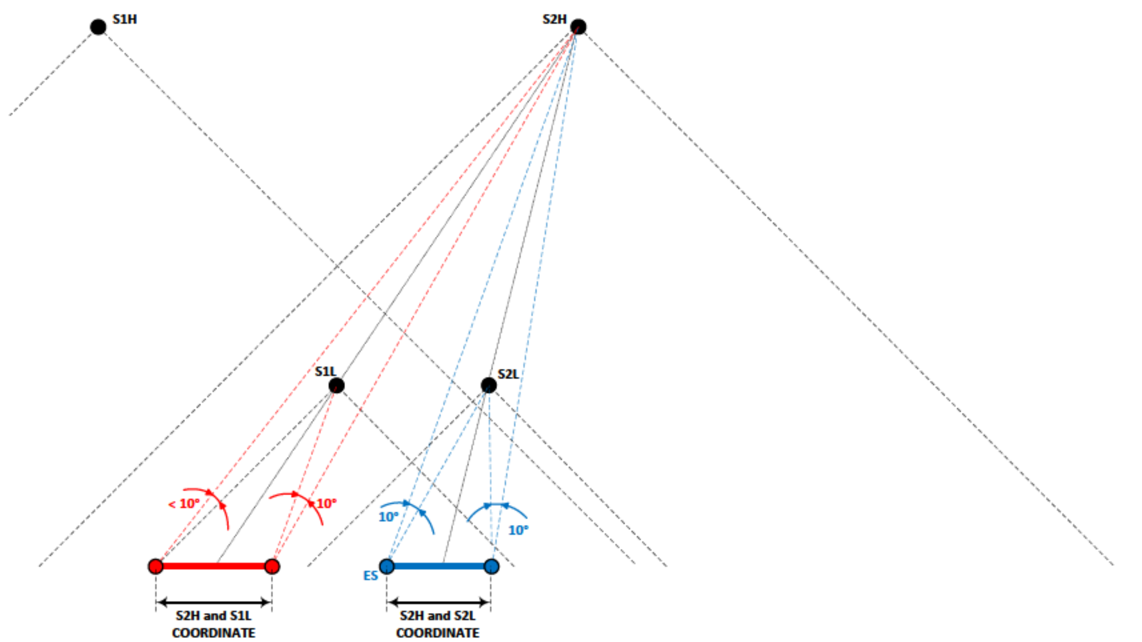

Figure A.2-2: Coordination of Service From LEO and VLEO Constellations

In this situation, the LEO and VLEO satellites could simply split the available V-band spectrum to serve the user. However, because each satellite has many steerable beams to use within its footprint, that flexibility allows unused frequencies/beams to shift to other locations to provide service, preventing valuable satellite capacity from going unused. In addition, because of the overlapping satellite coverage areas, SpaceX can direct beams from satellites that are not part of the in-line event where needed to address a capacity demand. Thus, if demand is high in the blue area of Figure A.2-2, SpaceX could serve it using beams from various configurations of satellites (S2H and S1L, S1H and S2H, or S1H and S2L).

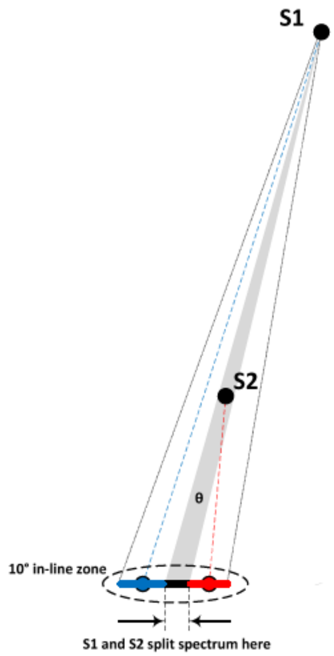

Figure A.2-3: Efficient Spectrum Split

Moreover, because the transmit and receive beams on each SpaceX satellite can discriminate between earth stations at different locations, the LEO and VLEO constellations can even work together to minimize the geographic area affected by an in-line event. Figure A.2-3 illustrates a case with a user within the 10 degree in-line zone of one LEO satellite and one VLEO satellite. Rather than split the spectrum across that entire zone, satellite S1 can operate with all frequencies to serve users to the West while satellite S2 does the same with respect to users to the East. This strategy significantly reduces the areas where the satellites are forced to operate on only half the available spectrum. For example, for a SpaceX satellite operating with 1.5° beamwidth, the area denoted as θ in the diagram (where spectrum splitting or some other strategy is still required) could be reduced to 3.5° while maintaining a C/I ≈ 25dB.

Thus, the V-band operations of the LEO and VLEO constellations will enhance the operations of the Ku/Ka-band system previously proposed in several ways. First, the increase in capacity, frequency availability, and frequency reuse dramatically increases the number of customers who can be served. Second, the increase in bandwidth available per user improves the quality of service, bringing more high-speed, low-latency broadband to unserved areas and injecting additional competition in areas where terrestrial alternatives are available. Third, as demonstrated above, the combination of satellites with narrow, steerable spot beams in higher and lower orbits creates opportunities to optimize spectrum use, which will reduce interference both within the SpaceX System and in coordination with other GSO and NGSO systems.

Spectrum

The V-band frequency ranges used by the SpaceX System are summarized in Table A.2-3 below. Figure A.2-4 provides a visual depiction of the spectrum used for gateway and user beams and for telemetry, tracking, and control ("TT&C") operations, along with an indication of the U.S. frequency allocations and designations that exist in these bands. A representative illustration of the detailed channelized frequency plan is provided in the associated Schedule S, and a comprehensive specification is included in the Technical Database submitted herewith.

Type of Link and Transmission Direction	**Frequency Ranges**
Downlink Channels Satellite to User Terminal or Satellite to Gateway	37.5 – 42.5 GHz
Uplink Channels User Terminal to Satellite or Gateway to Satellite	47.2 – 50.2 GHz 50.4 – 52.4 GHz
TT&C Downlink Beacon	37.5 – 37.75 GHz
TT&C Uplink	47.2 – 47.45 GHz

Table A.2-3: Frequency Bands Used by the SpaceX System

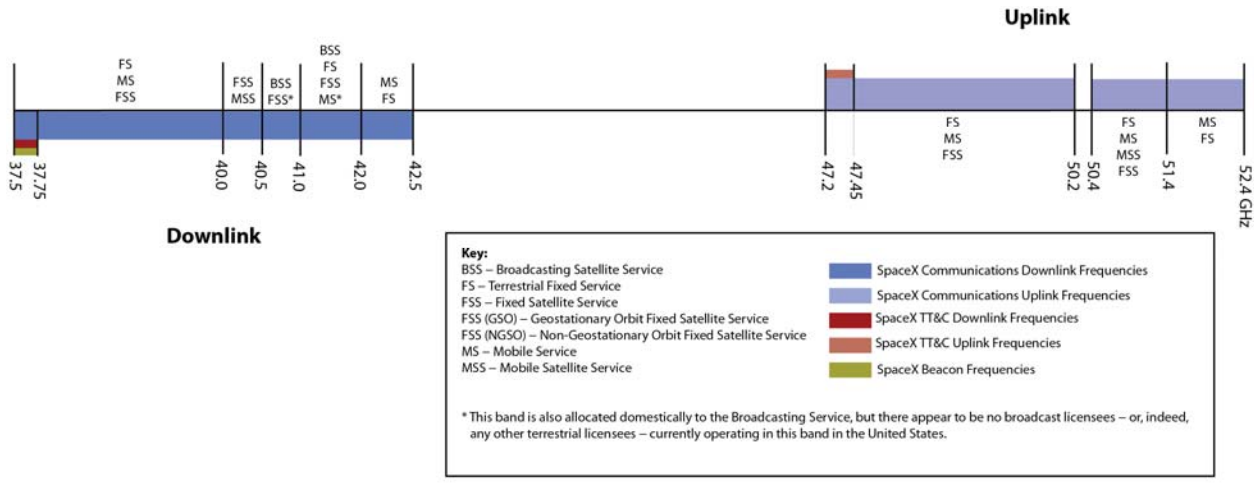

Figure A.2-4: V-Band Spectrum Used by the SpaceX System

SpaceX recognizes that not all of the frequencies that it proposes to use are designated in the United States for use by NGSO FSS systems on a primary basis. As discussed below, SpaceX believes that its system can operate without causing harmful interference to or requiring protection from any other service duly licensed in these bands with higher priority.[5]

A.3 PREDICTED SPACE STATION ANTENNA GAIN CONTOURS

All satellites in each of the two SpaceX System constellations have been designed with the same V-band transmit and receive antenna beams. The antenna gain contours for the beams of representative space stations in each constellation, which are essentially the same for satellites operating in all planes and altitudes within that constellation, are embedded in the associated Schedule S and in the Technical Database submitted herewith. Below we describe the methodology for their presentation therein.

A.3.1 User and Gateway Beams

For both the LEO and VLEO Constellations, all downlink spot beams on each satellite are independently steerable over the full field of view of the Earth. However, user terminals and gateways communicate only with satellites at an elevation angle of at least 35 degrees. Consequently, as shown in Figure A.3.1-1 below, each satellite in the LEO Constellation, operating at an altitude of 1,150 km, will provide service only up to 43.95 degrees away from boresight (nadir), while each satellite in the VLEO Constellation operating at 335.9 km will provide service only up to 51.09 degrees from boresight as shown in Figure A.3.1-2.[6]

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[5] Where appropriate, SpaceX has requested waivers for non-conforming use of spectrum.

[6] While the 35 degree minimum elevation angle remains the same from the earth station point of view, the

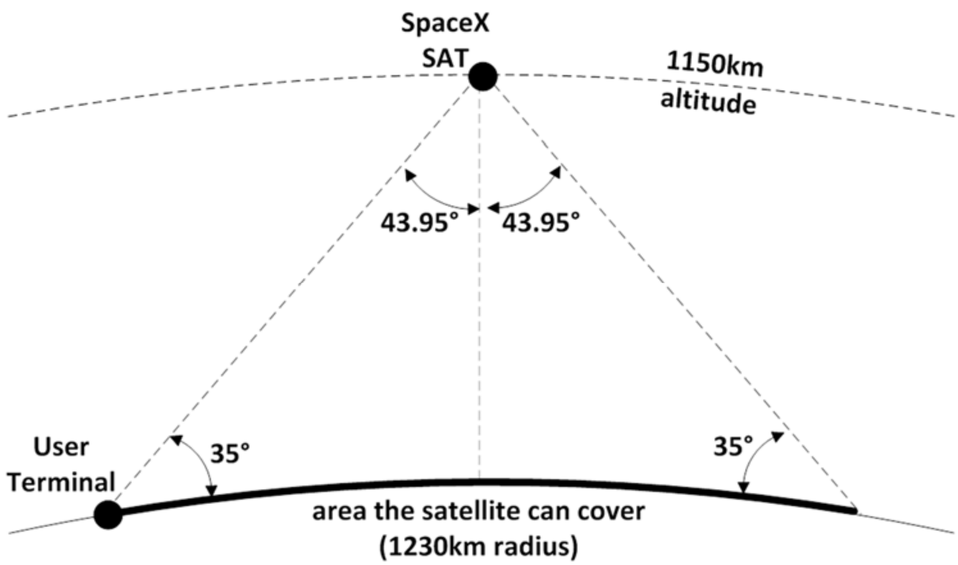

Figure A.3.1-1: Steerable Service Range of LEO Beams (1,150 km)

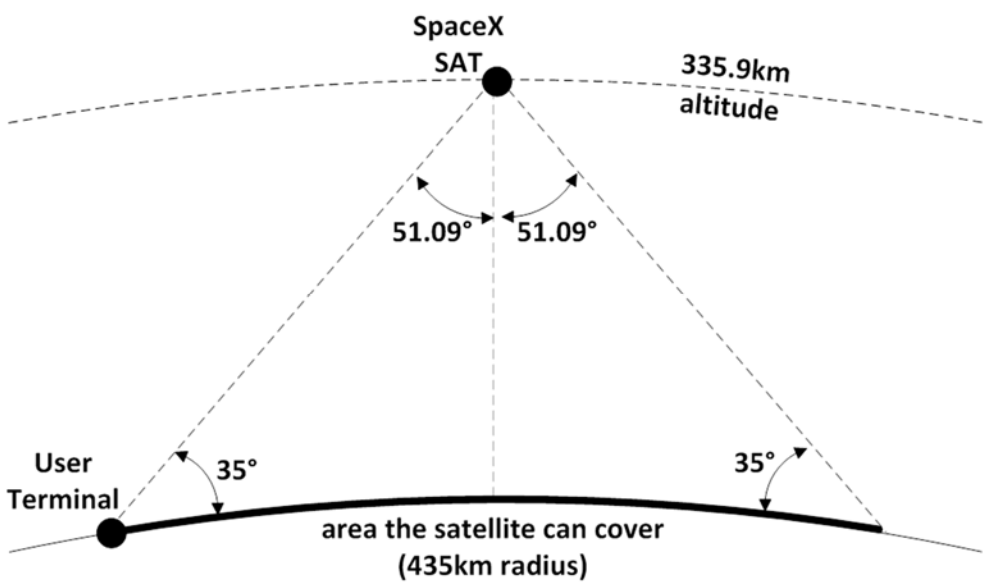

Figure A.3.1-2: Steerable Service Range of VLEO Beams (335.9 km)

User and gateway beams use narrow beamwidths of 1.5 and 1.0 degrees, respectively. These beams will be divided into channels that are a multiple of 7.8125 MHz which, depending on

maximum angle from boresight at which service can be provided from the satellite changes slightly depending upon altitude. Thus, for example, satellites operating at 1,110 km, 1,130 km, 1,275 km, and 1,325 km altitude can provide service up to 44.24, 44.10, 43.05, and 42.71 degrees away from boresight, respectively.

utilization and other factors, may be bonded into channels as large as 1 GHz. Each satellite can transmit two beams at the same frequency (with right hand and left hand circular polarization ("RHCP and LHCP")), but may use only one or the other in specific circumstances.

Generally, beams from antennas using phased arrays widen incrementally as they are steered away from boresight.[7] However, this widening occurs only in the plane formed by boresight and the center of the beam ("elevation"), and not in the plane normal to that plane formed by boresight and the center of the beam ("azimuth"). As a result, the shape of a phased array beam at boresight is circular but becomes increasingly elliptical when steered away from boresight. Figures A.3.1-3 through A.3.1-5 provide beam contours that illustrate beamwidth changes when user and gateway beams are steered to 0, 20, and 40 degrees away from nadir, in each case at a roll off of -2 dB, -4 dB, -6 dB, -8 dB, -10 dB, -15 dB, and -20 dB. These contours apply to both uplink and downlink beams for both constellations, though the actual size of the beam on the Earth will be far different as illustrated in Figure A.2-1.

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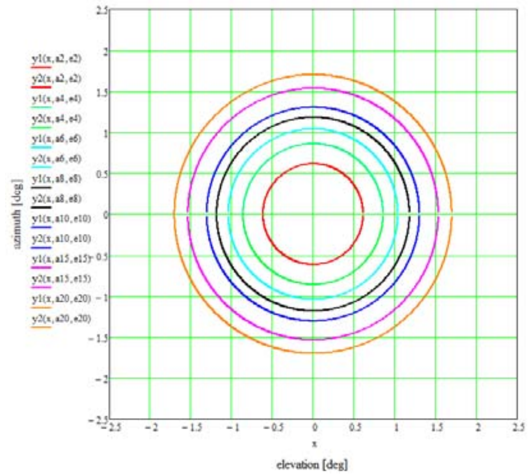
[7] For this purpose, we use "boresight" to refer to the direction normal to the phased array plane.

