A Risk Assessment Framework for NGSO-NGSO Interference

Satellite Communication Plan Working Group*

FCC Technological Advisory Council

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The Working Group recognizes that the issues discussed in this paper are the subject of pending adversary proceedings at the Commission, including in individual satellite license and market access applications. Many of these proceedings are the subject of pending Petitions to Deny, Opposition and separate comments currently under consideration. It is not possible to reflect all views without a complete analysis. This paper describes a method but does not offer a complete analysis or comparison to other methods. It draws no conclusions that are applicable to matters pending before the Commission.

Abstract

The Federal Communications Commission (FCC) Technical Advisory Committee (TAC) recommended the use of quantitative risk assessment to evaluate radio interference two years ago (FCC TAC, 2015a). This paper explores the potential of quantitative risk assessment in studying the radio coexistence of multiple non-geostationary satellite orbit (NGSO) systems.

Engineering risk can be defined as the combination of likelihood and consequence for multiple failure scenarios. A Risk-Informed Interference Assessment (RIIA) has four elements: make an inventory of hazards (i.e., potential sources of harm); define a consequence metric to quantify the impact of those hazards; calculate likelihood-consequence values for each hazard; and aggregate the results to inform analysis of a coexistence situation. This paper focuses on the first two elements, and does not perform any risk calculations.

The analysis considers baseline hazards (those that occur in the absence of interference) as well as co-channel and adjacent-channel interference hazards. It identifies possible consequence metrics, notably percentage degradation in throughput from a reference value, and percentage degradation in unavailability. It then outlines how percentage throughput degradation might be calculated, resulting in likelihood-consequence distributions; and considers how some system parameter assumptions (e.g., channelization and antenna patterns) might affect the results. An approach to NGSO-NGSO interference risk management based on observed degradation is offered for discussion in an appendix.

The paper concludes that the FCC, network operators and/or other analysts could apply risk-informed interference assessment to NGSO-NGSO interference, where appropriate.

Contents

1 Introduction

This document explores ways to assess and manage the coexistence of non-geostationary satellite orbit (NGSO) systems. It focuses on a frequency band not subject to Article 9 of the ITU Radio Regulations (RR), the V-band (37.5 GHz to about 51 GHz). An outline of the contents is provided in Section 1.4.

1.1 Motivation

The FCC 2017 TAC Working Group on Satellite Communication was asked to consider "streamlining the regulatory process, the impact on current satellite operations from expected scaling of operations in both frequency and number, the effect of possible interference from satellites operation in low- and medium-Earth orbit (LEO and MEO), and proposals that would allow for higher spectral efficiency and lower costs for satellite communication needs" (FCC TAC, 2017, p. 71).

The Working Group tasked a sub-group to explore whether and how framing a Risk-Informed Interference Assessment (RIIA) could assist in maximizing the value of non-geostationary satellite orbit (NGSO) systems. The sub-group decided to focus discussion about RIIA for NGSO operations in the V-band.

The TAC recommended the use of quantitative risk assessment to evaluate radio interference two years ago (FCC TAC, 2015a). At a high level, risk assessment can provide a common currency for comparing different hazards—a term that generally denotes potential sources of harm, and in this context can refer to radio interference scenarios—and enhance the completeness of analysis and increase the chances of identifying unexpected harmful interference mechanisms. Ultimately, RIIA can provide objective information to policy decision makers balancing the benefits of a new service and its adverse technical impact on incumbents (FCC TAC, 2015a).

NGSO systems

For this analysis, satellite systems are classified by their orbits. Systems in geostationary orbit (GSO) are at an altitude of about 36,000 km, so that their orbital period equals the Earth's rotation; they thus appear motionless in the sky to ground observers.

Non-GSO (NGSO) systems are loosely classified as low-Earth orbit (LEO) with approximate altitudes 500–2,000 km, medium-Earth orbit (MEO) at 8,000–20,000 km, and highly elliptical orbit (HEO) with perigee around 500 km and apogee less than 50,000 km.

The corresponding approximate orbital periods for LEO are 1.5–2 hours, and MEO 4.7–11.8 hours. If one assumes a satellite passing over the zenith, its duration of visibility above 45° elevation is 2–8 minutes for LEO at 500–2,000 km, and 0.7–2.3 hours for MEO at 8,000–20,000 km.

