# Interference-to-Noise (I/N) Compliance Validation of Telesat, OneWeb and SpaceX's 2020 Ka-Band NGSO FCC Processing Round Applications

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## Keywords

Interference, Validation, Satellites, Compliance, Ka-Band, NGSO, PFD, I/N

## Abstract

In March 2020, the Federal Communications Commission (FCC) initiated a processing round calling for additional applications for non-geostationary satellite orbit (NGSO) fixed-satellite service (FSS) operations in Ka-band. Satellite operators submitted descriptions of their planned constellations and provided proof that their systems would comply with interference limits set by the FCC and the International Telecommunications Union (ITU). All ten companies in this processing round provided power flux density (PFD) compliance calculations. Three companies optionally submitted interference-to-noise (I/N) compliance calculations: Telesat, SpaceX, and OneWeb. This paper documents a standardized process to calculate I/N and analyzes I/N compliance for these three companies. I/N analyses consist of static analyses, which considers the worst-case interference scenario, and dynamic analyses, which computes the interference over time. In ITU-R F.1495, the long-term I/N limits are defined to not exceed -10 dB for greater than 20% of the year, requiring dynamic analyses to prove compliance. Static I/N analysis is calculated in this paper, which allows for verification of compliance with the long-term dynamic -10 dB limit in the worst-case scenario. Dynamic I/N analyses are required to verify compliance fully and will be addressed in future work. This study shows that Telesat, OneWeb, and all SpaceX operations at a minimum elevation angle of 25° complied with I/N long-term dynamic limits of -10 dB, but SpaceX operations at altitudes of 360 km and 373 km with a minimum elevation angle of 5° exceeded I/N limits in the worst-case scenario.

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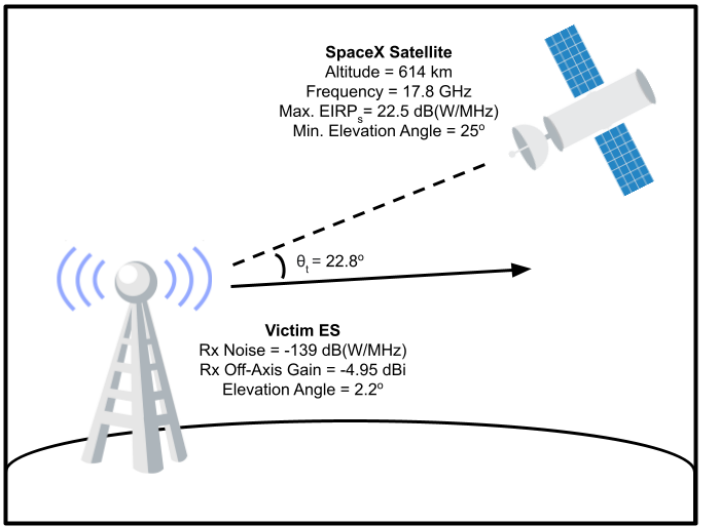
In "Interference-to-Noise (I/N) Compliance Validation of Telesat, OneWeb and SpaceX's 2020 Ka-Band NGSO FCC Processing Round Applications", authors Tan, Boyalakuntla, Oh, Gupta and Lohmeyer analyze the static I/N assessments of three non-geostationary (NGSO) systems. These networks were the only three of the ten participants that provided interference computations into terrestrial networks in their FCC submission for U.S. market access. In analyzing the static I/N, the authors validate the worst-case interference scenario, and found that Telesat and OneWeb's network complied with requirements for static I/N, despite discrepancies in OneWeb's approach, and that more granular dynamic assessment is needed to validate SpaceX's I/N assessment.




## Introduction

Radio spectrum is a limited resource that must be shared across a multitude of systems including, but not limited to: terrestrial, satellite, navigation, passive science, and amateur radio networks. Interference occurs when these networks operate over the same frequency and geographic area, which impacts availability and leads to decreased performance. To limit interference and enable the coexistence of diverse services, regulatory agencies like the Federal Communications Commission (FCC) and the International Telecommunication Union (ITU) define radiocommunications rules and spectrum allocations at the national and international levels.

Companies that plan to operate a satellite constellation, and intend to provide service to the U.S., must file a market access application with the FCC that details their constellation plans and demonstrates compliance with the FCC and ITU rules. Two of the required application documents are the Schedule S and Technical Narrative. The Schedule S contains technical and operational information about a company's system, like orbital parameters and channel performance, whereas the Technical Narrative includes mathematical procedures and calculations to prove a lack of harmful interference into incumbent networks, thereby demonstrating compliance with FCC rules.

In calculating interference compliance, one system is defined as the interferer that transmits a signal, and another system is defined as the victim that receives the unintended signal. Figure 1 depicts a scenario where the interfering signal is transmitted by a satellite into a victim terrestrial fixed service (FS) earth station.

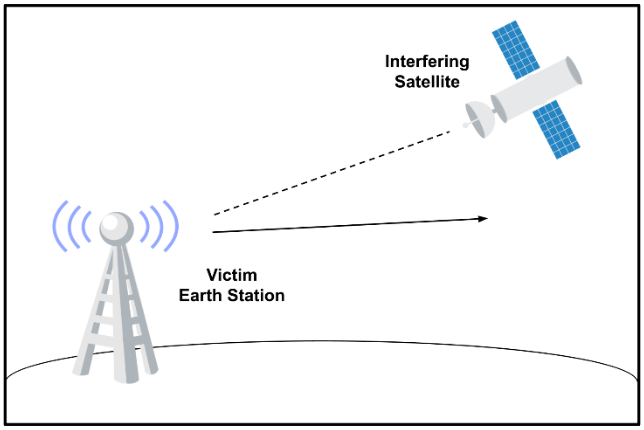



**Figure 1: Interfering Signal into a Victim Earth Station**

Article 21 of the ITU's Radio Regulations limits power flux density (PFD) of a satellite in the direction of a victim FS Earth station and ensures that there will not be harmful interference into terrestrial networks. PFD takes into account the interfering system's transmissions, as defined by the effective isotropic radiated power (EIRP), where EIRP is a measure of the transmitter's performance that considers the power that can be radiated from the antenna given the emitted transmitted power and the transmitter antenna gain [1].