Figure A.3.1-3: Beam Contours at 0 Degrees Elevation (Nadir)

User (1.5 Degree Beamwidth)



Gateway (1.0 Degree Beamwidth)

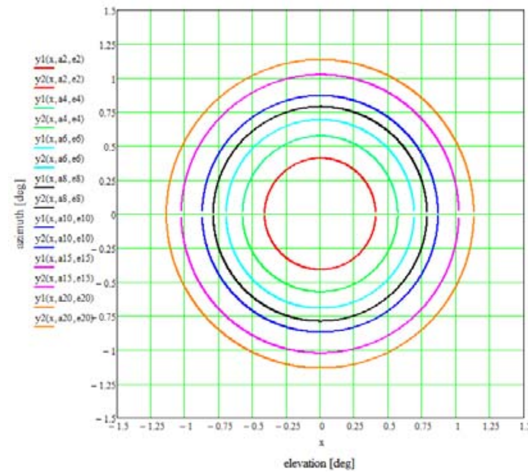
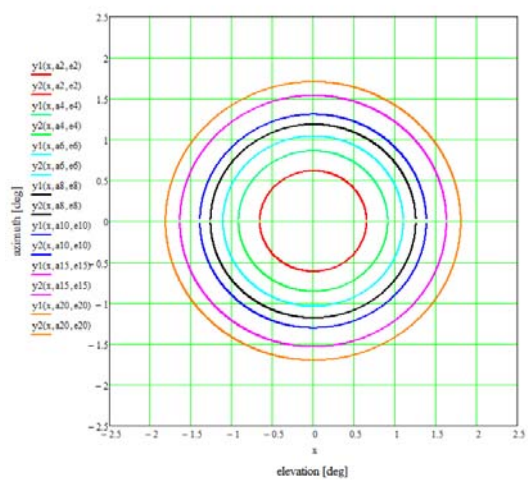


Figure A.3.1-4: Beam Contours at 20 Degrees Elevation

User (1.5 Degree Beamwidth)



Gateway (1.0 Degree Beamwidth)

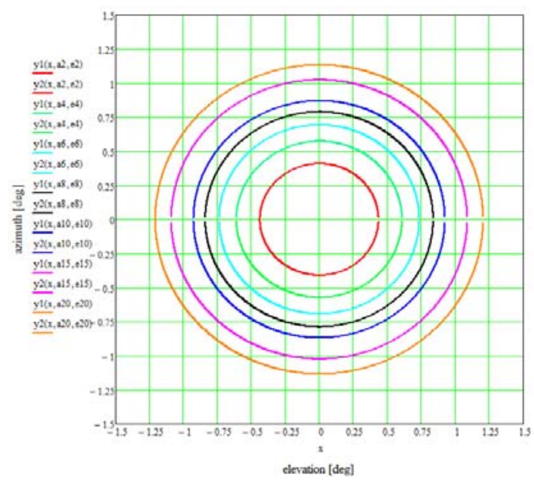
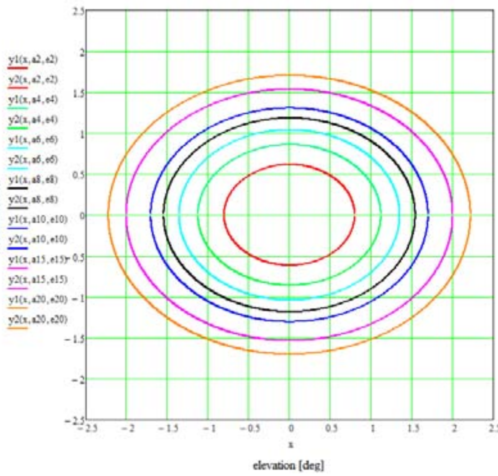
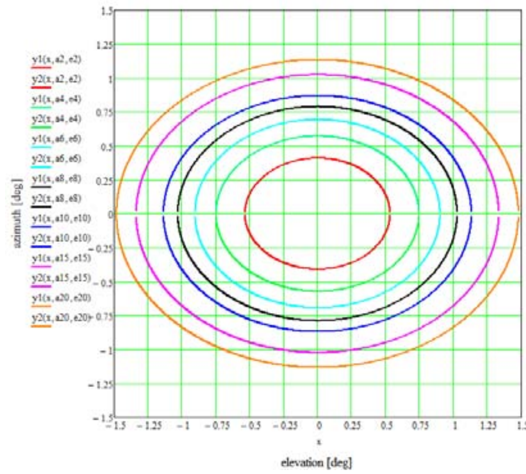


Figure A.3.1-5: Beam Contours at 40 Degrees Elevation

User (1.5 Degree Beamwidth) **Gateway (1.0 Degree Beamwidth)**





The intended coverage area for each user beam is a cell inside the -3 dB contour, as illustrated in Figure A.3.1-6 below. At a given frequency, only a single beam (with either RHCP or LHCP) typically would cover a user cell on the ground. Alternatively, two beams (one with RHCP and one with LHCP) can cover a single user cell on the ground at a given frequency, but in this case their equivalent isotropically radiated power ("EIRP") will be reduced by 3 dB to maintain the same power flux-density ("PFD") (see below).

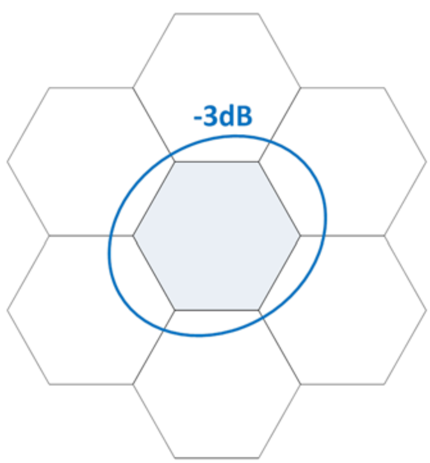


Figure A.3.1-6: Intended Beam Coverage Area

As the transmitting beam is steered, the power is adjusted to maintain a constant PFD at the surface of the Earth, compensating for variations in antenna gain and path loss associated with the steering angle. Figures A.3.1-7 and A.3.1-8 below illustrate this relationship for the LEO and VLEO satellites, respectively. The highest EIRP density (29.91 dBW/MHz for LEO and 20.21 dBW/MHz for VLEO) for both user and gateway beams occurs at maximum slant.

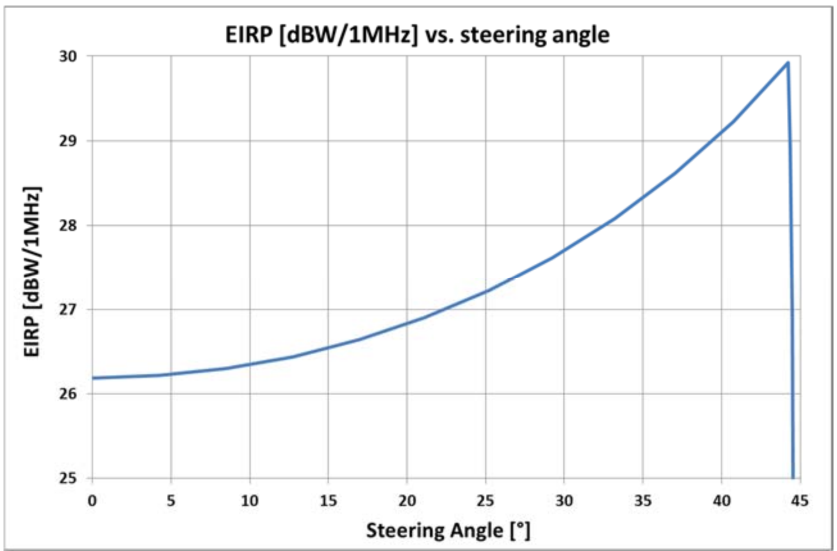


Figure A.3.1-7: LEO EIRP Density Variation by Beam Steering Angle

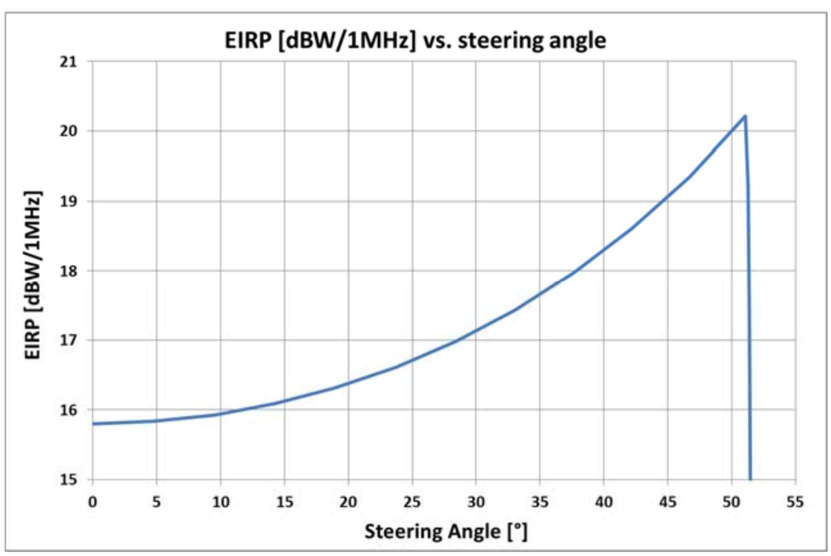


Figure A.3.1-8: VLEO EIRP Density Variation by Beam Steering Angle

When both polarizations are used simultaneously on the same spot on the ground, the maximum EIRP above is reduced by 3 dB to maintain a constant PFD at the surface of the Earth.

For receiving beams, the antenna gain drops slightly as the beam slants away from nadir. As a result, for user and gateway uplink beams for satellites in both constellations, the maximum G/T (12.8 dB/K and 14.3 dB/K, respectively) occurs at nadir, while the minimum G/T (10.8 dB/K and 12.3 dB/K, respectively) occurs at maximum slant.[8]

A.3.2 Beacon Beams (Downlink)

Satellites in both the LEO and VLEO Constellations will use spectrum in the 37.5-37.75 GHz band for beacons to facilitate rapid satellite acquisition by earth station antennas and smooth handovers from satellite to satellite. Each beacon beam would support multiple 1-MHz modulated beacon channels on each polarization – one LHCP beam and one RHCP beam – though these may be bonded into channels as large as 10 MHz. Because the spectrum used for these beacons will overlap with the TT&C channels and the user/gateway communication channels, their usage will be carefully coordinated so as to prevent transmission where the beacon frequencies would also be used for other links (which could result in self-interference) and to observe applicable regulatory limits.

Each beacon beam used in the LEO and VLEO Constellation will have a maximum EIRP of 7 dBW/MHz and -2.8 dBW/MHz, respectively, with the following gain contours:

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8 Section 25.114(c)(4)(v) requires both the minimum and maximum saturation flux density ("SFD") values for each space station receive antenna that is connected to transponders. The concept of SFD only applies to "bent pipe" satellite systems, and thus is not relevant to the SpaceX System. However, because the Schedule S software requires a numerical entry for SFD (which must be different for maximum and minimum), SpaceX has entered values of "0" and "-0.1."

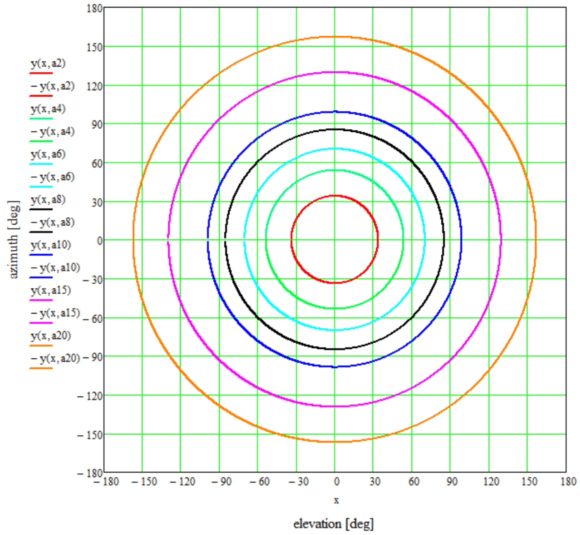

Figure A.3.2-1: LEO Beacon Beam Gain Contours

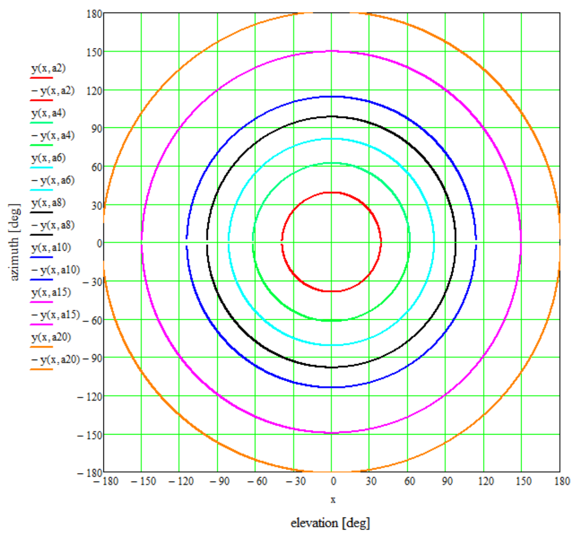

Figure A.3.2-2: VLEO Beacon Beam Gain Contours

A.3.3 TT&C Beams

The SpaceX System conducts its tracking, telemetry and control functions using omni-directional antennas on each satellite that are designed to communicate with earth stations at virtually any attitude (95% lowest of the 4 pi steradian antenna-gain sphere). The maximum transmit EIRP density, maximum and minimum G/T for receiving beams, and diagrams of the antenna gain contours are provided with the associated Schedule S and Technical Database submitted herewith. Communication to and from the TT&C earth stations will operate at an elevation above the local horizon of 5 degrees or higher.[9]

Each satellite will perform TT&C functions in the 250 MHz of uplink and downlink spectrum in the 37.5-37.75 GHz (down) and 47.2-47.45 GHz (up) bands. Each TT&C beam would support multiple 1-MHz modulated channels on each polarization – one LHCP beam and one RHCP beam – though these may be bonded into channels as large as 10 MHz. Because these TT&C operations will overlap with the beacon channels and the user/gateway communication channels, their usage will be carefully coordinated to avoid self-interference and to observe applicable regulatory limits.

A.4 TT&C CHARACTERISTICS

The SpaceX TT&C operations communicate with spacecraft during pre-launch, transfer orbit, and on-station operations, as well as during spacecraft emergencies.[10] During all phases of the mission, TT&C operations will use the following frequencies:

- For space-to-Earth: 37.5-37.75 GHz.
- For Earth-to-space: 47.2-47.45 GHz.

TT&C operations will cause no more interference and require no greater protection than the ordinary communications traffic in those bands, in compliance with the requirements of Section 25.202(g). SpaceX will use primary and back-up TT&C ground station facilities at two locations within the United States – one on the East coast and one on the West coast – with additional TT&C

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9 *See* 47 C.F.R. § 25.205(a) (establishing presumption that Earth station antennas normally will not be authorized for transmissions at elevation angles less than five degrees).

10 The information provided in this section complements that provided in the associated Schedule S and Technical Database. In addition, TT&C for the LEO Constellation would also include the capabilities discussed in the Ku/Ka Technical Supplement.

ground station facilities at locations distributed internationally.

A.5 GEOGRAPHIC COVERAGE

Section 25.143(b)(2) sets the default geographic coverage requirements for all NGSO systems where band-specific rules do not apply.[11] That provision includes both an international and a domestic requirement. First, the system must have at least one satellite that would be visible above the horizon at an elevation angle of at least 5 degrees for at least 18 hours each day, for any location between 70 degree north latitude and 55 degree south latitude. Second, the system must have at least one satellite that would be visible above the horizon at an elevation angle of at least 5 degrees at all times throughout the fifty states, Puerto Rico, and the U.S. Virgin Islands. At Final Deployment, the SpaceX System will meet this requirement.[12]

A.6 CESSATION OF EMISSIONS

Each active satellite transmission chain (channel amplifiers and associated solid state power amplifier) can be individually turned on and off by ground telecommand, thereby causing cessation of emissions from the satellite, as required by Section 25.207 of the Commission's rules.

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[11] *See* 47 C.F.R. § 25.217 (identifying default rules for NGSO operations in frequencies without band-specific rules, including Section 25.143(b)(2)(ii) and (iii)).

[12] SpaceX is requesting a partial waiver of the final system implementation milestone such that it would apply to the Initial Deployment only. Although SpaceX fully expects to meet all coverage requirements at Final Deployment, out of an abundance of caution, SpaceX is also requesting a corresponding waiver of the geographic service requirements for the operation of the Initial Deployment, to the extent the Commission deems it necessary.

A.7 COMPLIANCE WITH PFD LIMITS

As discussed herein, the SpaceX System has a variety of attributes that facilitate spectrum sharing, including narrow, steerable spot beams, operations at high elevation angles, and the ability to provide service from multiple satellites with overlapping coverage contours. These can be used in particular cases to address interference concerns with other licensed users. In addition, both the Commission and the ITU have established limits on the PFD of satellite downlink transmissions at the surface of the Earth in order to protect terrestrial systems operating in certain V-band frequencies. The application of these limits to the SpaceX System is discussed below.