In the NGSO-NGSO case, risk assessment could be used, first, to assess whether rules are necessary at all (i.e., is the risk large enough to warrant rules, given the effort needed to create and implement them, and the inevitable unintended side effects); second, if rules are necessary, to focus attention on the important hazards; and third, as a technique for technical studies such as the one reported in Canada (2017). For example, applicants in NGSO proceedings have calculated the worst-case probability of in-line interference events (Telesat Canada, 2017, Exhibit 1, and references therein). However, the occurrence of an in-line alignment event does not necessarily imply harmful interference (FCC 2017c, paras 47, 49), let alone quantify the severity of the interference in terms of, say, the degradation in throughput or the increase in received signal unavailability. If the risk—defined as the likelihood and severity of a hazard, see Section 2—is very low, specific rules on ways to conduct coordination may not be worthwhile. If there appears to be a significant risk, there needs to be an assessment of what the main difficulties are.

Quantitative risk assessment can, for example, inform judgments about the relative importance of interference hazards in the uplink versus the downlink, and between similar or dissimilar systems (e.g., LEO-LEO vs. LEO-MEO). It can also help determine which operating parameters (equivalent isotropic radiated power, antenna gain, out-of-band emission, receiver selectivity, etc.) have the most impact on the probability and severity of interference.

This paper will not provide the guidance described in the previous paragraph. Rather, it will outline a method by which such information can be obtained; in other words, we outline a framework for NGSO

Licensing

A company needs to obtain authority to launch and/or operate an NGSO constellation in a given frequency band from a national regulator, e.g., the FCC in the United States. For example, OneWeb was granted market access in the United States for its Ku-band/Ka-band NGSO FSS system in June 2017 (FCC, 2017b). Also, the Boeing Company has requested this authority from the FCC for the V-band (Boeing, 2017). If Boeing is successful, it will receive a license to operate satellites and space station transmitters.

In addition to obtaining this authority from one country, a company typically also needs to obtain regulatory authorizations from national administrations in each additional market where it in wishes to provide services.

At the FCC, when a company applies for a U.S. license for its satellite(s) or for U.S. market access to provide services in a frequency band, it may trigger a processing round (47 CFR 25.156 and 25.157) which may result in some, all or none of the applications being granted. Earth station licenses are issued separately (47 CFR 25.115).

The company also must file a Coordination Request with the ITU Radiocommunications Bureau through a national administration—for the United States, the FCC (see ITU Radio Regulations, Articles 9 and 11).

If the company plans to operate a commercial remote sensing space system in the U.S., the spacecraft are licensed by the Commerce Department's National Oceanic and Atmospheric Administration, pursuant to the National and Commercial Space Programs Act, with the commercial operating frequencies licensed by the FCC.

risk-informed interference assessment for the V-band, rather than performing such an assessment.

1.2 *Approach*

The FCC TAC's introduction to RIIA outlines the use of quantitative risk analysis to assess the potential harm that may be caused by changes in radio service rules (FCC TAC, 2015a). It adopts the ISO/IEC formulation that "the purpose of risk assessment is to provide evidence-based information and analysis to make informed decisions on how to treat particular risks and how to select between options"; in the spectrum management case, the risk is that of harmful interference and the selection is between various possible technical mitigations and service rules. This technique has been used for decades in many regulated industries (*see* De Vries, 2017, Section 2.2.2), and has been applied in spectrum policy (*see e.g.,* De Vries, Livnat & Tonkin, 2017; Voicu, Simić, De Vries, Petrova & Mähönen, 2017).

Engineering risk can be defined as the combination of likelihood and consequence for multiple failure scenarios. Figure 1 shows a generic risk chart with these two axes.

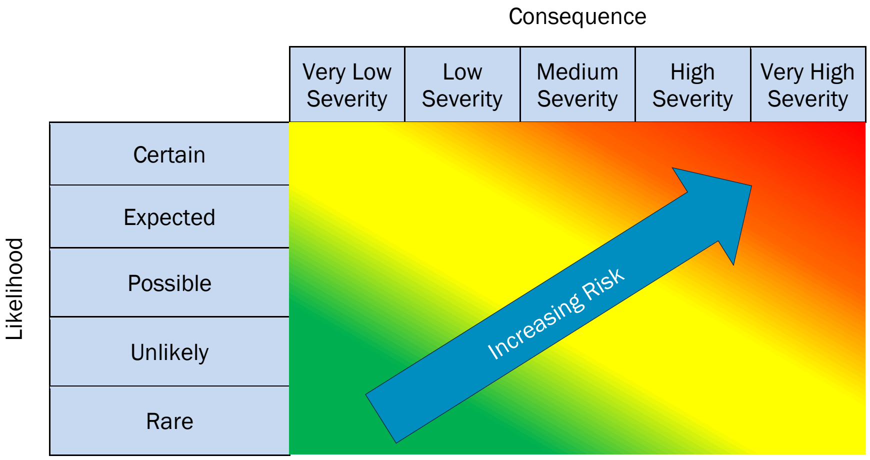


Figure 1. A generic risk chart.