For a more granular assessment of interference that accounts for the victim FS earth station, the interference-to-noise (I/N) ratio can be calculated. Unlike PFD, I/N takes into account the performance parameters of the victim system by comparing the interfering signal to the noise of a victim system's receiver. All companies seeking U.S. market access must provide ITU Article 21 compliance documentation but can optionally include I/N calculations in its Technical Narratives to show that its system's downlink transmissions do not cause harmful interference. The inclusion of I/N computations is particularly helpful if a company anticipates that its PFD calculations may raise additional questions regarding its system's compliance with Article 21 Limits.

In March 2020, the FCC held a processing round for additional applications and petitions for operations in Ka-band, specifically the 10.7 to 12.7 GHz, 12.75 to 13.25 GHz, 13.85 to 14.5 GHz, 17.7 to 18.6 GHz, 18.8 to 20.2 GHz, and 27.5 to 30.0 GHz bands, in which ten companies participated. An assessment and validation of the PFD compliance of the ten companies in this processing round were provided in the paper, "Power Flux Density (PFD) Compliance Validation of FCC's Ka-band NGSO Processing Round Participants" [2]. Of the ten applicants, three systems submitted I/N calculations in addition to PFD showings: Telesat, OneWeb, and SpaceX. This paper analyzes and validates the I/N compliance for these systems as an evolution of the interference studies shown in the aforementioned PFD study.

## I/N Overview

In this section an overview of the methodology for computing interference to noise ratio (I/N) as well as the different types of I/N assessment is provided.

### I/N to ΔT/T

Interference-to-noise (I/N) is the ratio of an interfering signal power to the noise power of a system. Specifically, it measures the increase in noise temperature at a receiver due to interference [3]. I/N (measured in dB), defined in Eq. 1, can also be expressed in terms of a percentage known as ΔT/T (%)

which is defined as the ratio between the interference or change in temperature, ΔT, to the noise temperature of a system, T. In other words, it is the percent change in noise temperature of the receiving system due to the presence of the interferer. The relationship between ΔT/T and I/N is shown in Eq. 1 and Eq. 2 [4].

$$\frac{I}{N} = 10\log_{10}\left(\frac{\Delta T/T}{100}\right) \tag{1}$$

$$\frac{\Delta T}{T} = 100 \times 10^{\left(\frac{I/N}{10}\right)} \tag{2}$$

For example, if a system has a ΔT/T of 13%, the corresponding I/N is computed as $10\log_{10}(0.13)$ or −8.86 dB.

**Static vs. Dynamic I/N**

There are two primary types of I/N assessment: static I/N analysis and dynamic I/N analysis. Static I/N analysis assumes a satellite constellation to be stationary with respect to the Earth in a worst-case interference geometry or the orbital parameters that cause the greatest interference. One such worst-case assumption includes collocated Earth stations meaning that the main beam of the interfering satellite points directly at the victim station. One way this type of analysis—static analysis—can be used is to determine the need for coordination with other co-frequency operators. The process of coordination is described in Article 9 of the ITU's Radio Regulations, and takes place when a coordination trigger of I/N greater than -12.2 dB is computed [6, 7].

Static analysis can also be used as a reference or a baseline for interference and can be thought of as the worst-case dynamic I/N analysis at an instance in time. The static I/N value is used to determine whether I/N would ever exceed the long-term dynamic limit, -10 dB, to protect an FS Earth station [5]. Thus, if the static value never exceeds -10 dB, even in the worst case, dynamic I/N does not need to be calculated.

To understand the interference from a satellite over time, dynamic I/N analysis can be performed. In dynamic I/N analysis, I/N is calculated at each time step as the position of a satellite changes relative to a respective Earth station. According to Recommendation ITU-R F.1495, for a satellite to protect a victim FS Earth Station, dynamic I/N analysis must comply with the following thresholds [5]:

Long-term: I/N should not exceed –10 dB for more than 20% of the time, or 73 days in any year.

Short-term: I/N should not exceed +14 dB for more than 0.01% of the time, or 4 minutes and 22.8 seconds in any month

I/N should not exceed +18 dB for more than 0.0003%, or 7.9 seconds of the time in any month

This paper uses static I/N analyses to evaluate each company's potential interference into terrestrial networks. In other words, each company will be evaluated for compliance against the long-term dynamic -10 dB threshold, but will not be evaluated for exceeding the limit for greater than 20% of the year. Since static analysis does not consider I/N over time, for which the ITU limits are written, a dynamic I/N analysis will be performed to determine compliance.

## Methodology

To demonstrate I/N compliance, static I/N assessments were performed for each company to confirm that the downlink emissions of the FSS operations will not cause harmful interference to FS systems, or terrestrial stations. The equation for downlink interference as defined in Appendix 8 is shown in Eq. 3 [7].

$$\frac{I}{N} = P_s' + G_3'(\eta_e) + G_4(\theta_t) - FSPL - N \tag{3}$$

where $P_s'$ is the maximum power density per Hz delivered to the antenna of the interfering satellite, $G_3'(\eta_e)$ is the transmitting antenna gain of the interfering satellite in the direction of the victim Earth Station, $G_4(\theta_t)$ is the receiving antenna gain of the victim Earth station in the direction of the interfering satellite, FSPL is the free-space path loss from the interfering satellite to the victim Earth station, and *N* is the equivalent satellite link noise temperature. *N* can be derived from *N* = *kTB*, where *k* is Boltzman's constant ($1.38 \times 10^{-23}$ Joules/Kelvin), *T* is absolute temperature in kelvin, and *B* is bandwidth in hertz.

To protect FS stations, each company must prove that its system protects an FS station with characteristics described in ITU-R SF.1483 and shown in Table 1. These characteristics are representative of a majority of links in the 17.7-19.3 GHz band [8].