The downlink user and gateway beams on each SpaceX satellite are designed to transmit only for angles of arrival between 35 degrees and 90 degrees above the horizontal plane (*i.e.*, to be received by earth stations at an elevation angle of 35 degrees or more). In addition, the system maintains a constant PFD at the surface of the Earth by adjusting the transmit power between slant and nadir depending on the angle of arrival. This accounts for variations in antenna gain with the steering angle and beam shaping and in dispersion loss when the angle of arrival changes. Table A.7-1 below shows the PFD calculations for the LEO Constellation at the surface of the Earth, both at the maximum slant of a 35 degree angle of arrival and at the nadir of a 90 degree angle of arrival, using the worst case altitude of 1,110 km.

	at slant	at nadir
EIRP density [dBW/Hz]	-30.09	-33.82
EIRP in 1 MHz [dBW/MHz]	29.91	26.18
Distance to Earth [km]	1,705.89	1,110.00
Spreading loss [dB]	-135.63	-131.90
PFD in 1 MHz [dB(W/m^2/1MHz)]	-105.72	-105.72

Table A.7-1: LEO PFD at the Surface of the Earth

Table A.7-2 presents similar calculations for the VLEO Constellation, using the worst case altitude of 335.9 km.

	at slant	at nadir
EIRP density [dBW/Hz]	-39.79	-44.20
EIRP in 1MHz [dBW/MHz]	20.21	15.80
Distance to Earth [km]	558.42	335.90
Spreading loss [dB]	-125.93	-121.52
PFD in 1 MHz [dB(W/m^2/1MHz)]	-105.72	-105.72

Table A.7-2: VLEO PFD at the Surface of the Earth

When both polarizations are used simultaneously on the same spot on the ground, the maximum EIRP above is reduced by 3 dB to maintain a constant PFD at the surface of the Earth. SpaceX also has the ability to manage the satellites' PFD levels during all phases of the mission, because the satellite downlink transmit power is adjustable on-orbit. Further, inter-satellite links enable the management of traffic on-orbit to ensure that communications are not interrupted while using any of the interference mitigation techniques discussed herein.

Under both the international and domestic allocation tables, the 37.5-42.0 GHz band is allocated on a co-primary basis to FSS (space-to-Earth) operations.[13] Nearly 20 years ago, however, the Commission concluded that this band could not feasibly be shared between terrestrial wireless service and FSS terminals. Accordingly, the Commission adopted a "soft segmentation" plan. Under this plan, the Commission sought to encourage FSS operators to use spectrum above 40 GHz by imposing a lower PFD limit in the 37.5-40.0 GHz band than allowed under the international limit and restricting downlink operations in that band to only gateway earth stations.[14]

Specifically, the Commission's downlink PFD limits in the 37.5-40.0 GHz band are set forth in Section 25.208(r) as follows:

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13 Although the international allocation table extends the co-primary allocation for FSS downlinks to the 42.0-42.5 GHz band as well, there currently is no corresponding FSS allocation in that band under the Commission's rules. Accordingly, while the ITU has adopted PFD limits for this band, the Commission has not.

14 *See Allocation and Designation of Spectrum for Fixed-Satellite Services in the 37.5-38.5 GHz, 40.5-41.5 GHz and 48.2-50.2 GHz Frequency Bands*, 18 FCC Rcd. 25428, ¶ 23 (2003).

- -132 dB(W/m^2) in any 1 MHz band for angles of arrival between 0 and 5 degrees above the horizontal plane;
- $-132+3(\delta-5)/4$ dB(W/m^2) in any 1 MHz band for angles of arrival δ (in degrees) between 5 and 25 degrees above the horizontal plane; and
- -117 dB(W/m^2) in any 1 MHz band for angles of arrival between 25 and 90 degrees above the horizontal plane.

The ITU PFD limits for this band (and for the 42.0-42.5 GHz band), set forth in Article 21, Table 21-4 of the Radio Regulations, are 12 dB higher in each instance (*i.e.*, ranging from -120 dB(W/m^2) to -105 dB(W/m^2)).

The Commission's downlink PFD limits for the 40.0-40.5 GHz and 40.5-42.0 GHz bands are set forth in Section 25.208(s) and (t) as follows:

- -115 dB(W/m^2) in any 1 MHz band for angles of arrival between 0 and 5 degrees above the horizontal plane;
- $-115+(\delta-5)/2$ dB(W/m^2) in any 1 MHz band for angles of arrival δ (in degrees) between 5 and 25 degrees above the horizontal plane; and
- -105 dB(W/m^2) in any 1 MHz band for angles of arrival between 25 and 90 degrees above the horizontal plane.

The ITU PFD limits applicable to NGSO systems operating in these bands, which are provided in Table 21-4 of the ITU Radio Regulations, are the same as the Commission's PFD limits described above.

Figures A.7.1 and A.7.2 below depict the PFD created by the LEO Constellation and VLEO Constellation, respectively, as they relate to each of these PFD limits.

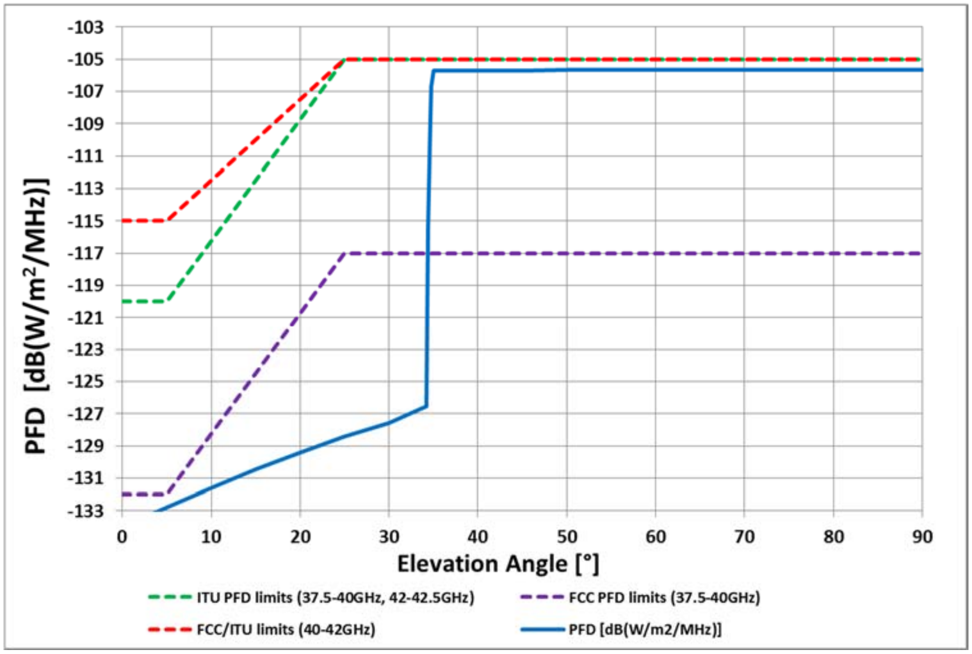

Figure A.7-1: LEO Constellation Downlink PFD Levels in the 37.5-42.5 GHz Band

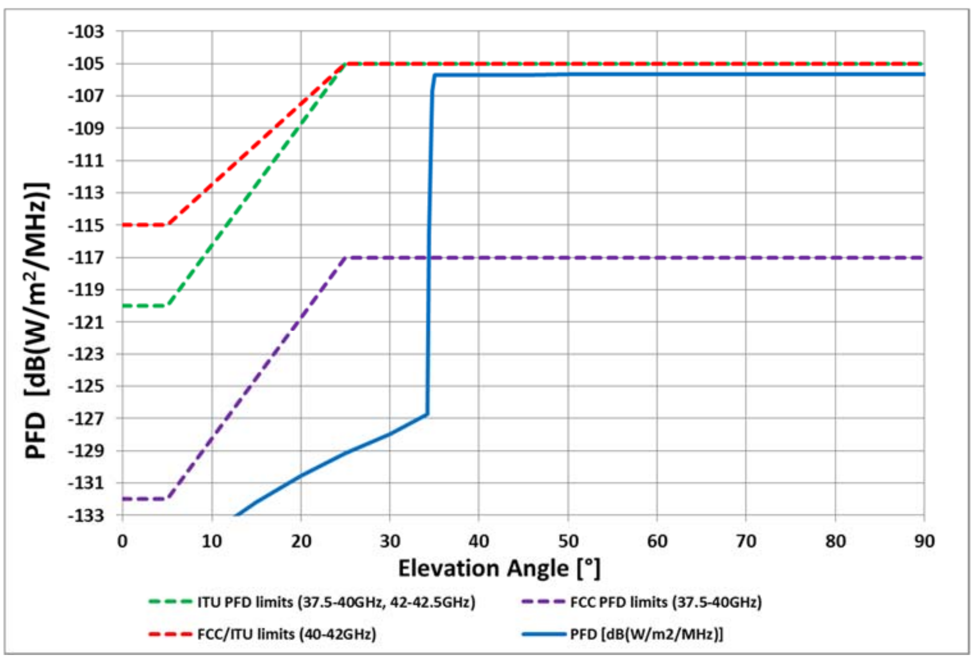

Figure A.7-2: VLEO Constellation Downlink PFD Levels in the 37.5-42.5 GHz Band

SpaceX seeks to use this spectrum band for downlink communications to user terminals, gateways, and TT&C facilities. Accordingly, the plots in Figures A.7-1 and A.7-2 show a worst case combined PFD for transmissions to users, gateways, and TT&C facilities (including beacons). The figures reflect the fact that the system adjusts power levels to maintain a consistent PFD level for transmissions above the minimum 35 degree elevation angle used for regular operations. The PFD drops sharply at lower elevation angles, as only side lobes and low power beacon/TT&C signals are found there.

As the figures also show, the SpaceX System will comply with the Commission and ITU PFD limits in the 40.0-42.0 GHz band, and with the higher ITU limits applicable in the 37.5-40.0 GHz band. As explained in the attached waiver request, application of these ITU limits would better serve the public interest than would using the Commission's unnecessarily restrictive limits imposed under Section 25.208(r). Note that the system would also comply with the ITU PFD limits in the 42.0-42.5 GHz band, where the Commission has not imposed similar limits.

A.8 INTERFERENCE ANALYSES

As shown in Figure A.2-4 above, the V-band frequency ranges SpaceX proposes to use are shared with other services in the U.S. table of frequency allocations. The SpaceX System design has been engineered to achieve a high degree of flexibility in order to facilitate spectrum sharing and to protect other authorized satellite and terrestrial systems in compliance with U.S. and international regulations and under reasonable coordination arrangements. For example, the system has the following attributes:

- *Operation at high elevation angles.* The SpaceX System constellation is designed to provide service at minimum operational elevation angles of 35 degrees for all gateway and user earth stations. This will minimize the cases in which transmissions would be expected to affect terrestrial systems.
- *Highly directional space station and earth station beams.* SpaceX satellites use narrow,

steerable spot beams that can be directed away from potential areas of interference. Similarly, the earth stations used to communicate with the SpaceX System will operate with aperture sizes that enable narrow, highly-directional beams with strong sidelobe suppression. Combined with the fact that these beams will be steered to track NGSO satellites at elevation angles of at least 35 degrees, the system will provide significant off-axis isolation to other GSO and NGSO satellites. This will ensure that interference to other satellite systems could only occur in cases where there is an in-line event for satellites from each system.

- *Ability to select from multiple visible satellites for service.* The SpaceX System will provide multiple NGSO satellites in the field of view of any given earth station, providing the advantages of satellite diversity. The number of satellites in view will depend on the geographic location and the phase of deployment of the SpaceX System. Where appropriate, the system will have the intelligence to select the specific satellite that would avoid a potential in-line interference event with GSO and other NGSO operations.

Applying these and other sharing mechanisms, SpaceX is confident that it can successfully coordinate its system with other authorized satellite and terrestrial networks.[15]

A.8.1 Interference with Respect to Terrestrial Networks

Downlink Bands

Under both the international and domestic allocation tables, the 37.5-42.0 GHz band is allocated on a co-primary basis to FSS (space-to-Earth) operations. As explained in Section A.7,

[15] In addition, as discussed above, these same attributes give SpaceX the flexibility to coordinate its own operations so as to optimize the combined performance of the LEO and VLEO Constellations while avoiding self-interference.

however, the Commission nearly 20 years ago adopted a "soft segmentation" plan under which the PFD limit in the 37.5-40.0 GHz band is 12 dB lower than the international limit and downlink operations in that band are restricted to only gateway earth stations.[16] SpaceX seeks to use this spectrum for downlink communications to both user terminals and gateways.

SpaceX earth stations receive in this band, and are designed to reject signals that do not fall within the minimum 35 degree service angle. In the unlikely event that SpaceX earth stations experience interference from terrestrial activity, there are several options available to mitigate that interference. For example, SpaceX earth stations could preferentially communicate with satellites less likely to be affected by terrestrial operations, increase the minimum elevation angle used in that area, apply earth station shielding, or any combination of these options. SpaceX is confident that it would be able employ such strategies to protect its earth stations and share this spectrum with terrestrial systems.

Satellite downlink transmissions could potentially affect terrestrial systems operating in the 37.5-42.5 GHz band.[17] In order to assess the likely impact of these transmissions, we must analyze both fixed and mobile systems. With respect to FS, both transmitters and receivers use highly-directional antennas, typically in the 0.2 to 0.5 meter range, with high gain and directivity along a near-horizontal link. As a consequence, terrestrial FS transmitters will typically provide a high level of receive isolation to the satellite downlink transmissions operating at an elevation angle of at least 35 degrees.

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[16] Both of those restrictions are currently under review by the Commission. *See Use of Spectrum Bands Above 24 GHz for Mobile Radio Services et al.*, Report and Order and Further Notice of Proposed Rulemaking, 31 FCC Rcd. 8014, ¶¶ 492-502 (2016) ("*Spectrum Frontiers Order and FNPRM*").

[17] There are no existing non-federal FS licenses effective in the 37.5-38.6 GHz or the 40.0-42.5 GHz bands. There are a limited number of licenses outstanding for the 39 GHz Fixed Service, operating in the 38.6-40.0 GHz band, as well as a very small number of nationwide common carrier licenses in the 39.5-40.0 GHz band.

Tables A.8.1-1 and A.8.1-2 summarize an analysis of V-band spectrum (39 GHz) sharing between the SpaceX System and FS systems with various characteristics. In both tables, the analysis covers FS receive antennas ranging in diameter from 0.2 to 0.5 meters, and uses the antenna gain and antenna rejection values drawn from ITU reference patterns.[18] Both also assume that SpaceX is operating its satellites at the maximum PFD allowed for high elevation angles under the ITU limits (-105 dBW/m^2/MHz), and that the FS receiver noise floor is -139 dBW/MHz. The analyses then assess potential interference with respect to a range of separation angles between the desired FS beam and the satellite beam. Because the SpaceX System operates its user and gateway downlinks with a minimum angle of 35 degrees, Table A.8.1-1 analyzes separation angles of 35 degrees and greater than 50 degrees, which should be the most relevant assuming that most FS links will be pointed horizontally.

FS Rx Antenna Diameter [m]	0.20		0.30		0.40		0.50	
FS Rx Antenna Gain [dB]	36.00		39.52		42.02		43.96	
FS Rx Antenna aperture [m^2]	0.02		0.04		0.07		0.12	
Separation angle [deg]	35.00	>50.00	35.00	>50.00	35.00	>50.00	35.00	>50.00
FS Rx Antenna Rejection [dB]	36.75	40.15	42.03	45.43	45.78	49.18	48.69	52.09
SAT Interference [dBW/MHz]	-159.02	-162.42	-160.78	-164.18	-162.03	-165.43	-163.00	-166.40
Interference / Noise [dB]	-20.02	-23.42	-21.78	-25.18	-23.03	-26.43	-24.00	-27.40
(I + N) Floor [dBW/MHz]	-138.96	-138.98	-138.97	-138.99	-138.98	-138.99	-138.98	-138.99
Desense [dB]	0.04	0.02	0.03	0.01	0.02	0.01	0.02	0.01

Table A.8.1-1: Analysis of Sharing Between SpaceX Downlinks and FS Systems at Expected Elevation Angles

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[18] *See* Recommendation ITU-R F.699-7, "Reference radiation patterns for fixed wireless system antennas for use in coordination studies and interference assessment in the frequency range from 100 MHz to about 70 GHz."

As this analysis shows, SpaceX's operations should have a negligible effect (no greater than 0.04 dB) on FS systems in the band operating under expected conditions. However, in order to demonstrate the absence of interference even in a worst case (*e.g.*, where the FS antenna is pointing at an elevated angle or where there are unusual reflections from the surrounding terrain), Table A.8.1-2 sets forth an analysis of the impact at lower separation angles of 15 and 25 degrees as well.

FS Rx Antenna Diameter [m]	0.20		0.30		0.40		0.50	
FS Rx Antenna Gain [dB]	36.00		39.52		42.02		43.96	
FS Rx Antenna aperture [m^2]	0.02		0.04		0.07		0.12	
Separation angle [deg]	15.00	25.00	15.00	25.00	15.00	25.00	15.00	25.00
FS Rx Antenna Rejection [dB]	27.55	33.10	32.83	38.38	36.58	42.13	39.49	45.04
SAT Interference [dBW/MHz]	-149.82	-155.37	-151.59	-157.13	-152.83	-158.38	-153.80	-159.35
Interference / Noise [dB]	-10.82	-16.37	-12.59	-18.13	-13.83	-19.38	-14.80	-20.35
(I + N) Floor [dBW/MHz]	-138.65	-138.90	-138.77	-138.93	-138.82	-138.95	-138.86	-138.96
Desense [dB]	0.35	0.10	0.23	0.07	0.18	0.05	0.14	0.04

Table A.8.1-2: Analysis of Sharing Between SpaceX Downlinks and FS Systems at Worst Case Elevation Angles

As this analysis demonstrates, the SpaceX System will have a *de minimis* impact on terrestrial fixed systems, with no more than a 0.35 dB effect on small antennas even under worst case assumptions.