A pro forma RIIA has four elements:

1. Make an inventory of hazards.
2. Define a consequence metric to quantify impact of those hazards.
3. Calculate likelihood-consequence values for each hazard.
4. Aggregate the results to inform analysis of a coexistence situation and the requirement for service rules.

According to a risk analyst with decades of experience in many industries, it is important to start with the top-down view, and focus analytical effort to establish in broad terms which domains are more—or less—risky. At an operational level, risk assessment can focus attention on key elements of design; determine system features; and identify design weaknesses (J. Fragola, presentation to TAC Satellite WG, July 13, 2017).

This paper focuses on the first two RIIA elements:

1. *Make an inventory of hazards*. This inventory should list possible interference scenarios and express these in terms of hazards. In addition to interference from known, intentional radiators, there may also be degradation due to spurious, unintentional and incidental emissions; non-linearities in receiving systems; and intentional jamming (which are outside the scope of this assessment). There may be degradation of the desired signal, and non-interference faults and failures. An inventory would attempt to identify all significant potential hazards. In a full RIIA, this list could be refined iteratively as risk calculations (elements 3 and 4) indicate which can be safely ignored, and which require more attention.

2. *Define consequence metric(s)*. A consequence metric represents the degree of harm posed by a hazard. It is a tool for comparing the risks of different hazards, and to compare new risks against the baseline situation. There are usually many candidate consequence metrics, including radio frequency (RF) metrics and service indicators. Limiting attention to one or at most a few metrics will help decision makers process the results of an analysis.

A quantitative risk assessment entails doing probability calculations. The common use of probabilistic input and output parameters in satellite studies facilitates this. The most obvious in this context is tables of values of equivalent power-flux density produced by NGSO systems that may not be exceed for the given percentages of time; see e.g., Table 1G in 47 CFR 25.208 (g). Probabilities are also used elsewhere; for example, ITU-R Recommendation P.618-12 uses a variety of such parameters, e.g., the predicted attenuation exceeded for 0.01% (~ 52 minutes) of an average year, and the probability of rain at an Earth station (ITU-R, 2015).

1.3 NGSO satellite constellations

The RIIA framework used in this paper is not limited to specific frequency bands; however, the discussion focuses on the V-band. This band is not subject to formal coordination between NGSO systems under Article 9 of the ITU Radio Regulations. Because the V-band has not yet been extensively used by satellite operators, it could therefore be well suited to a RIIA approach. The FCC's "V-band processing round" considers applications for operation by NGSO systems in the 37.5–40.0, 40.0–42.0, 47.2–50.2 and 50.4–51.4 GHz frequency bands (FCC 2016a). The U.S. Non-Federal Table of Allocations (FCC, 2017a) includes the following for Fixed-Satellite Service (FSS):

- Space-to-Earth: 37.5–42 GHz (4.5 GHz bandwidth)
- Earth-to-space: 47.2–50.2, 50.4–51.4 GHz (3 + 1 GHz bandwidth)

Table 1 summarizes some key characteristics of proposed V-band NGSO systems filed for licenses (market access and space station) at the FCC and currently pending.

1.4 Outline of document

Sections 2 through 5 describe the four elements of a risk-informed interference assessment, and describes how they would be applied to NGSO-NGSO coexistence. Section 6 provides a conclusion. The Appendix offers for discussion an approach to NGSO-NGSO interference risk management based on observed degradation rather than on predictive measures. The discussion is limited to Earth-space and space-Earth links, but a similar method can be used for interference between inter-satellite links.

2 First element: Identify Hazards

The first step in quantitative risk assessment is to make an inventory of all expected hazards, a term of art used in RIIA that includes phenomena that could, but do not necessarily, cause harm. The interaction between two radio systems is affected by the locations of the interfering and affected systems, the characteristics of the transmitters and receivers of the two systems, and the coupling between them. The coupling depends on factors such as antenna gain patterns and propagation loss.

We next distinguish between baseline and coexistence hazards.