For this assessment, the worst-case values from Table 1, namely a minimum elevation angle of 2.2 degrees and an antenna gain of 48 dBi were chosen, as both of these inputs increase off-axis gain, which in turn increases total interference. Note that the elevation angles for the described victim Earth station are low because FS stations point towards the horizon or lower to communicate with other terrestrial objects.

To calculate the I/N for each system, Eq. 3 was modified based on the parameters available in each company's FCC market access application. Thus, $P_s' + G_3'(\eta_e)$ was substituted with $EIRP_S$ because $EIRP_S = P_s' + G_3'(\eta_e)$ , where $EIRP_S$ is the Effective Isotropic Radiated Power spectral density, or $EIRP$ per Hz. The original equation is shown in Eq. 4.

$$\frac{I}{N} = P_s' + G_3'(\eta_e) + G_4(\theta_t) - FSPL - N \tag{4}$$

Simplifying Eq. 4 further yields Eq. 5us

$$\frac{I}{N} = EIRP_S + G_4(\theta_t) - FSPL - N \tag{5}$$

Note that while Eq. 4 and Eq. 5 do not include feeder loss, several systems include a receiver feeder loss of 3 dB in its Technical Narratives. To assume the worst-case scenario, the 3 dB feeder loss as mentioned in ITU-R SF.1483 was excluded from the validation computations. To find the necessary parameters to compute the I/N using Eq. 5, the victim station was assumed to be a FS Earth Station with the characteristics tabulated in Table 1, and the interfering satellite characteristics were found in the FCC filings for each company. For companies that had multiple values for the same parameter, such as a range of frequencies or different $EIRP_S$ values for different satellites, the worst-case value was chosen. Therefore, for each company, the highest $EIRP_S$ and the lowest frequency were used in calculations, as a lower frequency corresponds to a lower FSPL.

The specific steps used to calculate I/N for each company were as follows:

1. Find the altitude, frequency, minimum elevation angle, and the satellite max. $EIRP_S$ for the interfering system from companies' Schedule S and Technical Narratives.
2. Find the elevation angle and the Rx antenna gain and thermal noise (N) of the victim system from ITU-R SF.1483.
3. Calculate the off-axis angle $(\theta_t)$ between the boresight of the victim station and the line between the interferer satellite and victim station, where interferer minimum elevation angle ($\theta_i$), victim elevation angle ($\theta_v$), and $\theta_t$ are all in degrees.

$$\theta_t = \theta_i - \theta_v \tag{6}$$

4. Calculate the victim Rx off-axis antenna gain $G_4(\theta_t)$ according to ITU-R F.1245, where $G_4(\theta_t)$ is in degrees [9]. Eq. 7 applies for max $(\varphi_m, \varphi_r) < \varphi < 48^o$.

$$G_4(\theta_t) = 29 - 25 \times \log_{10}(\theta_t) \tag{7}$$

where:

$$\varphi_m = \frac{20\lambda}{D}\sqrt{G_{max} - G_1}$$

$$\varphi_r = 12.02(\frac{D}{\lambda})^{-0.6}$$

$G_1$: gain of the first side lobe

$$= 2 + 15\log_{10}(\frac{D}{\lambda})$$

$$\frac{D}{\lambda} = 10^{(G_{max}-7.7)/20}$$

5. Calculate the path length ($d$) from the interfering satellite to the victim station, where altitude ($h$), the radius of the Earth ($R_e$), and $d$ are all in meters.

$$d = \sqrt{R_e^2 + (h+R_e)^2 - 2R_e(h+R_e) \times \sin(\theta_t \times \frac{\pi}{180} + \arcsin(\frac{R_e}{h+R_e} \times \cos(\theta_t \times \frac{\pi}{180}))} \tag{8}$$

6. Calculate the Free Space Path Loss (FSPL) from the interfering satellite to the victim station, where wavelength ($\lambda$), $d$, and $FSPL$ are all in meters [10].

$$FSPL = 20 \times \log_{10}(4 \times \pi \times \frac{d \times 1000}{\lambda}) \tag{9}$$

7. Calculate the power from the interfering satellite at the input of the victim receiver ($I$), where $I$ is in decibels.

$$I = EIRP_S - FSPL + G_4(\theta_t) \tag{10}$$

8. Calculate I/N, where *I/N*, *I*, and *N* are in decibels. Note that the I/N in Eq.11 does not denote division, but rather is used as a symbol to represent interference-to-noise in decibels.

$$\frac{I}{N} = I - N \tag{11}$$

## I/N Compliance Validation

As previously mentioned, three systems submitted I/N calculations in the 2020 Ka-Band processing round: Telesat, OneWeb, and SpaceX. This section introduces each company and its proposed satellite constellation, provides a static I/N assessment, and assesses each company's FCC provided I/N assessment against the static I/N coordination trigger of -12.2 dB and the long-term dynamic limit of -10 dB, established in ITU-R F.1495.

### Telesat

Telesat, headquartered in Canada, submitted an FCC market access application to serve the U.S. market with its global NGSO FSS constellation. In its application, Telesat sought to modify its non-geostationary satellite orbit (NGSO) low Earth orbit (LEO) constellation in two phases. In the first phase, Telesat requested to increase the number of satellites from 117 to 298 satellites. In the second phase, Telesat requested to add 1373 satellites to bring the total to 1671 satellites [11]. Additionally, Telesat requested to modify its constellation by combining polar orbits with inclined orbits to provide global coverage and additional capacity over highly-populated mid-latitude areas.

In Telesat's interference assessment, Telesat exceeded PFD limits for the operational angles of arrival between 10 to 13 degrees. Therefore, Telesat provided both a static and dynamic I/N analysis. Figure 2 shows the worst-case scenario used to perform static analysis.