Next, we analyze the potential impact of SpaceX's operations on mobile wireless systems operating in the 37.5-42.5 GHz downlink band. The Commission recently added a mobile allocation and service rules to the 37.5-40.0 GHz band for use by the new Upper Microwave

Flexible Use Service ("UMFUS").[19] In order to assess potential interference to terrestrial mobile systems, we must look at base stations and mobile users separately.

At these high frequencies, mobile base stations likely will use dynamic beamforming techniques to produce narrow beams for communications with mobile handsets.[20] In addition, one can assume that "such stations' antennas will be tilted downward at a slight angle, typically from a street lamp pole or a location on a building at a similar height," as "this configuration is necessary not only to direct transmissions toward user equipment but also to limit interference between adjacent cellular base stations."[21] As a consequence, terrestrial transmitters will typically provide a high level of receive isolation to the satellite downlink transmissions operating at an elevation angle of at least 35 degrees.

Table A.8.1-3 provides an analysis of V-band spectrum sharing between the SpaceX System and a mobile base station with characteristics that should be typical for this band. As noted in the footnotes to the table, many of the parameters used in the analysis are drawn from documents recently submitted to ITU working parties that are examining the compatibility of satellite and mobile systems in these bands, as is the assumption that the base station antenna operates with a ten degree downtilt.[22] The analysis also assumes that SpaceX is operating its satellites at the maximum PFD allowed for high elevation angles under the ITU limits (-105 dBW/m^2/MHz). In

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19 *Spectrum Frontiers Order and FNPRM*, ¶¶ 76, 105.

20 *See id.*, ¶ 65.

21 *Id.*

22 *See* Document 5D/XYZ-E, XX February 2017, DEPLOYMENT-RELATED PARAMETERS FOR IMT-2020 TO BE USED IN SHARING AND COMPATIBILTY STUDIES FOR WRC-19 AGENDA ITEM 1.13, ATTACHMENT 4.11, Document 5D/TEMP/184, WORKING DOCUMENT ON SHARING PARAMETERS TOWARDS A DRAFT LIAISON STATEMENT TO TASK GROUP 5/1, Characteristics of terrestrial IMT systems for frequency sharing/interference analyses in the frequency range between 24.25 GHz and 86 GHz ("Document 5D/XYZ-E").

order to examine the worst case scenario, the analysis further assumes that the base station beam is pointed at boresight,[23] that the satellite signal comes straight into the main beam of the base station antenna, and that there is no attenuation from the atmosphere or ground clutter.

Frequency [GHz]	38
Wavelength λ [m]	0.0079
BS Noise Figure [dB]	12.00[24]
BS Noise Floor [dBW/Hz]	-191.98
BS Antenna Physical Aperture Area [m^2]	0.00199[25]
BS Antenna Aperture Efficiency [%]	60%
BS Antenna Effective Aperture at Boresight [m^2]	0.00120
Interference PFD [dBW/m^2/Hz]	-165.00
Max Received Interference [dBW/Hz]	-194.22[26]
Max I/N (Interference at Boresight) [dBW/Hz]	-2.24
Worst Case Desense [dB]	**2.03**
Add'l Interference Rejection – Example [dB]	-10.00
BS Received Interference [dBW/Hz]	-204.22
I/N [dBW/Hz]	-12.24
Desense [dB]	**0.25**

Table A.8.1-3: Analysis of Sharing Between SpaceX Downlinks and Mobile Base Station

As the calculations above demonstrate, in the worst case, SpaceX's operations result in a 2.03 dB desensing of the mobile base station. In assessing this effect, however, it is important to remember that the analysis incorporates several assumptions that are highly unlikely to hold true

[23] In this context, we use boresight for the direction of the normal to the phased array plane. This assumption results in the maximum effective aperture and maximum gain, both of which increase the potential for interference. As the beam is steered away from boresight, the gain drops due to cosine loss (the illuminated area is reduced by the cosine of the angle between boresight and the beam direction) and also due to the antenna elements' gain drop.

[24] See Document 5D/427-E, 31 January 2017, REPLY LIAISON STATEMENT TO ITU-R WORKING PARTY 5D ON CHARACTERISTICS OF TERRESTRIAL IMT SYSTEMS FOR FREQUENCY SHARING/INTERFERENCE ANALYSIS IN THE FREQUENCY RANGE BETWEEN 24.25 GHZ AND 86 GHZ ("Document 5D/427-E").

[25] According to Document 5D/XYZ-E, the base stations are composed of up to 8 x 16 elements, ½ wavelength spacing. The physical aperture area of the base station antenna is estimated as 8*λ/2*16*λ/2.

[26] Received Interference [dB/Hz] = PFD [dB/m^2/Hz]+10*log(Effective Aperture [m^2]).

in the large majority of cases. For example, given the downtilt of the base station antenna and the 35 degree minimum elevation angle for service from SpaceX satellites, the satellite signal is extremely unlikely to come straight into the base station antenna's main beam. Moreover, to the extent the antenna is not pointing at boresight, it would not direct maximum gain and maximum effective aperture toward the satellite signal. In addition, given that both the base station beam and the satellite beam move around, any interference event will be transient in nature – especially given the relatively narrow beamwidth of the base station antenna.[27]

As shown in Table A.8.1-3, assuming just 10 dB in additional signal rejection would reduce the effect to 0.25 dB. This additional rejection could easily result from atmospheric attenuation of the satellite signal, which at V-band frequencies can be expected to be at least 0.5 dB (in a very dry area) and potentially much more, but was ignored in the calculation above. It could also occur if the base station antenna gain is lower than the value used in the calculation (*i.e.*, if it uses an array of less than 8 x 16 elements, or if the beam is steered away from boresight), or if that antenna uses linear polarization while the satellite signals use circular polarization (which alone would result in up to 3 dB rejection). And if the main beam of the antenna used in the calculation had angular separation of just 15 degrees from the direction of the satellite signal, that alone would be sufficient to achieve 10 dB greater rejection. Thus, it is much more likely that SpaceX will have a *de minimis* effect on mobile base stations in this band.

The analysis of the effect upon mobile user stations is similar. Here again, the analysis uses parameters from the ITU study group materials and incorporates the worst case assumptions that SpaceX is operating its satellites at the maximum PFD allowed for high elevation angles under

[27] We can estimate the peak gain as 23.83dB (calculated from Gain = 4π*effective_aperture/λ^2), and use that to estimate the 3dB base station antenna beamwidth to be around 13 degrees, using the equation 3dB Beamwidth [rad] = $\sqrt{(4\pi/\text{Linear Gain})}$.

the ITU limits (-105 dBW/m^2/MHz), that the user station beam is pointed at boresight, that the satellite signal comes straight into the main beam of the mobile antenna, and that there is no satellite signal attenuation from the atmosphere or ground clutter. The results are shown in Table A.8.1-4.

Frequency [GHz]	38
Wavelength λ [m]	0.0079
MS Noise Figure [dB]	12.00[28]
MS Noise Floor [dBW/Hz]	-191.98
MS Antenna Physical Aperture Area [m^2]	0.00025[29]
MS Antenna Aperture Efficiency [%]	60%
MS Antenna Effective Aperture at Boresight [m^2]	0.00015
Interference PFD [dBW/m^2/Hz]	-165.00
Max Received Interference [dBW/Hz]	-203.25
Max I/N (Interference at Boresight) [dBW/Hz]	-11.27
Worst Case Desense [dB]	**0.31**
Add'l Interference Rejection - Example [dB]	-10.00
MS Received Interference [dBW/Hz]	-213.25
I/N [dBW/Hz]	-21.27
Desense [dB]	**0.03**

Table A.8.1-4: Analysis of Sharing Between SpaceX Downlinks and Mobile User Station

As this analysis shows, the worst case effect is desense of just 0.31 dB. Moreover, this calculation very likely overstates the potential effect for the reasons discussed with respect to the mobile base station – *e.g.*, antenna gain will likely be lower, atmospheric and ground clutter attenuation were not considered,[30] linear polarization achieves greater isolation, and the likelihood of angular

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[28] *See* Document 5D/427E.

[29] According to Document 5D/XYZ-E, the mobile stations are up to 4 x 4 elements, ½ wavelength spacing. The physical aperture area of the mobile antenna is estimated as 4*λ/2*4*λ/2.

[30] As the Commission has recognized, "most mmW transmissions will likely not occur in environments that have line of sight to satellites. By some estimates, as much as 80 percent of smartphone use occurs indoors, with much of the remainder occurring in vehicles. Because mmW signals are heavily attenuated by exterior walls, roofs and windows, signals originating from handheld smartphones will be largely confined within any buildings or vehicles where they are used, and would need to be relayed to mobile base stations by other devices with exterior antennas that will likely have sufficient beamforming ability to limit skyward transmissions." *Spectrum Frontiers Order*

separation of the mobile antenna boresight and the satellite signal. Were such factors to have a 10 dB effect, the desense would be reduced to an unnoticeable level of just 0.03 dB.

As these analyses demonstrate, the SpaceX System can be expected to have a *de minimis* effect on terrestrial operations in the satellite downlink bands under expected conditions, and only slightly greater (but still acceptable) effect under worst case scenarios. Moreover, given that the SpaceX satellites and mobile users are constantly in motion with respect to each other, any interference that did result would be fleeting.

Uplink Bands

Under both the international and domestic allocation tables, the 47.2-50.2 GHz and 50.4-51.4 GHz bands are allocated on a co-primary basis to FSS (Earth-to-space) operations, while the 51.4-52.4 GHz band is currently allocated only to FS and Mobile on a co-primary basis.[31] According to the Commission's IBFS and ULS databases, there currently are no satellite or terrestrial licenses active in these bands.[32] Part 25 of the Commission's rules provides rules for satellite services in the 47.2-50.2 GHz band. There are no terrestrial service rules applicable to any of these bands, and also no requirements for inter-system sharing between FSS and terrestrial systems.[33] Nonetheless, for the reasons discussed above, SpaceX is confident that the

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and FNPRM, ¶ 66. The use of such a relay antenna would essentially involve a fixed point-to-point link, to which the analyses in Tables A.8.1-2 and A.8.1-3 would apply.

31 The Commission is currently considering a petition for rulemaking filed by Boeing that requests addition of a co-primary allocation for FSS in the 51.4-52.4 GHz band. *See* Public Notice, Rep. No. 3051 (Sep. 16, 2016) (opening RM-11773).

32 The Commission has licensed two satellite systems in this band, but both operators surrendered their licenses prior to deployment. *See Northrop Grumman Space & Mission Systems Corp.*, 24 FCC Rcd. 2330 (IB 2009) (NGSO system); Stamp Grant, Hughes Network Systems, LLC, IBFS File No. SAT-LOA-20111223-00248 (Aug. 3, 2012) (hybrid GSO/NGSO system).

33 The Commission is currently considering service rules and sharing criteria for terrestrial and FSS systems in these bands. *See Spectrum Frontiers Order and FNPRM*, ¶¶ 410-15, 420-21.

characteristics of its proposed system will facilitate an operational approach that will allow equitable sharing of this spectrum.

A.8.2 Interference with Respect to GSO Satellite Systems

Although Section 25.278 of the Commission's rules generally requires NGSO and GSO systems to coordinate their operations,[34] neither the Commission nor the ITU provides specific rules for GSO/NGSO sharing in the V-band frequencies where SpaceX seeks to operate.[35] In fact, there are no GSO satellite systems currently licensed or granted U.S. market access in these bands. However, SpaceX is confident that the sophisticated sharing capabilities of its proposed system will facilitate sharing with any future GSO systems.

The sharing and interference mitigation techniques described above will minimize interference to and promote sharing with future GSO operators. In particular, the combination of narrow, steerable beams and significant satellite diversity for virtually every user on the ground will allow SpaceX to greatly reduce the number of in-line events with GSOs. In addition, the SpaceX constellation will be able to reduce power and/or direct beams away from the GSO arc to the extent necessary to protect GSO earth stations from harmful interference.

A.8.3 Interference with Respect to Other NGSO Satellite Systems

As with GSOs, there currently are no commercial NGSO operations in the V-band frequencies that SpaceX seeks to use and the Commission has not adopted any specific sharing rules for these

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[34] *See* 47 C.F.R. § 25.278.

[35] SpaceX recognizes that the ITU is currently engaged in technical studies to develop EPFD limits applicable to these bands to promote a more predictable radiofrequency environment for future V-Band GSOs. *See* ITU-R Res. 159 (WRC-15).

frequencies. There are, however, three applications pending for NGSO systems operating in these bands.[36] The sharing mechanisms described above for use with GSO systems would also be effective in facilitating sharing with other future NGSO systems.

To the extent that other future NGSO systems employ some of the same sharing techniques as SpaceX, however – such as narrow, steerable spot beams with satellite diversity – these technologies would unlock even more efficient spectrum use by easing coordination. For example, SpaceX and another NGSO operator could agree in advance that one operator's satellites would use only eastward beams, while the other would use only beams pointing to the west, when there would otherwise have been an in-line event. This would greatly reduce the number of cases where other, less efficient techniques (such as spectrum splitting) would be required, and could be pre-programmed to occur automatically, allowing more rapid and efficient implementation of such a coordination arrangement.

The efficacy of such an approach is, of course, a matter of degree, and depends on the technical flexibility of the systems involved. Satellites with narrower, more nimble beams, with greater potential for satellite diversity, promise greater efficiency. Systems characterized by wide, fixed beams and little or no satellite diversity correspondingly decrease efficiency. Therefore, SpaceX has sought to maximize the flexibility of its system along each of these dimensions, promoting the most efficient and flexible use of spectrum.

A.8.4 Interference with Respect to the Radio Astronomy Service

A limited number of the bands used by the SpaceX System are either shared with or adjacent to bands used by the Radio Astronomy Service ("RAS"). SpaceX will ensure that such

[36] *See* IBFS File Nos. SAT-LOA-20160622-00058 (Boeing), SAT-LOA-20161115-00117 (Audacy), and SAT-LOI-20161115-00120 (ViaSat).

systems are protected from any in-band and out-of-band interference from its NGSO system's operations. To this end, the SpaceX System will comply with the PFD limits and other protections described under the relevant ITU footnotes, resolutions, and recommendations for the protection of RAS. It will similarly comply with all applicable procedures for coordination with RAS users. SpaceX has already begun discussions with RAS stakeholders to address any interference concerns.

A.9 COORDINATION WITH U.S. GOVERNMENT NETWORKS

There are a variety of Federal allocations in the V-band spectrum used by the SpaceX System.[37] SpaceX has provided various U.S. government agencies initial information on the operational parameters of its system, and is committed to successful coordination with all government satellite and terrestrial networks operating in these bands to protect critical national security and government systems. For the reasons discussed above, SpaceX is confident that the characteristics of its proposed system will facilitate an operational approach that will allow equitable sharing of this spectrum with government systems.[38] SpaceX will inform the Commission when such coordination has been completed.

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[37] *See, e.g.,* Letter from Paige Atkins to Julius Knapp, GN Docket No. 14-177, *et al.* (July 12, 2016); NTIA Office of Spectrum Management, *Federal Spectrum Use Summary, 30 MHz – 3000 GHz* at 78 (2010), *available at* https://www.ntia.doc.gov/files/ntia/Spectrum_Use_Summary_Master-06212010.pdf.

[38] It is worth noting that Section 8.2.36 of the NTIA Manual of Regulations and Procedures for Federal Radio Frequency Management allows FSS operations at PFD levels similar to those authorized by ITU Article 21 (*e.g.*, up to -105 dBW/m^2/MHz at angles of 25 degrees or more). *See* Manual of Regulations and Procedures for Federal Radio Frequency Management, U.S. Department of Commerce, National Telecommunications and Information Administration, Section 8.2.36 (Sept. 2015 Revision of the May 2013 Edition), *available at* https://www.ntia.doc.gov/page/2011/manual-regulations-and-procedures-federal-radio-frequency-management-redbook. Presumably, government-authorized terrestrial systems are designed to coexist with satellites operating at that PFD level.

A.10 ITU FILINGS FOR SPACEX

SpaceX has not yet submitted system information for ITU publication. SpaceX will submit this information at the appropriate time and will unconditionally accept all consequent ITU cost-recovery responsibility for the filing.

A.11 ORBITAL DEBRIS MITIGATION

SpaceX's launch and space experience provides the knowledge base for implementing an aggressive and effective space-debris mitigation plan. The company's current and planned space-based activities underscore its unparalleled commitment to safe space. SpaceX has had extensive experience in safe-flight design and operation through many missions of both the Falcon 9 launch vehicle and the Dragon spacecraft carrying out missions to the International Space Station ("ISS"). The company is highly experienced with cutting-edge debris mitigation practices and has deep ties with the domestic and international institutions tasked with ensuring the continued safety of space operations. SpaceX has a long-standing collaborative working relationship with the Joint Space Operations Center ("JSpOC"), a multinational focal point for management of space traffic, debris, and other space coordination functions associated with the U.S. Department of Defense. It also has existing relationships with both NASA and the Air Force Center for Space Situational Awareness in the support of its space-based activities, and will continue to utilize these experiences and relationships as resources while developing the SpaceX System and spacecraft.