2.1 Baseline hazards

Baseline hazards in RIIA are those that occur in the absence of radiofrequency interference, and include degradation of the desired signal due to propagation impairment, as well as non-interference faults and failures such as operator error, power outages, device misconfiguration, and device degradation due to environmental factors. One common baseline hazard, especially in the frequency bands of concern here, is propagation impairment. ITU-R Recommendation P.618-12 notes that propagation loss on an Earth-space path, relative to the free-space loss, is the sum of different contributions including attenuation by atmospheric gases, rain, other precipitation and clouds, and sand and dust storms; focusing and defocusing; beam-divergence and beam-bending; decrease in antenna gain due to wave-front incoherence; scintillation and multipath effects; path depolarization; all related to the varying elevation angle to the satellite (ITU-R 2015, Sections 1 and 2).

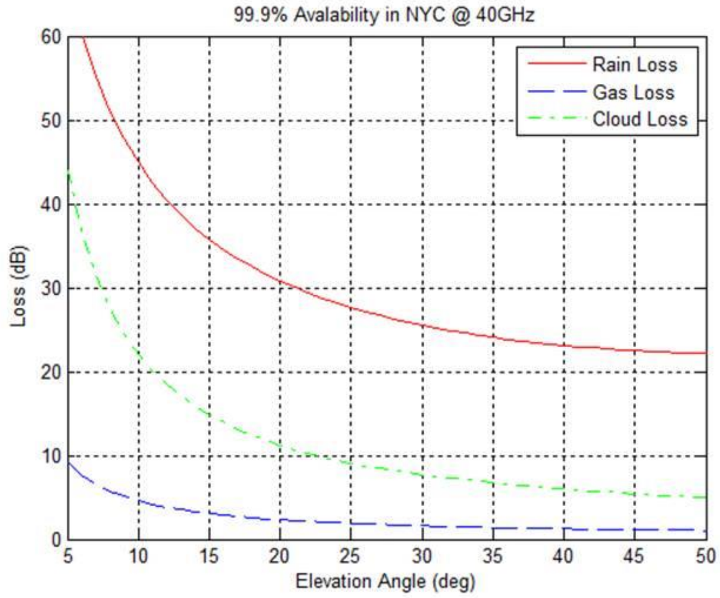
Table 1. Proposed V-band deployments.

Network	Constellation	Purpose	Call sign
Audacy	3 MEO (FSS and RF ISS); circular orbits inclined at 25°, 13,892 km altitude	Space-based data relay constellation; V-band communications with data centers in San Francisco and Singapore	S2982
Boeing NGSO System	Initial deployment: 1,395 LEO at 1,030 and 1,082 km altitude, 45° and 55° Final deployment: 2,956 LEO including near-polar (88°) at 970 km	Broadband internet and communications services	S2966
Boeing V-band Constellation	132 LEO at 1,056 km altitude 15 inclined NGSO at approximately GSO elevation, 63.4° inclination RF ISS within the constellation	Broadband internet and communications services	S2993
O3b	24 MEO in equatorial orbits, altitude 8,062 km	Low-latency, high-throughput satellite connectivity	S2935
OneWeb (WorldVu)	720 LEO at 1,200 km, polar 1,280 MEO at 8,500 km, inclined at 45°	High-throughput connectivity	S2994
SpaceX (Space Exploration Holdings)	Initial deployment: 1,600 LEO at 1,150 km altitude, 53° inclination Final deployment: 4,425 LEO at altitudes 1,110 km to 1,325 km, 53° to 81° inclination VLEO (Very Low Earth Orbit) deployment: 7,518 satellites operating at altitudes 335 km to 346 km	Broadband services	S2992
Telesat Canada	72 polar LEO at 1,000 km, 99.5° inclination 45 LEO at 1,248 km, 37.4° inclination	Broadband offerings in currently unserved and underserved areas	S2991
Theia	120 polar LEO at 750 to 809 km, 98.4° to 98.6° inclination	Communications and remote sensing	S2986
ViaSat	24 polar MEO at 8,200 km, 87° inclination	Broadband internet and communications services	S2985

Note: References are to radio services only; for example, ISS here refers only to radio inter-satellite service.

Propagation impairments such as rain, cloud and gaseous absorption can substantially affect fixed-satellite service (FSS) satellite links. In higher frequency bands, such as the V-band, these propagation impairments can have significant impacts on FSS intra-service sharing parameters: larger atmospheric fades can affect the difference in attenuation between two satellite signal paths.