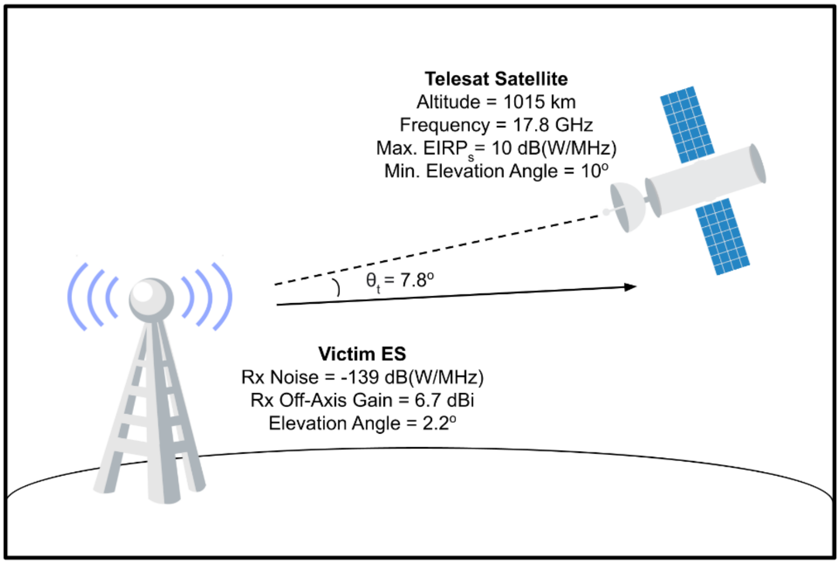



**Figure 2: Telesat Interference into Victim Earth Station**

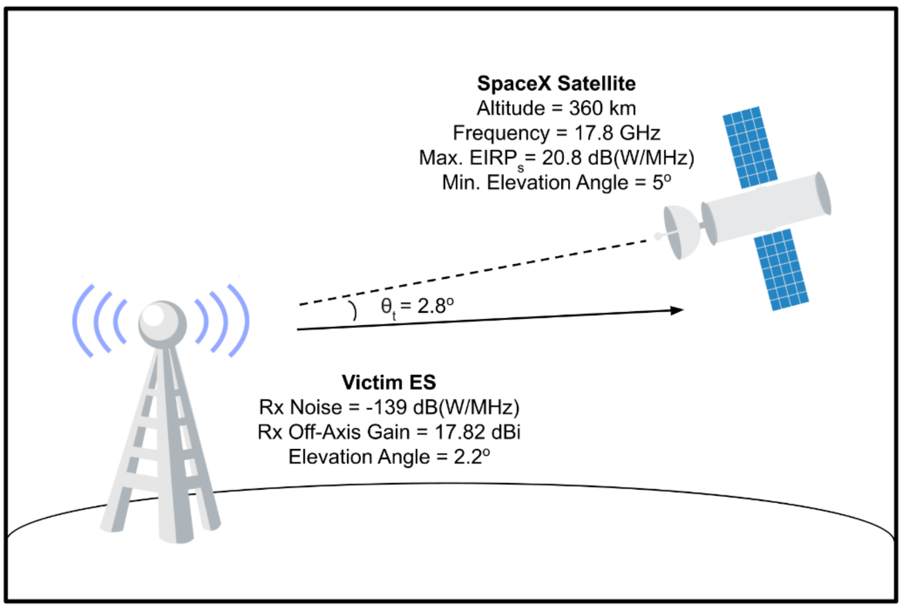
As seen in Figure 2, Telesat's modified constellation was reported to operate at an altitude of 1015 km with a maximum $EIRP_S$ of 10 dB(W/MHz). The minimum elevation angle provided for the Telesat constellation was 10°, making the Rx off-axis angle 7.8°, or the difference between the minimum elevation angle and the victim earth station elevation angle, and the Rx off-axis gain 6.7 dBi. The Table 2 column "I/N Static Validation Assessment" includes these calculations and provides an I/N assessment of Telesat as defined in the Methodology section of this paper. The Table 2 column labeled "Telesat FCC Provided I/N Analyses" collates the parameters taken from the I/N static analysis that Telesat provided in its FCC Technical Narrative [11].

As seen in the second column of Table 2, Telesat had a static I/N of -31.21 dB, meaning it complied with the I/N coordination trigger of -12.2 dB and the long-term dynamic I/N of - 10 dB at the worst case interference scenario. As seen in the third column of Table 2, Telesat's provided static I/N analysis produced an I/N of -14.6 dB. One source of discrepancy between the second and third column of Table 2 is that Telesat included an extra 10 polar satellites, $S_{SL}$, in its calculations. These ten satellites are assumed to be perfectly aligned with the boresight of the victim terrestrial Earth station, and interfere with the station through its side lobes with an EIRP of 30 dB lower on average than at beam peak. These satellites were included to further the worst-case assumptions of the system and contributed to an I/N of -14.6 dB [11]. Without these extra satellites included in the total interference, the calculated I/N for Telesat's assessment is -34.0 dB. This value is 2.79 dB below the I/N validation produced in this assessment due to Telesat including a 3 dB feeder loss and using 17.3 GHz in its FSPL calculations. A frequency of 17.3 GHz was derived from the FSPL equation in Eq. 9 and is below the range of frequencies provided in Telesat's Technical Narrative, but was most likely chosen because it is the lowest frequency in the downlink Ka-band range at which Telesat satellites will operate. Although Telesat's method of calculating I/N led to a higher I/N than the method stated in the Methodology section of this paper, both calculated values complied with the long-term dynamic I/N threshold of -10 dB [5].