SpaceX will largely be using recommendations set forth in both NASA Technical Standard 8719.14A and AIR FORCE INSTRUCTION 91-217, typically choosing the more restrictive of the two and, where deemed applicable, choosing a more restrictive value than either reference due to the scope of the project. SpaceX intends to incorporate the material objectives set forth in this application into the technical specifications established for design and operation of the SpaceX System. SpaceX will internally review orbit debris mitigation as part of the preliminary design review and critical design review for the spacecraft, and incorporate these objectives, as appropriate, into its operational plans. Because this mitigation statement is necessarily forward looking, the process of designing, building, and testing may result in minor improvements to the parameters discussed herein. In addition, SpaceX will continue to stay current with the Space Situational Awareness community and technology and, if appropriate, SpaceX will modify this mitigation statement to continue its leadership in this area.

In this regard, it is worth noting that the VLEO Constellation offers even greater assurances against the creation of orbital debris. Its orbital characteristics have been chosen in order to maximize the spacing between satellites and thereby preclude the risk of conjunction. Moreover, at this very low altitude, atmospheric drag will quickly trigger the demise of any debris, whether released by a VLEO satellite (in the very unlikely event that such a release occurs) or caused by some other source. Thus, for VLEO satellites, the orbital characteristics themselves create an essentially self-cleaning operating environment, providing an additional layer of protection over the measures described below.

Spacecraft Hardware Design

SpaceX has assessed and limited the amount of debris released in a planned manner during normal operations, and does not intend to release debris during the planned course of operations of the SpaceX System.

SpaceX is also aware of the possibility that its system could become a source of debris in the unlikely case of a collision with small debris or meteoroids that could either create jetsam or cause loss of control of the spacecraft and prevent post-mission disposal. SpaceX is undertaking steps to address this possibility by incorporating redundancy, shielding, separation of components, and other physical characteristics into the satellites' design. Tanks are designed to suffer impact penetration without explosive consequences, while batteries are shielded and have isolation features to prevent cascading failure from impacted battery cells to other battery cells.

SpaceX will continue to review these aspects of on-orbit operations throughout the spacecraft manufacturing process and will make such adjustments and improvements as appropriate to assure that its spacecraft will not become a source of debris during operations or become derelict in space due to a collision.

Minimizing Accidental Explosions

SpaceX is designing its spacecraft in a manner that limits the probability of accidental explosion. The key areas reviewed for this purpose will include rupture of propellant tanks and batteries. The basic propulsion design (including a dual wall shielding effect from the bus walls), propulsion subsystem component construction, preflight verification through both proof testing and analysis, and quality standards will be designed to ensure a very low risk of tank failure. A burst disk ensures that sudden failure of propulsion containment cannot overpressure and fragment the spacecraft. During the mission, batteries and various critical areas of the propulsion subsystem will be instrumented with fault detection, isolation, and recovery (similar or in many cases identical to flight-proven methods utilized onboard the SpaceX Dragon capsule for its missions to ISS) to continually monitor and preclude conditions that could result in the remote possibility of energetic discharge and subsequent generation of debris. Through this process, SpaceX will assess and limit the possibility of accidental explosions during mission operations and assure that all stored energy at the end of the satellite's operation will be removed.

Safe Flight Profiles

SpaceX takes seriously the responsibility of deploying large numbers of satellites into space, and intends to exceed best practices to ensure the safety of space. Through detailed and conscientious mission planning, SpaceX has carefully assessed and limited the probability of its system becoming a source of debris by collisions with large debris or other operational space stations. It will maintain the accuracy of its orbital parameters at a level that will allow operations with sufficient spacing to minimize the risk of conjunction with adjacent satellites in the constellation and other constellations. SpaceX has and will continue to work closely with JSpOC to ensure the service provided for conjunction assessment to SpaceX and all operators is robust, reliable, and secure. Significant coordination must be performed with other satellite operators in nearby orbits to safely ascend and descend through constellations and to ensure any altitude perturbations do not result in unnecessarily close approaches. The propulsion system onboard can respond quickly and at high cadence, allowing SpaceX to coordinate in advance and respond to conjunction risks, whether with debris or other active spacecraft. SpaceX is willing to engage with any operators of nearby constellations to ensure safe and coordinated space operations.

SpaceX has determined that no other system is currently licensed by the Commission for, is currently operating in, or has submitted a request for coordination to the ITU with respect to the same nominal orbital planes sought by SpaceX. SpaceX determined this after review of the list of licensed systems and systems that are under consideration by the Commission for the orbital planes it has requested. In addition, in order to address non-U.S. licensed systems, SpaceX has reviewed the list of NGSO satellite networks for which a request for coordination has been published by the ITU.

Post-Mission Disposal

Each satellite in the SpaceX System is designed for a useful lifetime of 5 to 7 years. SpaceX intends to dispose of satellites through atmospheric reentry at end of life. As suggested by the Commission,[39] SpaceX intends to comply with Section 4.6 and 4.7 of NASA Technical Standard 8719.14A with respect to this reentry process.

LEO Constellation

SpaceX anticipates that its LEO Constellation satellites will reenter the Earth's atmosphere within approximately one year after completion of their mission – much sooner than the international standard of 25 years. After the mission is complete, the spacecraft (regardless of operational altitude) will be moved to a 1,075 km circular orbit in its operational inclination, then gradually lowered until the propellant is exhausted, achieving a perigee of at most 300 km. After all propellant is consumed, the spacecraft will be reoriented to maximize the vehicle's total cross-sectional area, a configuration also stable in the direction of aerodynamic drag. Finally, the spacecraft will begin to passivate itself by de-spinning reaction wheels and drawing batteries down to a safe level and powering down. Over the following months, the denser atmosphere will gradually lower the satellite's apogee until its eventual atmospheric demise.

SpaceX has conducted an assessment using NASA's Debris Assessment Software ("DAS"). That analysis indicates a total spacecraft Risk of Human Casualty rate of between 1:18,200 and 1:31,200 depending upon operational altitude for the LEO satellite – satisfying the requirement of 1:10,000 established by NASA. This analysis will be conducted regularly throughout the spacecraft design life cycle to ensure continued compliance. The results of the analysis done to date are included on the following pages.

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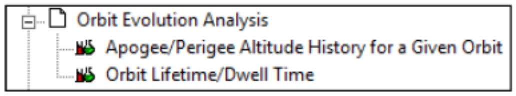
[39] *Mitigation of Orbital Debris*, 19 FCC Rcd. 11567, ¶ 88 (2004).

Re-Entry Timeline Estimates / Orbit Dwell Time

NASA's DAS provides tools to estimate spacecraft post-mission dwell time prior to atmospheric re-entry:



The solar cycle has a dynamic influence on the duration to demise of a spacecraft due to atmospheric reentry. During solar-max, the atmosphere swells up, making re-entry occur much more rapidly than during periods of solar-min. Figure A.11-1 shows a nominal re-entry time estimate using DAS across the foreseeable future. Periods of solar-min become evident at 2019/2029, while a favorable period of solar-max is anticipated around 2022-24.

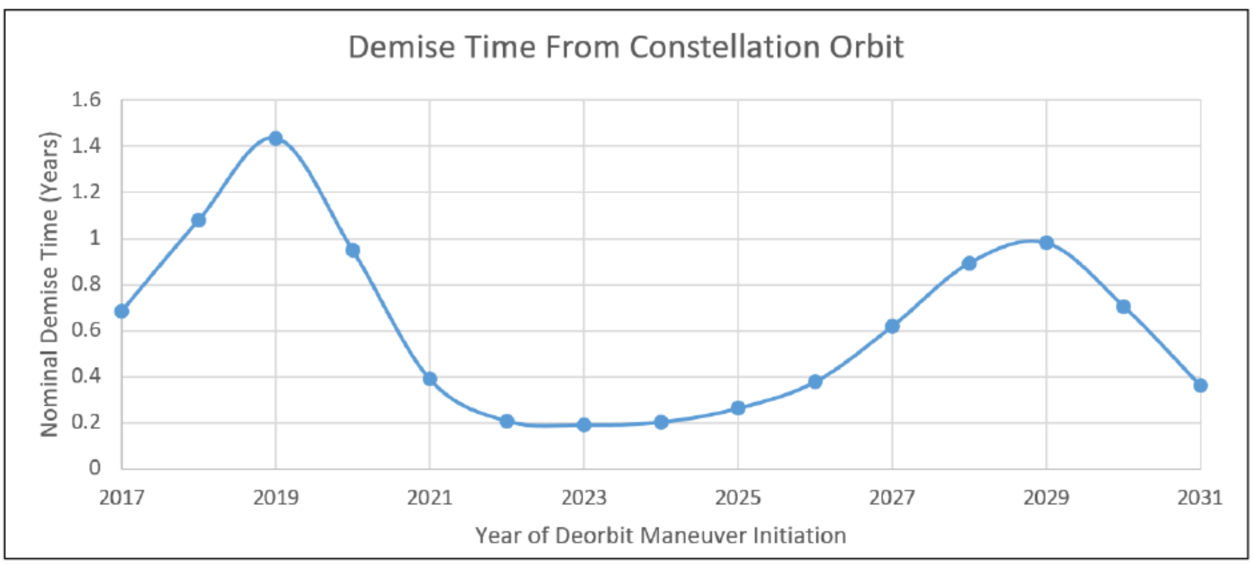
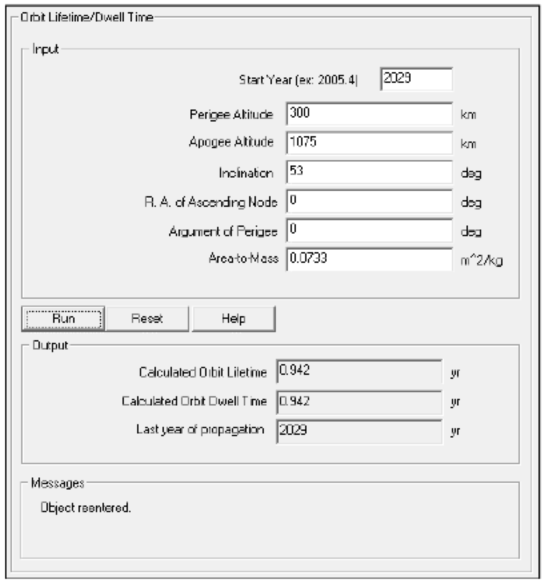
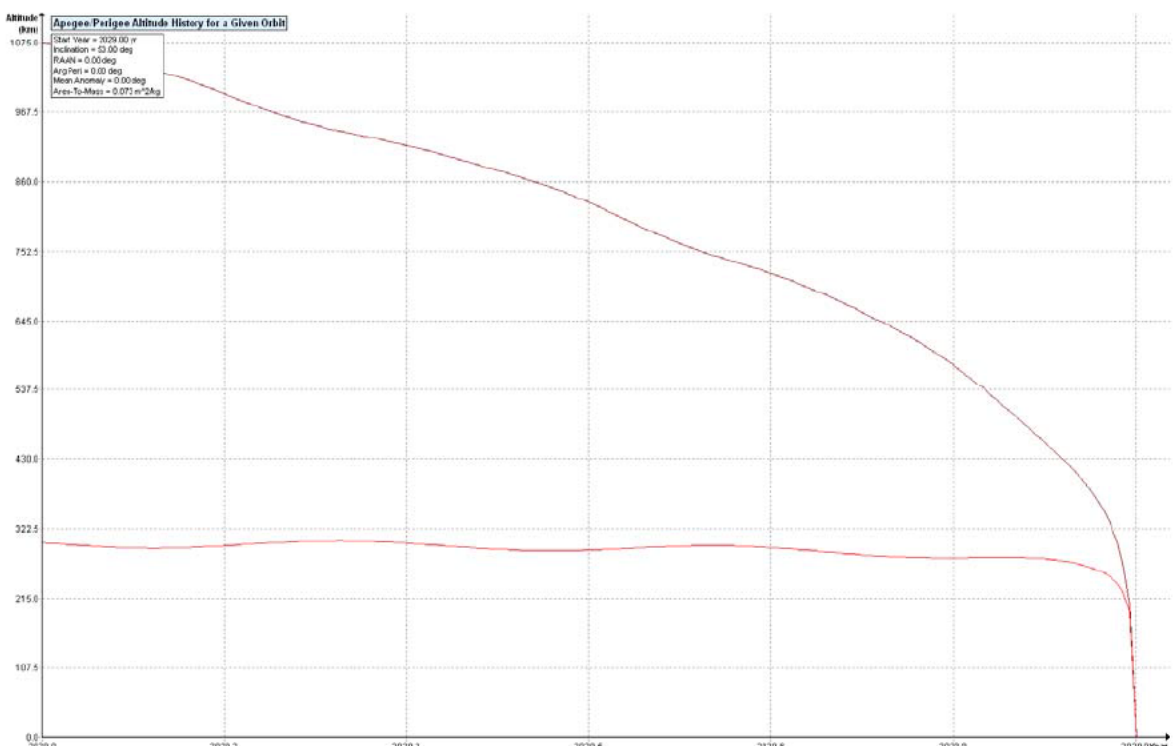


Figure A.11-1: Nominal Demise Time from Orbit

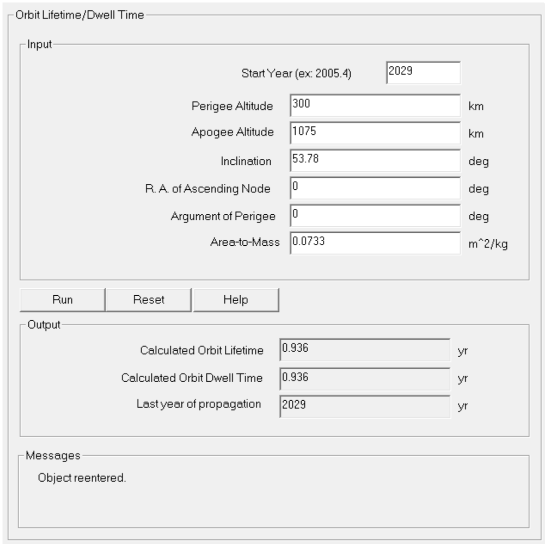
SpaceX satellites have a designed expected lifespan of between 5 and 7 years. Those satellites launched in 2019 that reach the end of life in 2024 will have a favorable de-orbit duration due to coincidence with solar-max. However, in the interest of margin, the de-orbit estimates provided below are calculated for 2029, corresponding to a local maximum for the following solar-min period. Because satellites are anticipated to reach end of life prior to 2029, satellite de-orbit performance is anticipated to exceed these reported values. Throughout the de-orbit phase, the satellite area-to-mass ratio is 0.0733 m^2/kg and is used in the following DAS input.