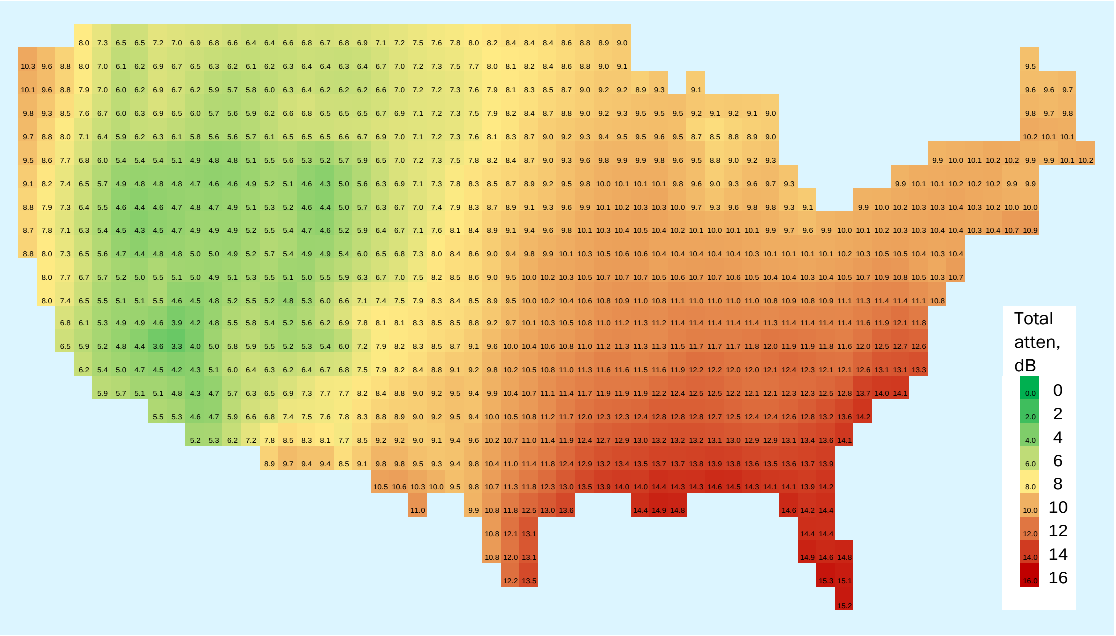
To illustrate potential losses, Figure 2 presents an overview of losses to a satellite link operating with 99.9% availability at 40 GHz. For this figure, rain fade was calculated using ITU-R Recommendation P.618, and cloud and gas losses were calculated using ITU-R Recommendation P.840.



Source: ITU-R WP4A/519 Annex 23 (ITU-R WP4A, 2017c)

Figure 2. Losses to a satellite link operating with 99.9% availability at 40 GHz.

Figure 3 illustrates the total attenuation due to atmospheric gases, clouds, rain, and scintillation, plotting the values exceeded 1% of the time over the continental U.S. It is an implementation of various ITU-R Recommendations for gas, cloud, rain attenuation, and scintillation models (CNES, 2016).



Source: CNES (n.d.). Visualization courtesy FCC staff.

Figure 3. Visualization of propagation losses for Earth to space transmission links.

2.2 *Coexistence hazards*

Coexistence hazards in RIIA include intentional, unintentional and incidental interference; and in-band, out-of-band and spurious emissions (harmonic emissions, parasitic emissions, intermodulation products and frequency conversion products); *see* 47 CFR 15.3. In the case of NGSO-NGSO interactions, the most common instance of such interference would likely be alignment events between satellites and Earth stations of two NGSO constellations. As most NGSO constellations are filed to use the entire spectrum available in each band (e.g., V-band), sharing between two NGSO systems is always a co-frequency case. Therefore, co-polarized and co-frequency interference will be much more significant than unwanted emissions (such as out-of-band and spurious emissions). An FSS sharing scenario that would involve adjacent channel or out-of-band emissions is two systems that split a band, as in the FCC default band segmentation approach in the absence of a coordination agreement (FCC, 2017c). Adjacent or overlapping channel use may occur if one or both links in an alignment use subchannels rather than the full band.

Co-frequency interference may result in harmful interference, i.e., interference “which endangers the functioning of a radionavigation service or of other safety services or seriously degrades, obstructs, or repeatedly interrupts a radiocommunication service operating in accordance with Radio Regulations” (47 CFR 2.1). The hazards caused by intentional interference (i.e., signal jamming) are beyond the scope of this study.