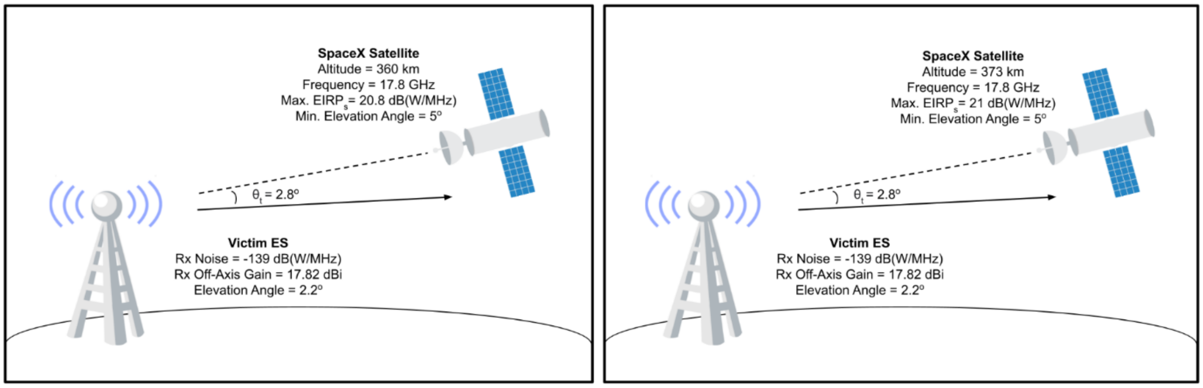
**SpaceX**

SpaceX, headquartered in California, submitted an FCC application in the FCC's March 2020 Ka-Band processing round for its second generation NGSO satellite system, referred to as the Gen2 System. This system included 30,000 ground control facilities, gateway Earth stations, and user Earth stations. The Gen2 system improved upon SpaceX's original Ku-/Ka-band system by increasing capacity and bandwidth, which in turn increases the number of users that can be served.

SpaceX requested authorization to communicate with satellites during the transition phases (orbit-raising and de-orbit), including permission to perform telemetry, tracking, and command (TT&C). In the SpaceX Technical Narrative, accompanying its Schedule S filing, SpaceX outlined that the Gen2 system will use Ka-band spectrum primarily for communication with gateway Earth stations and secondarily with user terminals. This system will operate at eight different altitudes (328 km, 334 km, 345 km, 360 km, 373 km, 499 km, 604 km, 614 km). Gateway beams at altitudes of 360 km and 373 km were reported to have a minimum elevation angle of 5° while all other user and gateway beams were detailed to have a minimum elevation angle of 25° [12]. Figure 3 illustrates the scenario when the minimum elevation angle is 25° as shown to the left of the satellite.




As seen in Figure 3, the SpaceX satellite at an altitude of 614 km has an off-axis angle of 22.8°, found by subtracting the minimum elevation angle of the terrestrial Earth station from the minimum elevation angle of the SpaceX satellite. Figure 4(a,b) illustrates the two scenarios where the minimum elevation angle is 5° for an altitude of 360 km and 373 km, respectively.




**(a)** **(b)**

In Figure 4(a,b) it is seen that the SpaceX satellites at 360 km and 373 km have an off-axis angle of 2.8°. These off-axis angles are dependent on the minimum elevation of the interferer (SpaceX) and victim terrestrial systems and were calculated according to Eq. 6.

PFD calculation verification as shown in "Power Flux Density (PFD) Compliance Validation of FCC's Ka-band NGSO Processing Round Participants" confirmed that SpaceX gateway beams in the polar regions at altitudes of 360 km and 373 km (with a minimum elevation angle of 5°) did not comply with PFD limits [2]. SpaceX justified this by stating that Ka-band PFD limits were not designed to scale up to dynamically controlled NGSO satellites with more than 840 satellites and requested a waiver of these PFD limits [12]. As such, SpaceX included dynamic I/N calculations in its Technical Narrative. SpaceX provided altitudes and the corresponding maximum EIRPs without providing static I/N analysis. Table 3 shows the worst-case static I/N and worst-case static ΔT/T calculations for SpaceX user beams calculated using the procedure described in the Methodology section of this paper. The EIRP values were found on page twelve of the SpaceX Technical Narrative [12].

As all Static I/N values in Table 3 are less than -23.2 dB, all values comply with static coordination trigger of -12.2 dB and the long-term dynamic I/N interference limits of -10 dB [5]. during the entire year. Table 4 shows the calculated worst-case static I/N and worst-case static ΔT/T calculations for SpaceX gateway beams.

In Table 4, gateway beams at all altitudes except 360 km and 373 km complied with an I/N of at least -26.34 dB in the worst-case scenario and there with both the static coordination trigger of -12.2 dB and the long-term dynamic I/N limit of -10 dB. If SpaceX maintains this worst-case scenario for greater than 20% of the year, gateway beams in the polar regions at 360 and 373 km do not comply with the long-term I/N limits established in ITU-R F.1495 [5]. Table 5 includes parameters used to obtain these worst case I/N values for the 360 km and 373 km altitudes.

As seen in Table 5, SpaceX gateway beams at elevations of 360 km and 373 km have I/N values of -5.33 and -5.31 dB, respectively. For both beams, a frequency of 17.8 GHz was used as it is the lowest downlink carrier frequency which leads to the worst-case static I/N. The gateway beam at 373 km has an I/N that is 0.02 dB higher than the gateway beam at 360 km due to having a higher EIRP spectral density which increases the interfering power. Both of these scenarios violate the static coordination trigger of -12.2 dB and the long-term dynamic I/N limit of -10 dB.

**OneWeb**

OneWeb, headquartered in the United Kingdom, submitted an FCC application to modify its low-earth orbit NGSO FSS constellation in two phases. In the first phase, OneWeb requested to deploy four fewer satellites than initially intended, resulting in 716 satellites total. OneWeb also requested to reduce the number of satellites operating in orbits with 87.9° inclination from 720 to 588 satellites. The orbital elements for these 588 satellites will be redistributed to provide more uniform service. In addition, 128 of the satellites in the 87.9° orbital plane are being shifted to a 55° inclination. In the second phase, OneWeb requested to launch up to 47,844 additional satellites, featuring satellites with different antenna beam designs from the current system. Despite updated beam patterns, these satellites will continue to operate at the same maximum EIRP density levels as were authorized by the FCC in 2017 [13].

To prove that the modified NGSO constellation would not increase interference into FS systems, OneWeb provided dynamic I/N assessments for its Phase 1 modifications and both static and dynamic I/N assessments for its Phase 2 modifications in the respective Technical Narratives [13]. However, the static I/N assessment in its Phase 1 modifications assessed interference into other NGSO systems, not terrestrial networks, so this analysis is not relevant for this work. Since the difference in the Phase 1 modification was to reduce four fewer satellites, OneWeb stated that there was no impact to PFD or interference into terrestrial networks from its previous application [13, 14]. Since OneWeb did not provide static I/N analyses for Phase 1, discrepancy between OneWeb's methodology for static I/N calculations for Phase 1 will not be assessed.