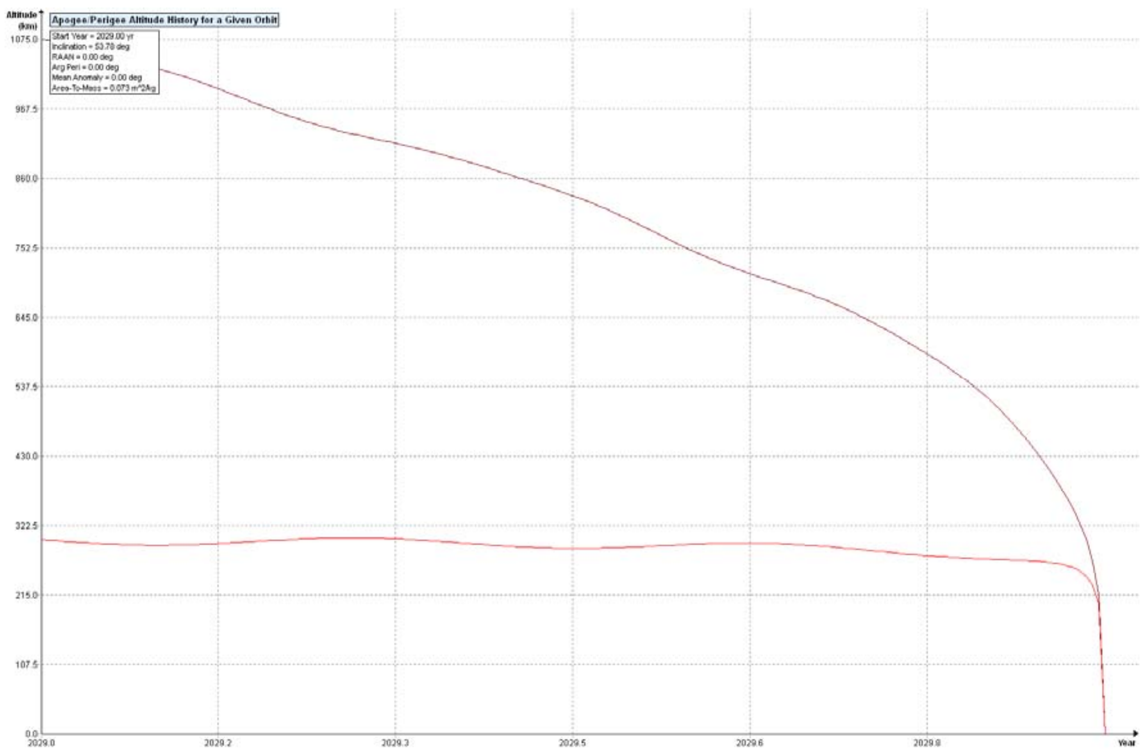
53 Degree Inclination DAS Input



53 Degree Inclination DAS Output

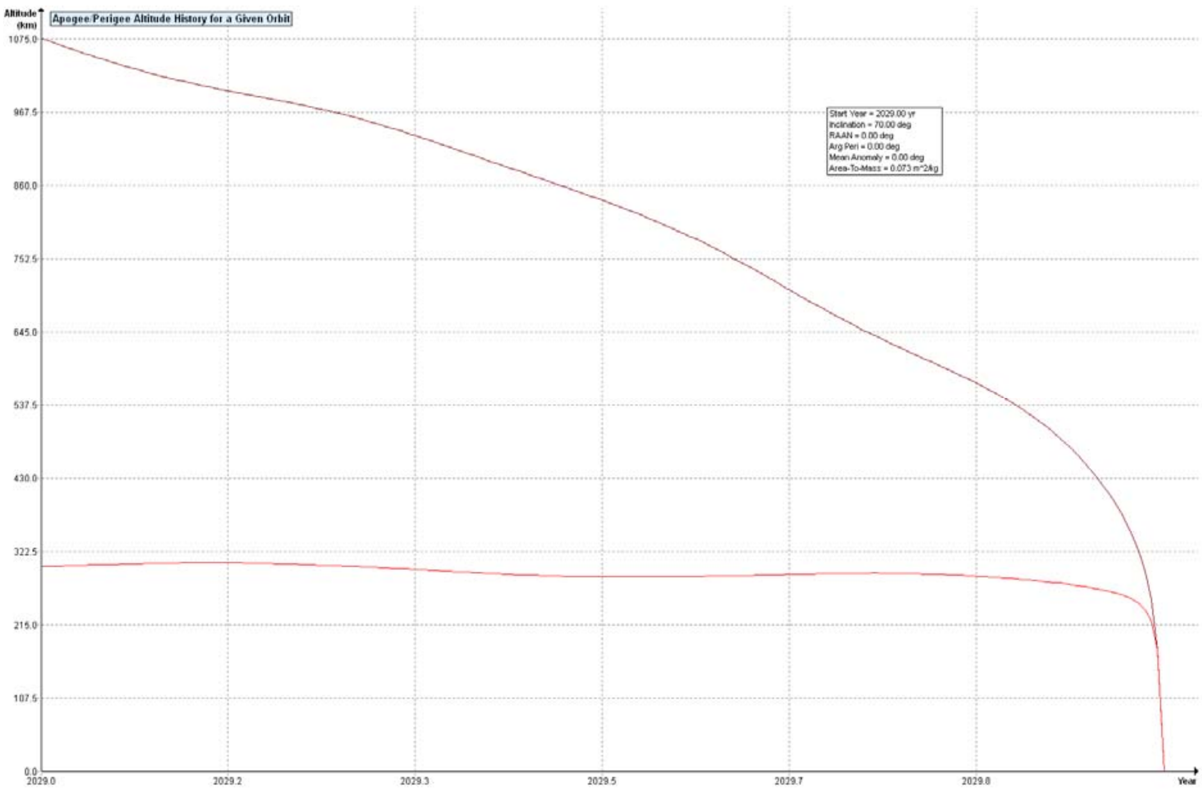


53.8 Degree Inclination DAS Input

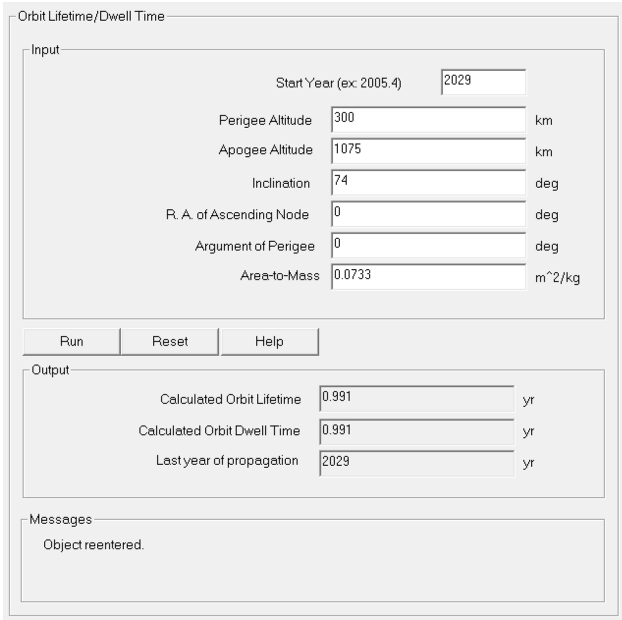


53.8 Degree Inclination DAS Output

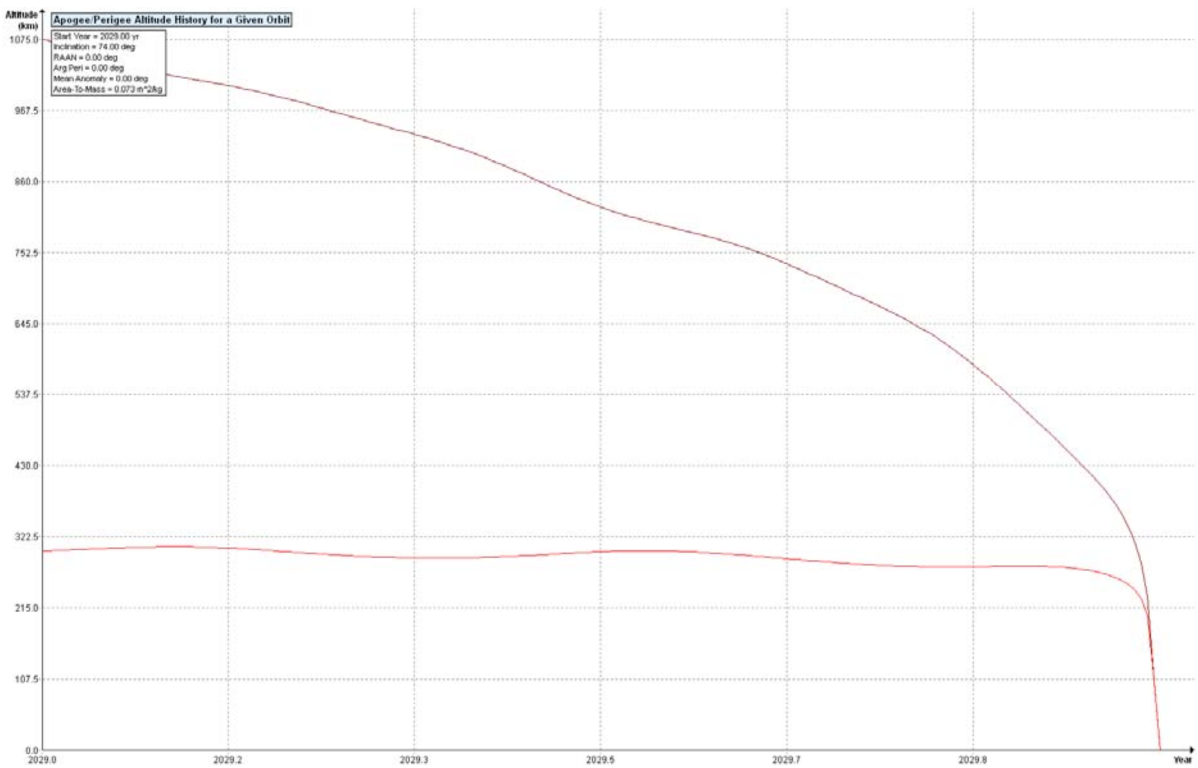
70 Degree Inclination DAS Input



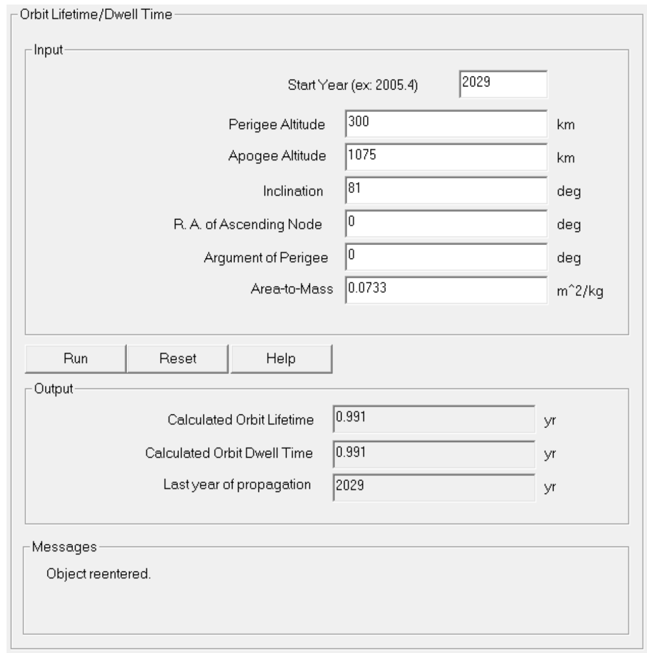
70 Degree Inclination DAS Output



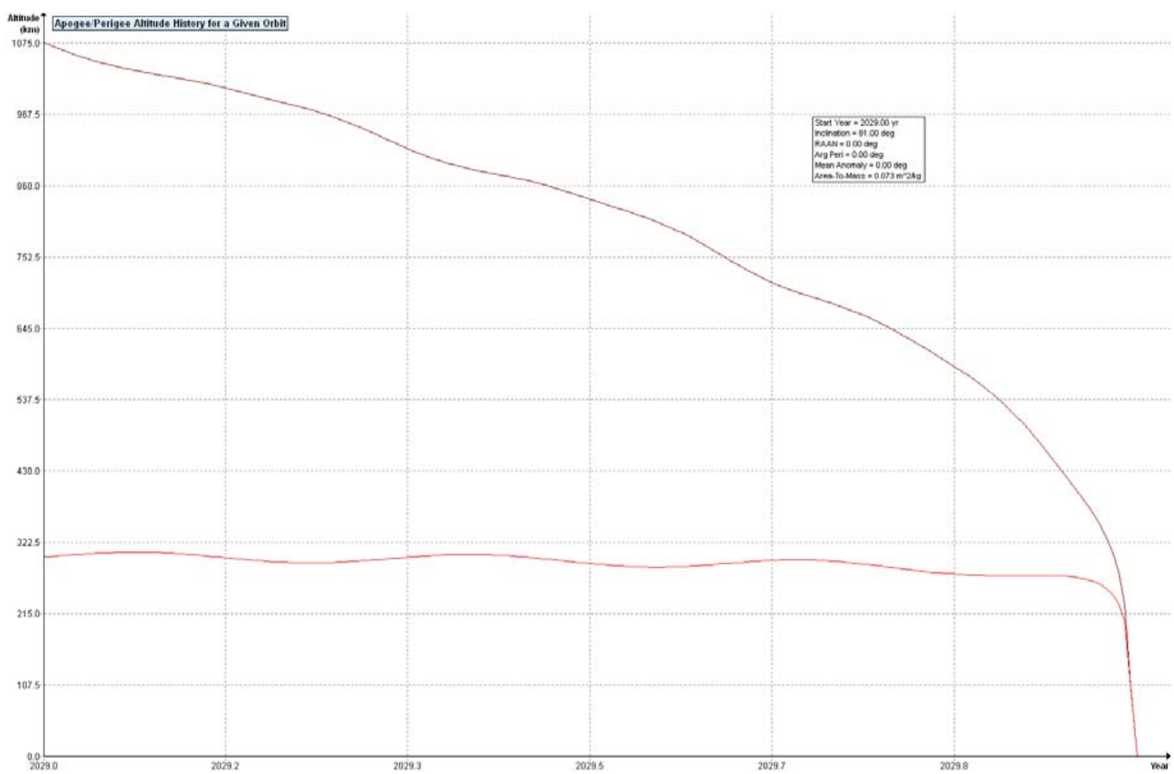
74 Degree Inclination DAS Input



74 Degree Inclination DAS Output



81 Degree Inclination DAS Input



81 Degree Inclination DAS Output

Re-entry timelines are also provided for several disposal perigees in proximity of the target. The 300 km target does not account for a fuel margin stack-up reserved for other uses. In the vast majority of cases, any remaining margin would allow LEO satellites to push their perigee even lower than 300 km. Nonetheless, satellites would hold some fuel in reserve for conjunction avoidance during the active de-orbit phase. Re-entry estimates for the year 2029 are set forth in the tables below.

53 Degree Inclination

Disposal Perigee	Time to Re-entry
200 km	22 days
250 km	100 days
> 300 km <	344 days
350 km	2.0 years
400 km	2.9 years

53.8 Degree Inclination

Disposal Perigee	Time to Re-entry
200 km	22 days
250 km	98 days
> 300 km <	342 days
350 km	2.0 years
400 km	2.9 years

70 Degree Inclination

Disposal Perigee	Time to Re-entry
200 km	24 days
250 km	118 days
> 300 km <	1.0 year
350 km	2.1 years
400 km	2.9 years

74 Degree Inclination

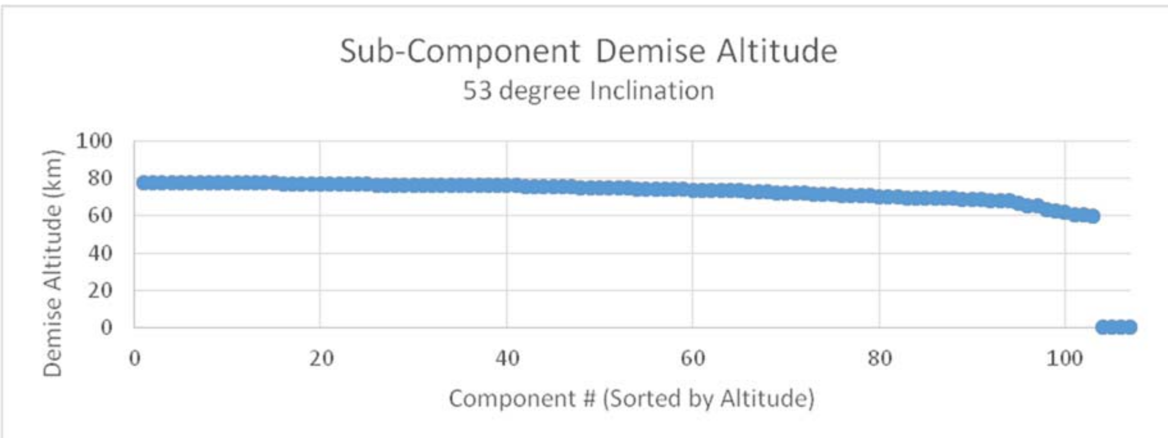
Disposal Perigee	Time to Re-entry
200 km	26 days
250 km	112 days
> 300 km <	1.0 year
350 km	2.1 years
400 km	2.9 years