Table 2. Major radio interference hazard scenarios

	Gateway transmitter	Satellite transmitter	User terminal transmitter
Gateway receiver	Gateway → Gateway Zero risk, unless bands are used bi-directionally (both as uplink and downlink) Negligible risk, if bands are used bi-directionally, gateways are both at ground level so their antenna beams, directed at satellites, have good angular separation, and gateway antennas can be maintained at sufficient distance from each other	Satellite → Gateway NGSO1 interfering downlink transmission co-channel & in beam alignment with desired downlink for NGSO2 received at gateway *Note: Downlink power limited by power flux density (pfd) to protect terrestrial services, so signals of both systems may be comparable in level*	User terminal → Gateway Zero risk, unless bands are used bi-directionally (both as uplink and downlink) Small risk, if bands are used bi-directionally, since gateways and user terminals are both at ground level. Thus, their antenna beams, directed at satellites, have good angular separation. However, this depends on distance between user terminal and gateway
Satellite receiver	Gateway → Satellite NGSO1 interfering uplink transmission from gateway co-channel & in beam alignment with desired uplink for NGSO2 from either its gateway or user terminal *Note: Gateways have higher transmit power than user terminals, although beams may be narrower*	Satellite → Satellite Zero risk, unless bands are used bi-directionally (both as uplink and downlink) or one system uses FSS bands for inter-satellite services Two applicants in the current round (Boeing V-band Constellation and Audacy) propose intra-system inter-satellite links Limited risk, given that, even if both proposals move forward, bilateral coordination is relatively straightforward; if additional systems seek to provide inter-satellite links, the risk would increase	User terminal → Satellite NGSO1 interfering uplink transmission from user terminal co-channel & in beam alignment with desired uplink for NGSO2 from either its gateway or user terminal
User terminal receiver	Gateway → User terminal Zero risk, unless bands are used bi-directionally (both as uplink and downlink) Small risk, if bands are used bi-directionally, gateways and user terminals are both at ground level so their antenna beams, directed at satellites, have good angular separation, however depends on distance from gateway to user terminal	Satellite → User terminal NGSO1 interfering downlink transmission co-channel, in line with desired downlink for NGSO2 received at user terminal *Note: Downlink power limited by pfd to protect terrestrial services, so signals of both systems may be comparable in level*	User terminal → User terminal Zero risk, unless bands are used bi-directionally (both as uplink and downlink) Small risk, since user terminals are both at ground level so their antenna beams, directed at satellites, have good angular separation, however it depends on distance between user terminals

Interference between any transmitter-receiver pair is possible in principle. Table 2 summarizes the major radio hazard scenarios for NGSO-NGSO coexistence. It distinguishes between gateways and user terminals, because gateway uplinks typically use higher transmit power, and likely use higher gain antennas, than user terminals. Figure 4 illustrates these hazards (without distinguishing between gateways and user terminals, for simplicity).

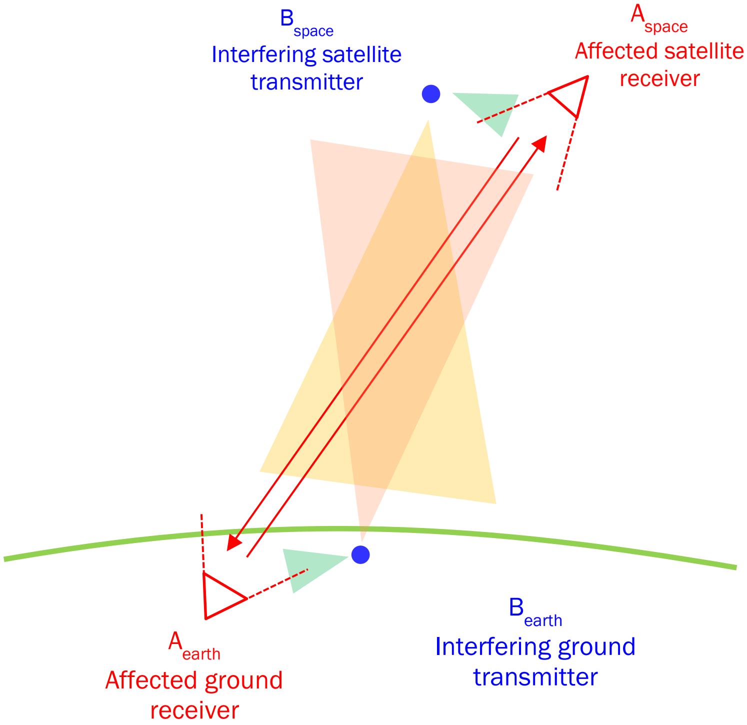


Figure 4. Illustration of major hazards listed in Table 2. (Affected service links as solid lines, interfering links as shaded triangles, colors corresponding to Table 2.)