Figure 5 provides the worst-case scenario used to perform the static I/N assessment described in the Methodology section of this paper.

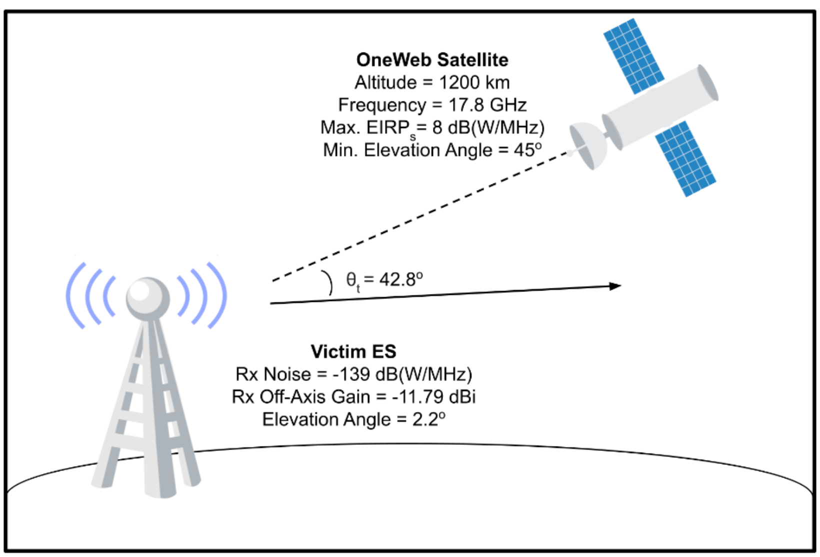



**Figure 5: OneWeb Interference into Victim Earth Station**

As seen in Figure 5, the OneWeb satellites operate at an altitude of 1200 km at a minimum elevation angle of 45° to its user. Note that OneWeb expects its elevation angle to be typically greater than 50° during service, but 45° was used in the validation assessment to create the worst case interference scenario [13]. Table 6 further presents the values used for the static I/N assessment of OneWeb's Phase 1 modification. The altitude, frequency, minimum elevation angle, and max EIRP spectral density shown in Table 6 are pulled directly from the OneWeb Phase 1 Technical Narrative [13].

As seen in Table 6, this study calculated OneWeb's Phase 1 I/N ratio to be -46.46 dB, which is 34.26 dB below the -12.2 dB coordination trigger and 36.46 dB below the -10 dB long-term dynamic threshold limit [5]. As previously mentioned, this I/N value can not be compared with OneWeb's own static I/N value because OneWeb did not report a static value for its Phase 1 static I/N.

Table 7 presents the values used for the static I/N assessment of OneWeb's Phase 2 modification. The altitude, frequency, minimum elevation angle, and max EIRP spectral density shown in Table 7 are pulled directly from the Phase 2 Technical Narrative [13]. Two calculation cases are shown: the static I/N validation assessment as defined in the Methodology, and OneWeb's provided static I/N analyses. Conducting this calculation with the methodology presented in the Methodology section of this paper yields a Phase 2 static I/N of -38.4 dB, a value higher than the Phase 1 I/N of -46.46 dB, but still 36.6 dB below the static I/N coordination trigger of -12.2 dB and long-term dynamic -10.0 dB limit. OneWeb reported a worst-case I/N of 4.7 dB, however, a value that is 43.1 dB greater than -38.4 dB. The approach OneWeb used for computing this value differed from the approach in this work, and followed the equation provided in Eq. 12s:

$$\frac{I}{N} = PFD - 10\log_{10}(4\pi\left(\frac{f}{0.3}\right)^2) + G_{Rx} - (kT_0B + NF) \tag{12}$$

In this equation, PFD is the power flux spectral density measured in dBW/m²/MHz, f is the transmitting frequency in GHz (the expression $\frac{f}{0.3}$ is thereby equivalent to the reciprocal of wavelength), GRx is the victim (receive) antenna gain, $kT_0B$ represents background thermal noise (-139.0 dB according to ITU-R SF.1483), and NF is a noise factor term. Three differences exist between the OneWeb calculation, and the calculation performed in this study, otherwise the methods are mathematically equivalent. These differences are:

1. OneWeb assumed a 0° elevation angle for the receiving system with the interfering satellite transmitting at boresight, resulting in no reduction in victim antenna gain due to off-axis effects.
2. OneWeb included a noise factor (NF) term in its calculation of background noise. Note that a noise factor term is not included in Appendix 8 calculations of I/N [7]. This noise factor decreased OneWeb's I/N estimate by 5 dB.
3. As seen in the third column in Table 7, OneWeb did not provide the frequency that they used for performing its static I/N calculations. However, a frequency of 10.7 GHz can be derived from Equation 12 as all other parameters in the equation are known. Equation 12 is listed in OneWeb's filings as a Ka-band calculation, which has a minimum frequency of 17.8 GHz, but OneWeb appears to have performed this calculation at Ku-band which has a minimum frequency of 10.7 GHz.

Note that OneWeb used a PFD spectral density of -135.2 dBW/m$^2$/MHz, which cannot be correlated to an EIRP spectral density without knowing the bandwidth of a OneWeb satellite (bandwidth was not reported in either Technical Narrative). The Phase 2 Technical Narrative does state, however, that the maximum EIRP spectral density is 8.0 dBW/MHz, and so this value was used in both assessments of OneWeb I/N. OneWeb did not explain the reason for using a spectral density of -135.2 dBW/m$^2$/MHz.

From these calculations it can be concluded that OneWeb complies with the static I/N coordination trigger of -12.2 dB and the long-term dynamic -10 dB I/N requirement in the scenario laid out by the ITU and that in the particular worst-case scenario that OneWeb constructed, the company complies with the short term dynamics I/N requirement of 14 dB, as defined in ITU-R F.1495 so long as it does not maintain that interference level for more than 73 days out of any year.