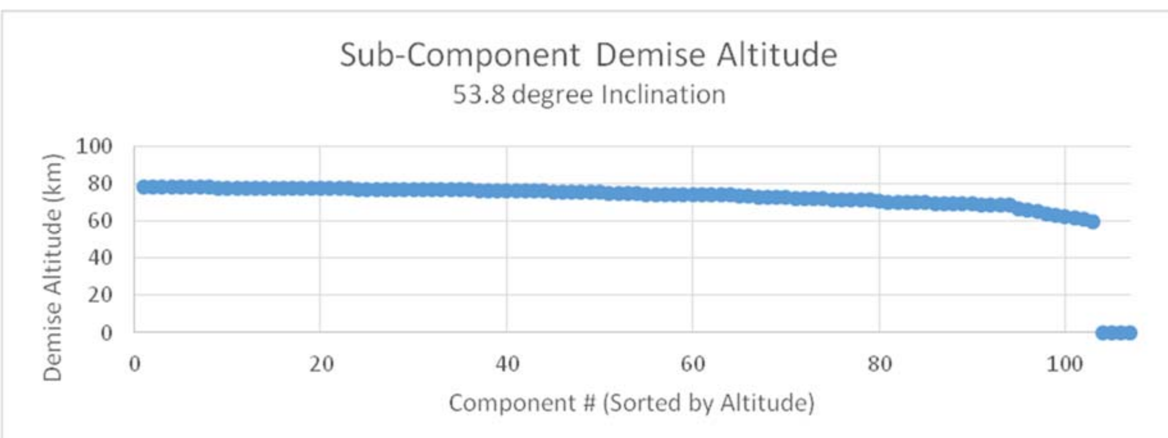
81 Degree Inclination

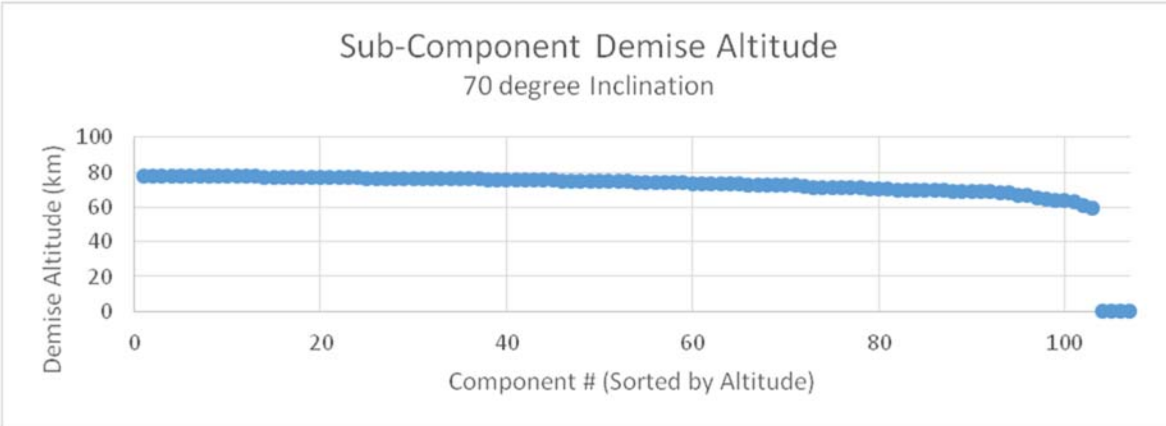
Disposal Perigee	Time to Re-entry
200 km	28 days
250 km	110 days
> 300 km <	1.0 year
350 km	2.1 years
400 km	2.9 years

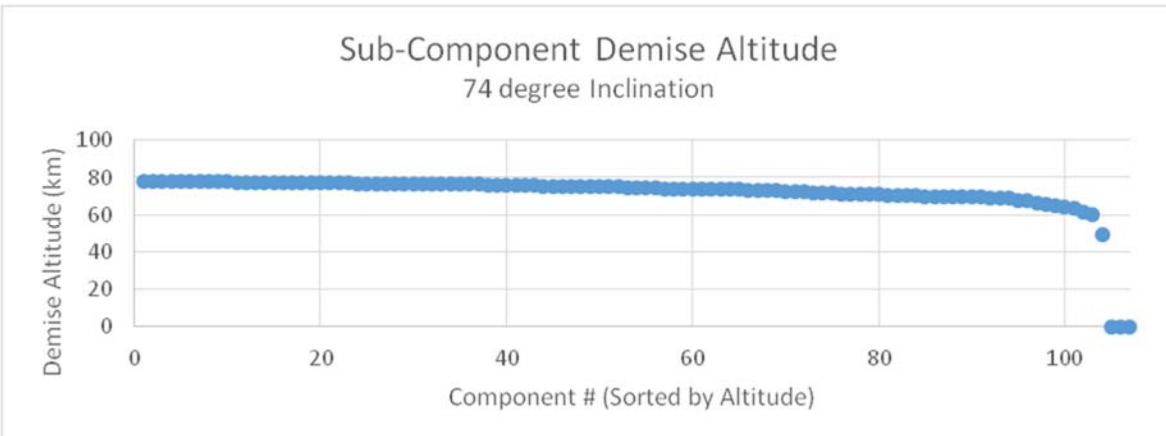
Atmospheric Demise

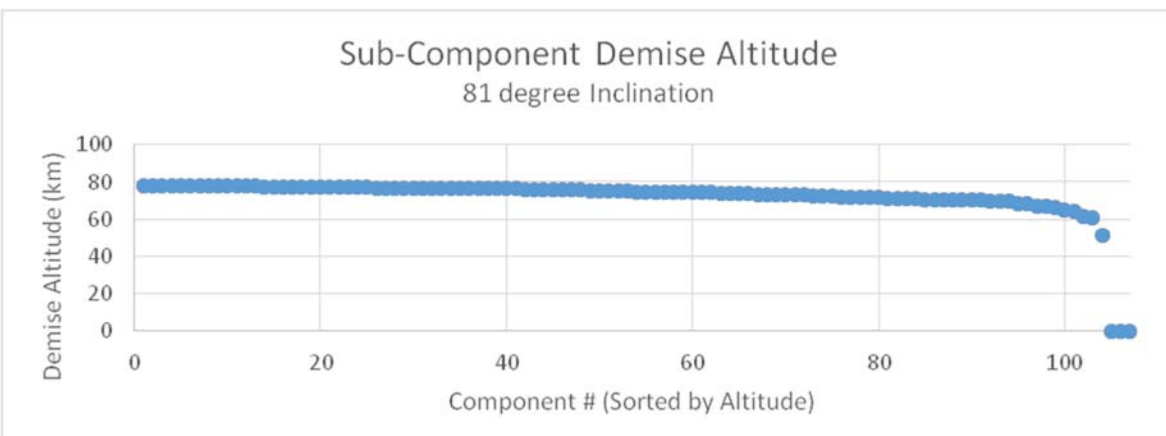
The spacecraft's small mass and predominantly aluminum construction make atmospheric demise a likely scenario upon re-entry. To verify this, SpaceX also utilized NASA's DAS. The satellite was broken down into approximately 100 major components, each defined with its own shape, material, mass and dimensions. Components were modeled in a nested fashion; a child component would not be exposed to the environment until its parent burned up. This enabled conservative re-entry survivability analysis of common problematic components, such as spherical fuel tanks contained within an enclosed spacecraft bus. DAS models the release of all root components 79 km above the surface; the demise altitudes of all modeled components at all inclinations is shown in the following figures:











Certain objects were identified as components of interest. This reflected objects which had a distinct mass, quantity, or shape factor which made them of particular concern during re-entry analysis. Those components and their corresponding demise altitudes are provided in the tables below:

53 Degree Inclination

Component	Demise (km)
First Bus Panel	76.6
Reaction Wheels	74.4
Batteries	70.9
Propellant Tank	70.9
Last Bus Panel	70.3

53.8 Degree Inclination

Component	Demise (km)
First Bus Panel	76.6
Reaction Wheels	74.4
Batteries	71.0
Propellant Tank	70.9
Last Bus Panel	70.3

70 Degree Inclination

Component	Demise (km)
First Bus Panel	76.4
Reaction Wheels	74.2
Batteries	71.3
Propellant Tank	70.8
Last Bus Panel	70.3

74 Degree Inclination

Component	Demise (km)
First Bus Panel	76.4
Reaction Wheels	74.2
Batteries	71.6
Propellant Tank	71.0
Last Bus Panel	70.7

81 Degree Inclination

Component	Demise (km)
First Bus Panel	76.7
Reaction Wheels	74.6
Batteries	72.1
Propellant Tank	71.7
Last Bus Panel	71.3

Although a major effort was made to avoid the use of components resistant to disintegration, some scenarios were unavoidable. DAS analysis indicates that four components may have a chance of reaching the Earth's surface; these components are listed in the tables below. Of the four, only two contribute substantially to the total Debris Casualty Area ("DCA") calculation.[40]

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[40] The Debris Casualty Area is a function of the dimensions of an average person and of the specific debris fragment. The model does not consider more complicated aspects, such as sheltering within structures. The total casualty area is the sum of the casualty areas of all surviving debris fragments which reach the ground with kinetic energy greater than 15 joules.

53 Degree Inclination

Component	Qty.	Material	Mass (kg)	Total DCA (m^2)	Energy (J)
Thruster Internals	1	Iron	1.66	0.47	2733
Comms. Component	5	Silicon Carbide	1.50	2.79	961
Rotor Bearing	5	Stainless Steel	0.07	2.45	8
Strut Fitting	12	Titanium	0.03	4.92	6

53.8 Degree Inclination

Component	Qty.	Material	Mass (kg)	Total DCA (m^2)	Energy (J)
Thruster Internals	1	Iron	1.66	0.47	2733
Comms. Component	5	Silicon Carbide	1.50	2.79	961
Rotor Bearing	5	Stainless Steel	0.07	2.45	8
Strut Fitting	12	Titanium	0.03	4.92	6

70 Degree Inclination

Component	Qty.	Material	Mass (kg)	Total DCA (m^2)	Energy (J)
Thruster Internals	1	Iron	1.66	0.47	2733
Comms. Component	5	Silicon Carbide	1.50	2.79	961
Rotor Bearing	5	Stainless Steel	0.07	2.45	8
Strut Fitting	12	Titanium	0.03	4.92	6

74 Degree Inclination

Component	Qty.	Material	Mass (kg)	Total DCA (m^2)	Energy (J)
Comms. Component	5	Silicon Carbide	1.50	2.79	961
Rotor Bearing	5	Stainless Steel	0.07	2.45	8
Strut Fitting	12	Titanium	0.03	4.92	6

81 Degree Inclination

Component	Qty.	Material	Mass (kg)	Total DCA (m^2)	Energy (J)
Comms. Component	5	Silicon Carbide	1.50	2.79	961
Rotor Bearing	5	Stainless Steel	0.07	2.45	8
Strut Fitting	12	Titanium	0.03	4.92	6

The DCA model does not consider components characterized by a ground impact energy of less than 15 joules. The two components in the simulation that meet this criterion are rotor bearings and strut fittings. The former may survive re-entry due to being nested in a larger sub-assembly, while the latter may survive because they are made of titanium. These components are 70 and 30 grams respectively, causing their impact at terminal velocity to remain benign.

Two other components with a chance of re-entry survivability are iron thruster internals and a set of silicon carbide communications components. While the majority of the thruster is expected to burn up in the atmosphere, the nested nature of the assembly leaves a chance of survivability for internal components. Fortunately, the DCA of these components is relatively small at 0.47 m^2. At higher inclinations, DAS indicates the thruster internals are no longer a risk, which is reflected by the disappearance of that row from the tables of 74 and 81 degrees of inclination. The high survivability of the silicon carbide communications components stems from the material properties, primarily its very high melting point of 2,730 °C.

The four components discussed above are the main contributors to the satellite's total DCA, set forth in Table A.11-1 below.

Inclination	DCA (m^2)	Risk of Human Casualty
53°	3.26	1:18,200
53.8°	3.26	1:18,200
70°	2.79	1:24,700
74°	2.79	1:29,900
81°	2.79	1:31,200

Table A.11-1: Summary of Human Casualty Risk Assessment (LEO)

Yet even with these components, the total spacecraft Risk of Human Casualty is no more than 1:18,200, satisfying the requirement of 1:10,000 established by NASA.

Post-Mission Disposal — VLEO Constellation

SpaceX anticipates that its VLEO satellites will reenter the Earth's atmosphere within approximately one month after completion of their mission – much sooner than the international standard of 25 years. After the mission is complete, or all propellant is consumed, the spacecraft will turn off its ion thruster, and be reoriented to maximize the vehicle's total cross-sectional area. The spacecraft will also passivate itself by de-spinning reaction wheels, drawing batteries down to a safe level and powering down. Due to the VLEO Constellation's very low altitude at the edge of the atmosphere, re-entry after end-of-life is anticipated within a matter of weeks.

SpaceX has conducted an assessment using NASA's DAS which indicates a total spacecraft Risk of Human Casualty rate of between 1:17,400 and 1:21,200, depending upon operational altitude for the VLEO satellite – satisfying the requirement of 1:10,000 established by NASA. This analysis will be conducted regularly throughout the spacecraft design life cycle to ensure continued compliance. The results of the analysis done to date are included on the following pages.

Re-Entry Timeline Estimates / Orbit Dwell Time

As discussed above, the solar cycle has a dynamic influence on the duration to demise of a spacecraft due to atmospheric reentry. As shown in Figure A.11-2 below, periods of solar-min can be expected in 2019/2029, while a favorable period of solar-max is anticipated around 2022-24. Accordingly, as for the LEO Constellation, the de-orbit estimates provided for the VLEO Constellation below are calculated for 2029, corresponding to a local maximum for the following solar-min period. Because satellites are anticipated to reach end of life prior to 2029, satellite de-orbit performance is anticipated to exceed these reported values. Throughout the de-orbit phase, the satellite area-to-mass ratio is 0.0696 m^2/kg and is used in the following DAS input.

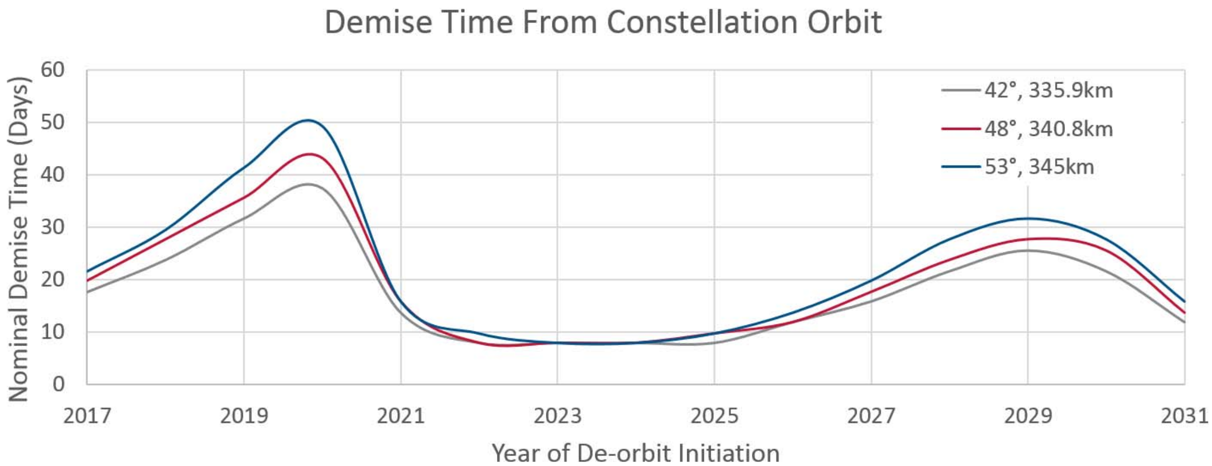
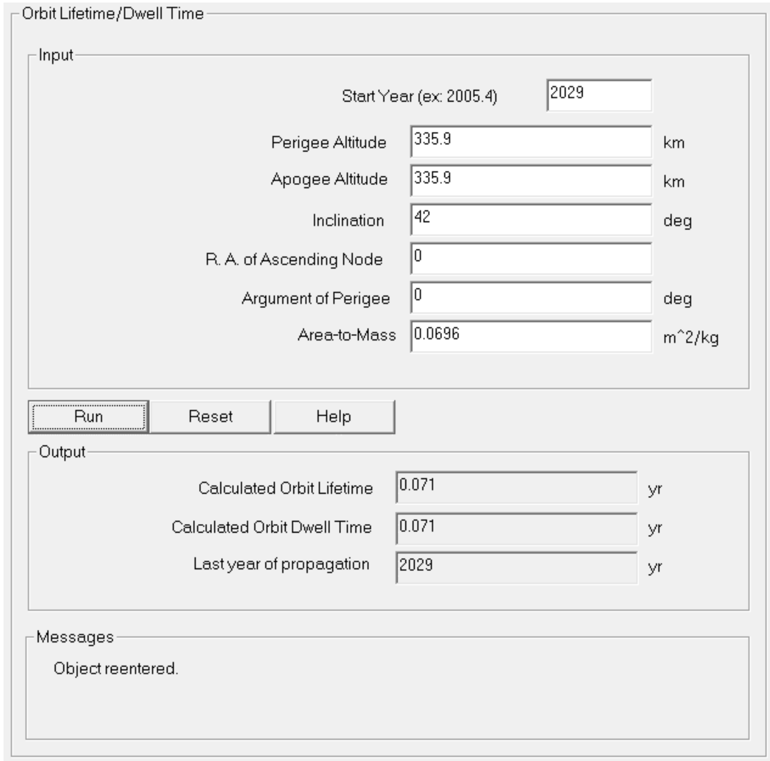
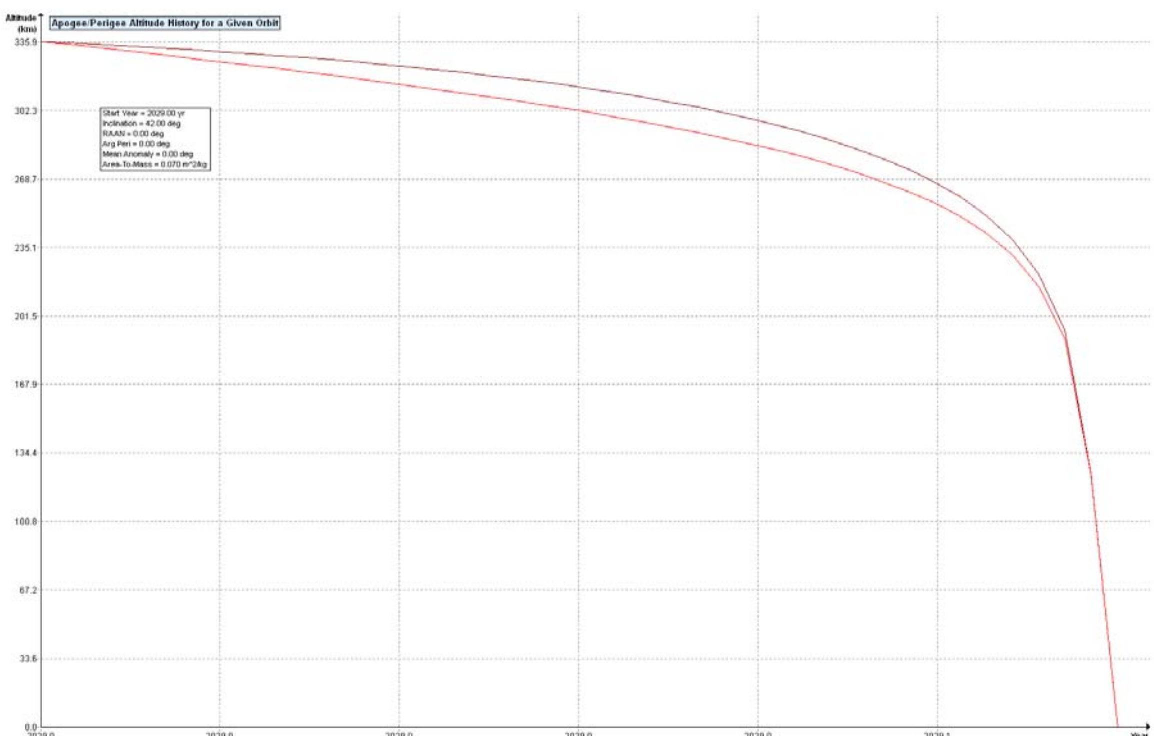