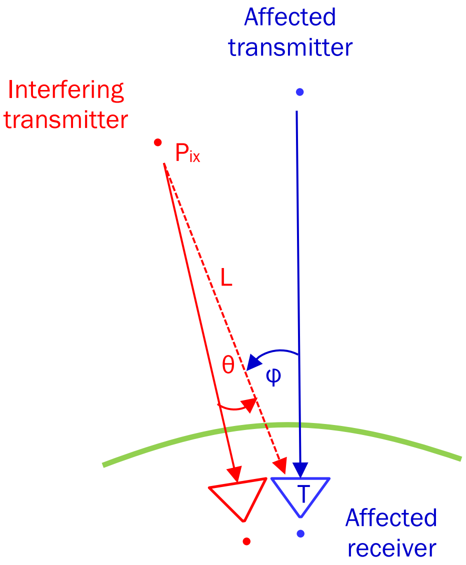
As discussed in Table 2 above, unless the frequency bands are allocated on a bi-directional basis (both uplink and downlink), there will be no interference between system A's Earth stations and system B's Earth station. To keep the number of options to a manageable level, we do not consider satellite-to-satellite hazards in the remainder of this document.

2.2.1 Rules for NGSO-NGSO interference: Coordination triggers

In December 2016, the Commission proposed to update, clarify, and streamline the regulatory framework for the operation of NGSO FSS constellations in a new Report and Order (FCC, 2016b, 2017c). Many of the rules applicable to NGSO FSS systems were created almost two decades ago and were based on the technical characteristics of NGSO satellite constellations proposed at the time.

The Report and Order adopts a rule requiring good faith operator-to-operator coordination among NGSO FSS systems for spectrum sharing. The goal of such coordination is to accommodate both systems. If a question arises regarding whether one operator is coordinating in good faith, the issue may be brought to the FCC, which may then intervene to enforce the condition and help the parties find a solution.

If coordination is ongoing without resolution or if good faith coordination is unsuccessful, the FCC will require band-splitting under circumstances where the ΔT/T of an interfered link exceeds 6% (FCC, 2017c).[1] Use of the 6% ΔT/T threshold is meant to provide a solution tailored to the particular interference situation, and provide both systems equal access to spectrum. The FCC will apply these rules to NGSO FSS operation with Earth stations with directional antennas anywhere in the world under an FCC license, or in the United States under a grant of U.S. market access. Sharing between systems of different administrations internationally is subject to coordination under Article 9 of the ITU Radio Regulations. The new Report and Order is not yet in effect and may be subject to petitions for reconsideration.



$$\Delta T/T = (P_{ix} . G_{ix}(\theta) . G_{aff}(\varphi)) / kLT$$

where

P_{ix}: power of interfering transmission

$G_{ix}(\theta)$: antenna gain of interferer in direction of affected receiver

$G_{aff}(\varphi)$: antenna gain of receiver in direction of interfering transmitter

k: Boltzmann's constant

L: Path loss from interfering transmitter to affected receiver

T: Affected link noise temperature

Figure 5. Factors influencing ΔT/T in downlink; uplink is similar.

The overall ΔT/T is computed as

$$\Delta T/T = \Delta T_e/T_e + \gamma\, \Delta T_s/T_s$$

where

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[1] The calculation of ΔT/T is described in Appendix 8 of the ITU Radio Regulations; Ciccorossi (2012, slide 8) provides a visual summary that is sketched in Figure 5. For more detail, see Mehrotra (2010).

T : equivalent satellite link noise temperature, referred to the output of the receiving antenna of the Earth station (K);

T_s : receiving system noise temperature of the space station, referred to the output of the receiving antenna of the space station (K);

T_e : receiving system noise temperature of the Earth station, referred to the output of the receiving antenna of the Earth station (K);

γ : transmission gain.

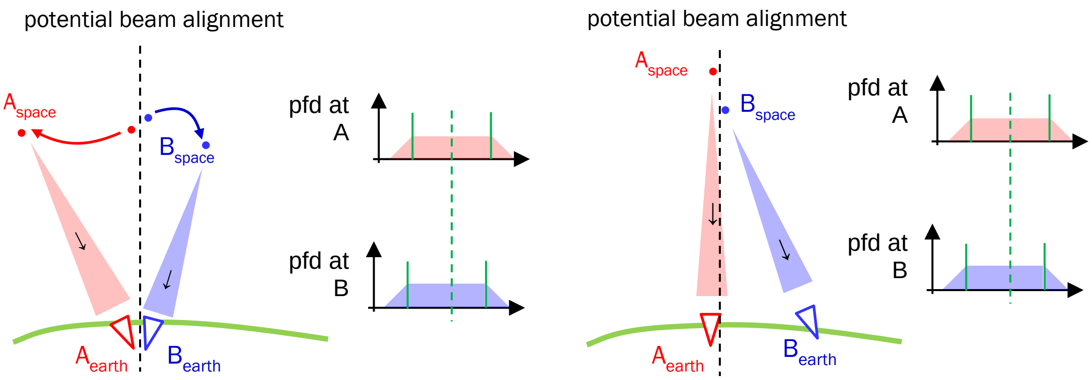
Note that $\Delta T/T$ depends, among other things, on the gains of the transmitting and receiving antennas in the direction of the transmitter, and on the noise temperature of the affected receiver. In contrast, a fixed-angle in-line alignment criterion just depends on the angle between the transmitters as seen from the affected receivers (φ in Figure 5). We will therefore use the generic term "beam alignment" to indicate an overlap of transmit and receive antenna patterns resulting in potentially harmful levels of interference power admitted into a receiver; it encompasses either in-line or $\Delta T/T$ triggers.