## Conclusion

This paper evaluated the static I/N of three companies (Telesat, SpaceX, and OneWeb) that participated in the March 2020 NGSO fixed-satellite service (FSS) Ka-band processing round. For each company, a static I/N analysis was performed to evaluate whether each company would protect the hypothetical FS earth station as described in ITU-R SF.1483.

The ITU defines a coordination trigger of I/N = -12.2 dB for static assessments and in ITU-R F. 1495's defines a long-term dynamic I/N limit of -10 dB limit for more than 20% of the time in a year [5]. Therefore, -10 dB was used as the threshold to determine if further dynamic studies are required to validate compliance. Table 8 provides a summary of each system's static I/N validation. As seen in Table 8, Telesat and OneWeb's static I/N validation assessments complied with both the coordination trigger of -12.2 dB and were below the long-term -10 dB threshold by more than 20 dB. Two of the SpaceX orbits, 360 km and 373 km exceeded the long-term -10 dB static I/N threshold for its gateway beams. These two SpaceX orbits, at altitudes of 360 km and 373 km, are both included in Table 8. All other SpaceX orbits (328 km, 334 km, 345 km, 499 km, 604 km, and 614 km) complied with the static I/N limit by at least -23.4 dB for user beams, and by at least -26.34 dB for gateway beams.

In accordance with ITU-R F. 1495, for satellites to protect a victim FS Earth Station, I/N should not exceed -10 dB for more than 20% of the time in any year [5]. SpaceX exceeded the long-term -10 dB I/N limit according to this study's static I/N analysis. Further dynamic I/N studies on SpaceX's system will be made to fully evaluate its compliance.

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## Tables

**Table 1. FS link characteristics as described in ITU-R SF.1483.**

| | |
|---|---|
| Elevation Angle (degrees) | 0 and 2.2 |
| Antenna Height (m) | 0 |
| Antenna Gain (dBi) | 32, 38 and 48 |
| Antenna Pattern | Recommendation ITU-R F.1245 [9] |
| Feeder Loss (dB) | 3 |
| Receiver Thermal Noise (dB(W/MHz)) | -139 |

**Table 2. Telesat Static I/N Validation Assessment vs. Telesat FCC Provided Static I/N Analyses**

| Parameter | **Telesat Static I/N Validation** | **Telesat FCC Provided I/N Analyses (including 10 additional satellites)** |
|---|---|---|
| Altitude (km) | 1015 | N/A |
| Frequency (GHz) | 17.8 | N/A |
| Telesat Minimum Elevation Angle (degrees) | 10 | N/A |
| Victim System Elevation Angle (degrees) | 2.2 | N/A |
| Victim Rx Antenna Gain (dBi) | 48 | 48 |
| Off-Axis Angle (degrees) | 7.8 | 7.8 |
| Victim Rx Off-Axis Antenna Gain (dBi) | 6.7 | 6.7 |
| Free Space Path Loss for Telesat Satellite (dB) | 186.9 | 186.7 |
| Free Space Path Loss from Telesat $S_{SL}$ Satellites | N/A | 188.7 |
| Telesat Satellite Max. $EIRP_S$ (dB (W/MHz) | 10.0 | 10.0 |
| Telesat Side-Lobe $EIRP_S$ from each of Satellites $S_{SL}$(dB (W/MHz)) | N/A | -20.0 |
| Telesat Total Interfering $EIRP_S$ from all Satellites $S_{SL}$ (dB (W/MHz)) | N/A | -10 |
| Feeder Loss (dB) | N/A | 3.0 |
| Interfering Power from Telesat Satellite at the input of the Victim Receiver(dB (W/MHz) | -170.21 | -173.0 |
| Interfering power from Telesat $S_{SL}$ Satellites at the input of the Victim Receiver (DB (W/MHz) | N/A | -153.7 |
| Total Interfering Power | -170.21 | -153.6 |
| Receive Thermal Noise (dB(W/MHz) | -139.0 | -139.0 |
| Max. I/N (dB) | -31.21 | -14.6 |
| ΔT/T (%) | 0.08 | 3.47 |

**Table 3: Static I/N Calculations for All Altitudes (User Beams)**

| Altitude (km) | Max EIRP (dBW/MHz) | Static I/N (dB) | Static ΔT/T (%) |
|---|---|---|---|
| 328 | 17.6 | -23.34 | 0.46 |
| 334 | 17.8 | -23.28 | 0.47 |
| 345 | 18.0 | -23.34 | 0.46 |
| 360 | 18.4 | -23.27 | 0.47 |
| 373 | 18.7 | -23.25 | 0.47 |
| 499 | 20.9 | -23.29 | 0.47 |
| 604 | 22.4 | -23.24 | 0.47 |
| 614 | 22.5 | -23.26 | 0.47 |

**Table 4: Static I/N Calculations for All Altitudes (Gateway Beams)**

| Altitude (km) | Max EIRP (dBW/MHz) | Static I/N (dB) | Static ΔT/T (%) |
|---|---|---|---|
| 328 | 14.6 | -26.34 | 0.23 |
| 334 | 14.8 | -26.28 | 0.24 |
| 345 | 15.0 | -26.34 | 0.23 |
| 360 | 20.8 | -5.33 | 29.32 |
| 373 | 21.0 | -5.31 | 29.45 |
| 499 | 17.9 | -26.29 | 0.23 |
| 604 | 19.4 | -26.24 | 0.24 |
| 614 | 19.5 | -26.26 | 0.24 |

**Table 5. SpaceX  Static I/N Validation Assessment for Gateway Beams at Altitudes = 360 km, 373 km**

| Parameter | Static I/NValidation Assessment (dB) for Gateway Beams at 360 km | Static I/N Validation Assessment (dB) for Gateway Beams at 373 km |
|---|---|---|
| Altitude (km) | 360 | 373 |
| Frequency (GHz) | 17.8 | 17.8 |
| SpaceX Minimum Elevation Angle (degrees) | 5 | 5 |
| Victim System Elevation Angle (degrees) | 2.2 | 2.2 |
| Off-Axis Angle  (degrees) | 2.8 | 2.8 |
| Victim Rx Off-Axis Antenna Gain (dBi) | 17.82 | 17.82 |
| Path Length (km) | 1883.64 | 1923.22 |
| Free Space Path Loss (dB) | 182.95 | 183.13 |
| SpaceX Satellite Max. EIRP Spectral Density (dB (W/MHz) | 20.8 | 21 |
| Interfering Power from SpaceX Satellite at the input of the Victim Receiver(dB (W/MHz) | -144.33 | -144.31 |
| Receive Thermal Noise (dB(W/MHz) | -139 | -139 |
| Max. I/N (dB) | -5.33 | -5.31 |
| $\Delta T/T$ (%) | 29.32 | 29.45 |