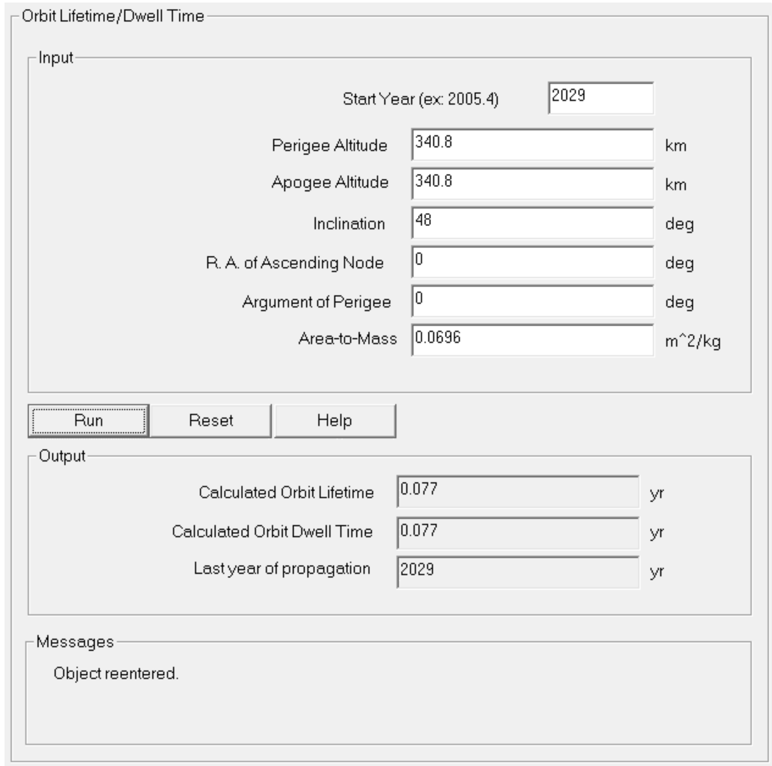
Figure A.11-2: Nominal Demise Time from Orbit



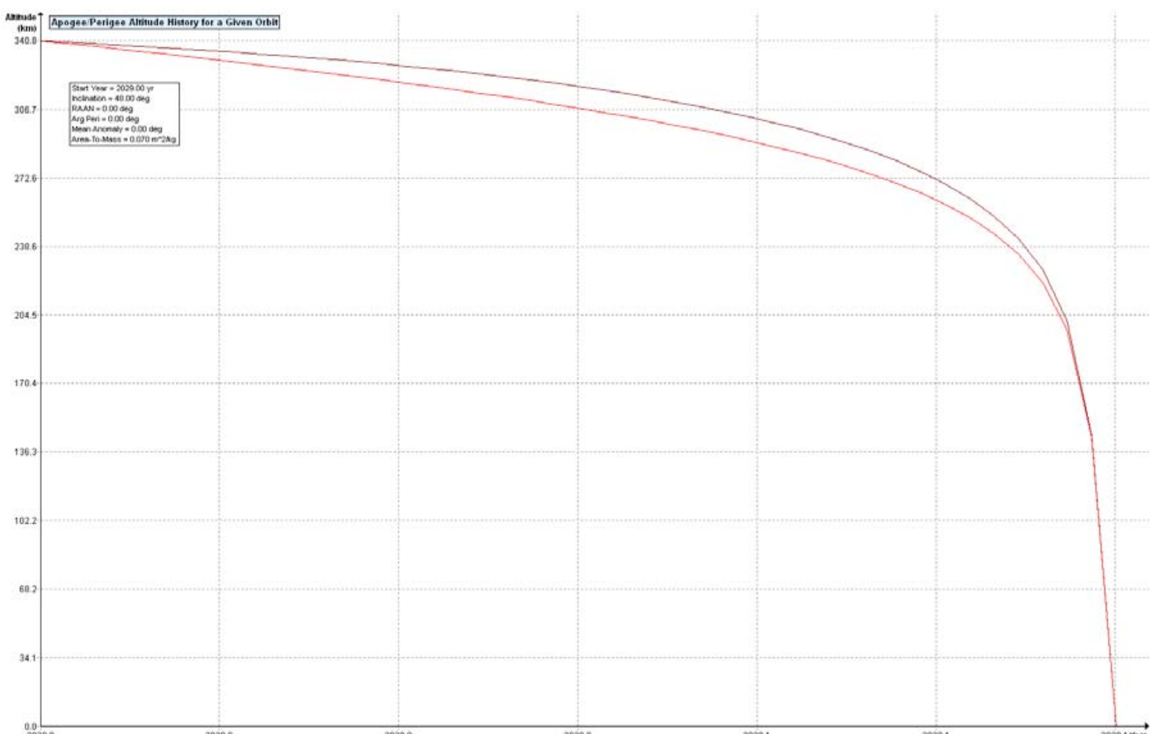
42 Degree Inclination DAS Input



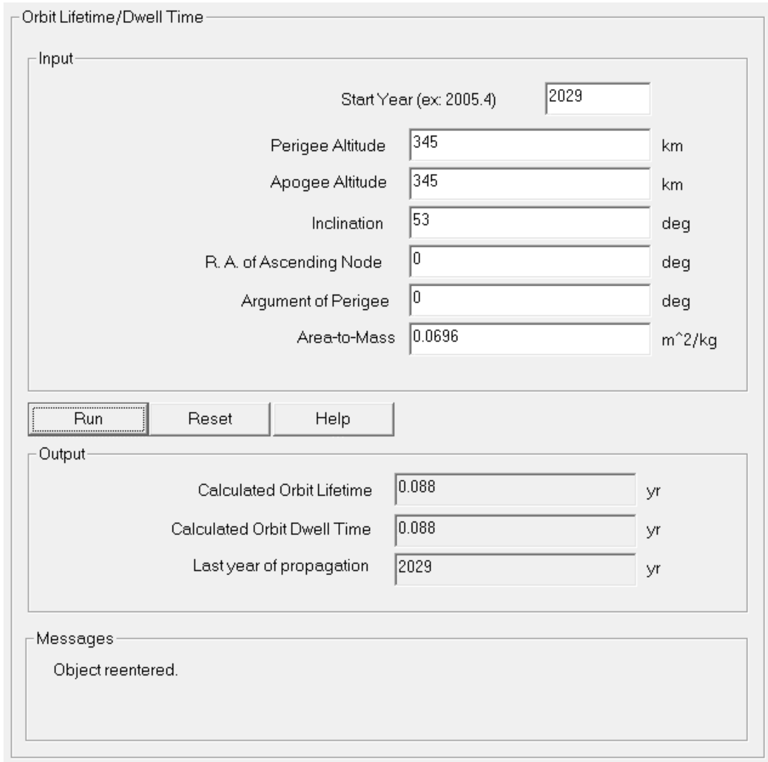
42 Degree Inclination DAS Output



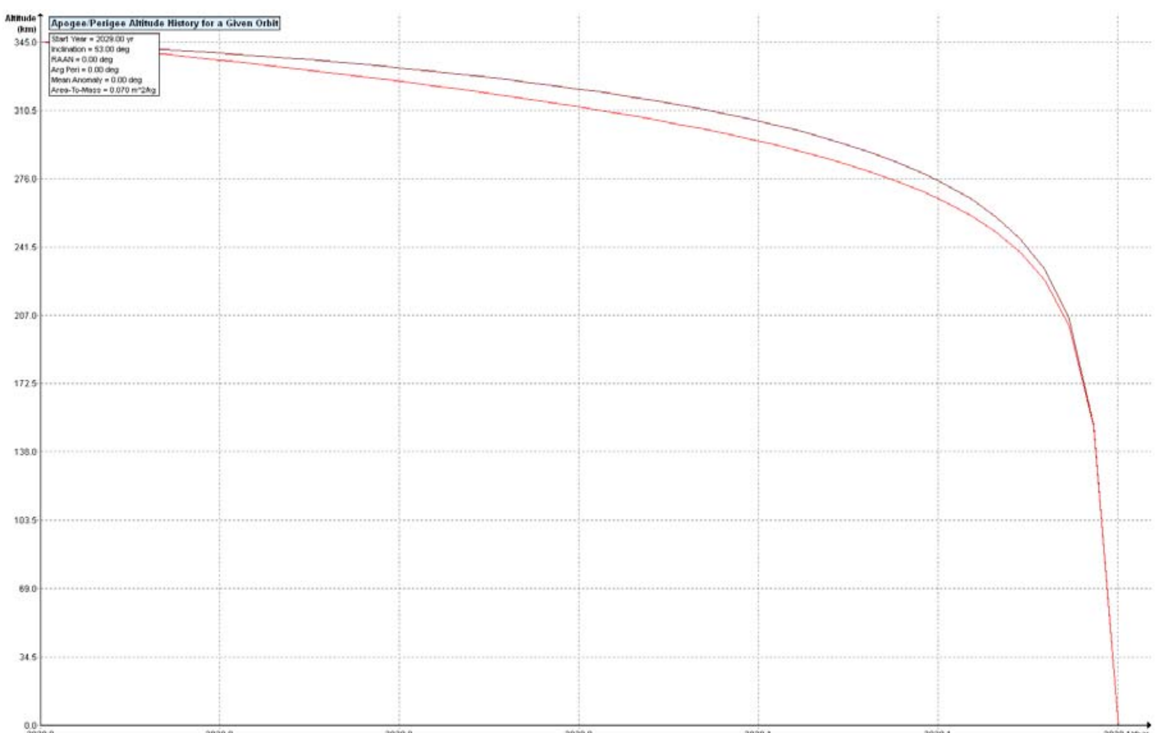
48 Degree Inclination DAS Input



48 Degree Inclination DAS Output



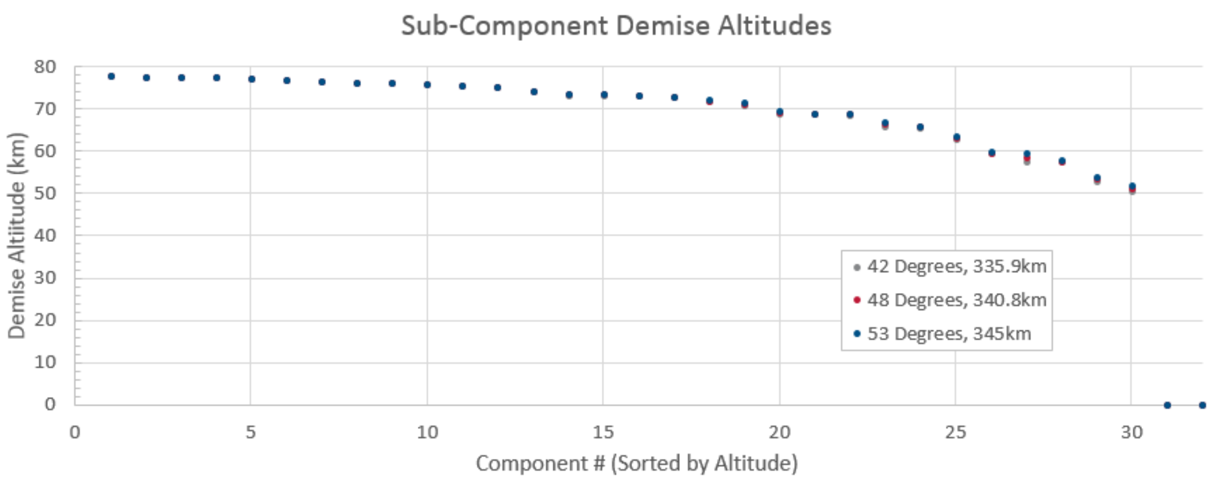
53 Degree Inclination DAS Input



53 Degree Inclination DAS Output

Atmospheric Demise

The spacecraft's small mass and predominantly aluminum construction make atmospheric demise a likely scenario upon re-entry. To verify this, SpaceX also utilized NASA's DAS. The satellite was broken down into 32 major components, each defined with its own shape, material, mass and dimensions. Components were modeled in a nested fashion; a child component would not be exposed to the environment until its parent burned up. This enabled conservative re-entry survivability analysis of common problematic components, such as spherical fuel tanks contained within an enclosed spacecraft bus. DAS models the release of all root components 79 km above the surface; the demise altitudes of the modeled components for all three inclinations is detailed in the figure below:



Several objects were identified as components of interest. This reflected objects which had a distinct mass, quantity, or shape factor which made them of particular concern during re-entry analysis. Those components and their corresponding demise altitudes are provided in the tables below:

	Demise Altitude by Inclination (km)		
Component	**42**	**48**	**53**
Largest Structural Panel	77.2	77.2	77.2
Propellant Tank	75.2	65.3	75.3
Reaction Wheels	68.9	69	69.1
Batteries	66.1	66.5	66.8
Antenna Panel	57.6	58.7	59.5
Thruster Internals	50.8	51.4	52

Although a major effort was made to avoid the use of components resistant to disintegration, some scenarios were unavoidable. DAS analysis indicates that two components may have a chance of reaching the Earth's surface; these components are listed in the tables below. Of the two, only one contributes to the total DCA calculation.

Component	Qty.	Material	Mass (kg)	Total DCA (m^2)	Energy (J)
Optical Component	5	Silicon Carbide	1.50	2.79	961
Rotor Bearing	5	Stainless Steel	0.07	2.45	8

The DCA model does not consider components characterized by a ground impact energy of less than 15 joules. The only component in the simulation that meets this criterion is a set of rotor bearings. Their candidacy for re-entry survivability is primarily driven by nesting within a larger sub-assembly. Because these components weigh only 70 grams, their impact at terminal velocity is anticipated to remain benign. The other component with a chance of re-entry survivability is a set of silicon carbide communications components. The high survivability of these components stems from their material properties, primarily silicon carbide's very high melting point of 2,730 °C. These two components are the main contributors to the VLEO satellite's total DCA, set forth for all three inclinations in Table A.11-2 below.

Inclination	DCA (m^2)	Risk of Human Casualty
42	2.79	1:17,400
48	2.79	1:20,200
53	2.79	1:21,200

Table A.11-2: Summary of Human Casualty Risk Assessment (VLEO)

Even with these components, the total spacecraft Risk of Human Casualty is no more than 1:17,400, satisfying the requirement of 1:10,000 established by NASA.

ENGINEERING CERTIFICATION

I hereby certify that I am the technically qualified person responsible for preparation of the engineering information contained in this application, that I am familiar with Part 25 of the Commission's rules, that I have either prepared or reviewed the engineering information submitted in this application, and that it is complete and accurate to the best of my knowledge and belief.

/s/ *Mihai Albulet*

Mihai Albulet, PhD
Principal RF Engineer
SPACE EXPLORATION TECHNOLOGIES CORP.

March 1, 2017

Date