**Table 6. OneWeb Phase 1 Static I/N Validation Assessment**

| Parameter | OneWeb Phase 1 Static I/N Validation |
|---|---|
| Altitude (km) | 1200 |
| Frequency (GHz) | 17.8 |
| OneWeb Minimum Elevation Angle (degrees) | 45 |
| Victim System Elevation Angle (degrees) | 2.2 |
| Off-Axis Angle (degrees) | 42.8 |
| Victim Rx Off-Axis Antenna Gain (dBi) | -11.79 |
| Path Length (km) | 1626.91 |
| Free Space Path Loss (dB) | 181.68 |
| OneWeb Satellite Max. EIRP Spectral Density (dB (W/MHz)) | 8.00 |
| Interfering Power from OneWeb Satellite at the input of the Victim Receiver(dB (W/MHz)) | -185.464 |
| Receive Thermal Noise (dB(W/MHz)) | -139.0 |
| Max. I/N (dB) | -46.46 |
| ΔT/T (%) | 0.002 |

**Table 7. OneWeb Phase 2 Static I/N Validation Assessment vs. OneWeb FCC Provided Phase 2 Static I/N Analyses**

| Parameter | OneWeb Phase 2 Static I/N Validation | OneWeb FCC Provided Static I/N Analyses |
|---|---|---|
| Altitude (km) | 1200 | N/A |
| Frequency (GHz) | 17.8 | N/A |
| OneWeb Minimum Elevation Angle (degrees) | 15 | N/A |
| Victim System Elevation Angle (degrees) | 2.2 | 0 |
| Off-Axis Angle (degrees) | 12.8 | 0 |
| Victim Rx Antenna Gain (dBi) | 1.32 (off-axis) | 48 (boresight) |
| Path Length (km) | 2916.402 | N/A |
| Free Space Path Loss (dB) | 186.747 | 185.269 |
| OneWeb Satellite Max. EIRP Spectral Density (dB (W/MHz)) | 8.00 | N/A |
| Interfering Power from OneWeb Satellite at the input of the Victim Receiver(dB (W/MHz)) | -177.427 | N/A |
| Receive Thermal Noise (dB(W/MHz)) | -139.0 | -139.000 |
| Noise Factor (dB) | N/A | 5 |
| Max. I/N (dB) | -38.427 | 4.7 |

**Table 8. Summary of the Static I/N Validation Assessment**

| System | I/N Static Validation Assessment |
|---|---|
| **Telesat** | **-31.21 dB** |
| **SpaceX (Gateway Beam at Altitude of 360 km)** | **-5.33 dB** |
| **SpaceX (Gateway Beam at Altitude of 373 km)** | **-5.31 dB** |
| **OneWeb** | **-46.46 dB** |

## Biographies

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Antoinette Tan is a second-year undergraduate student at Olin College majoring in Electrical and Computer Engineering. She currently works as a student researcher in the Olin Satellite + Spectrum Technology & Policy Group (OSSTP) where she is building a software suite for Link Budget computations and leading a research team focused on interference assessment and validation. On campus, Antoinette is part of Olin's Formula SAE team and is taking on the role of the Electrical Vehicle Subteam Lead this year.

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Pranavi Boyalakuntla is a fourth-year undergraduate student at Olin College of Engineering majoring in Electrical and Computer Engineering. She is a student researcher in the Olin Satellite + Spectrum Technology & Policy Group (OSSTP) where she is conducting research in satellite interference, link budget computations, and spectrum policy.

**Braden Oh**

Braden Oh is a third-year undergraduate student at Olin College of Engineering majoring in Engineering Physics. He currently works for OSSTP as a student researcher and systems engineer for the SWARM-EX CubeSat mission. Previous work of his has included leadership of teams developing miniature Hall effect thrusters and software system verification and validation for the Perseverance Mars rover at the NASA Jet Propulsion Laboratory.

**Utsav Gupta**

Utsav Gupta is an Electrical Engineer at Whoop where he works on the Platform R&D team. He graduated from Olin College with a B.S. in Electrical and Computer Engineering. At Olin, Utsav was a Research Assistant under Prof. Lohmeyer at OSSTP Group. His work at OSSTP includes Ka/Ku-band antenna systems for LEO satellites, interference mitigation for satellite communications, and ground station development. When not in the lab herding electrons, Utsav may be found cooking, rock climbing or biking around the city.

**Whitney Q. Lohmeyer**

Whitney Lohmeyer is an Assistant Professor of Engineering at Olin College and a Research Affiliate at MIT in Aeronautics and Astronautics. She leads the Olin Satellite + Spectrum Technology & Policy (OSSTP) Group, and manages and contributes to the field of satellite communications systems. She also works closely with industry to advise on end-to-end system design, antenna systems, RF power amplification, radiation tolerance and spectrum strategy. Whitney was the first engineer hired at OneWeb, a company launching hundreds of a low earth orbit communications satellites to provide global broadband. While at OneWeb, she held a variety of roles both technical and policy-focused. Prior to joining the OneWeb team, she worked as a hardware engineer at Google, and spent time in technical roles at Inmarsat and NASA. Whitney received her Ph.D. and M.S. in Aeronautics and Astronautics from MIT in 2015 and 2013, respectively. She earned her B.S. in Aerospace Engineering from NC State University in 2011, as the only female in her class of approximately ninety students, and now currently serves on the board of North Carolina State University’s Mechanical and Aerospace Engineering (MAE) Department.