2.2.2 Band segmentation and coordination

The new FCC rules state that "should coordination remain ongoing at the time both systems are operating, or if good faith coordination otherwise proves unsuccessful, we will require band-splitting when the $\Delta T/T$ of an interfered link exceeds 6 percent" (47 CFR 25.261; FCC, 2017c). One commercial incentive to coordinate is the prospect of operating over wider bandwidths. For example, if two large constellations—with frequent beam alignment events—fail to coordinate, they can only use half the bandwidth. Under the new rules, "the selection order for each satellite network will be determined by the date that the first space station in each satellite system is launched and capable of operating in the frequency band under consideration" (47 CFR 25.261; FCC, 2017c).

This creates an additional incentive to coordinate in bands where no coordination procedures apply under Article 9 of the ITU Radio Regulations, since all NGSO systems are on an equal footing and will strive to coordinate in good faith to avoid band segmentation.

If at least one of the networks has multiple satellites visible simultaneously, beam alignment can be avoided through coordination, as shown in Figure 6. There are many ways two operators could coordinate in practice. For example, the networks could sequentially number satellites in each of their constellations; when there is beam alignment for even-even or odd-odd cases, system A would look aside and point to an alternate satellite, while B would look aside for even-odd cases. If only one system has the capability to point to an alternate satellite, the entire burden of mitigation could fall on the other system.



(a) Satellite diversity. Both systems use alternate space stations

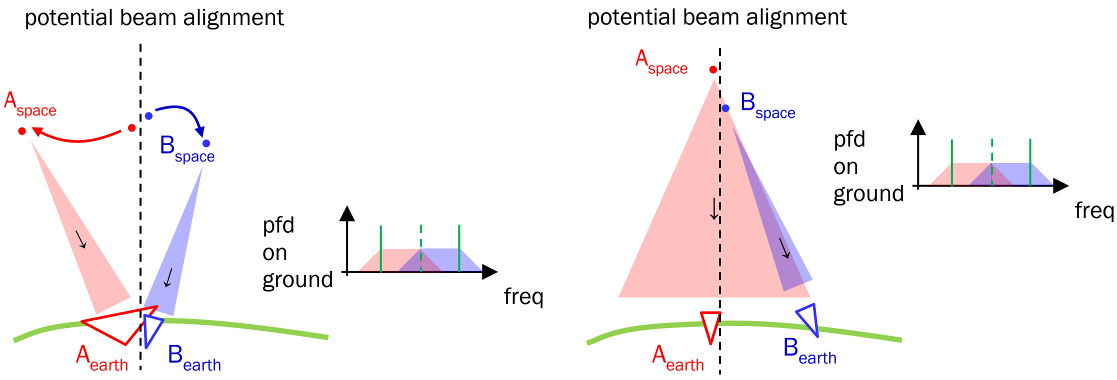
(b) Geographic diversity. If B_{space}'s beam isn't aligned with A_{earth}, both get full bandwidth

Figure 6. Coordination using satellite and geographic diversity.

The U.S. and ITU coordination rules emphasize good-faith operator-to-operator coordinations, but coordination requires willing participants. National administrations and even the ITU can encourage such good-faith negotiations, even among competitors, but additional coordination incentives are also important. The FCC default band segmentation approach overrides the ITU priority approach among U.S.-licensed systems and among U.S.-systems and non-U.S. systems operating within the U.S. (FCC, 2017c). Outside of these cases, other administrations may assert national coordination rules or apply the ITU approach, where the system with the earlier filing date at the ITU is entitled to protection from later-filed systems, while this later-filed system is not entitled to protection. Under this approach, the incentives for earlier and later filed entrants is affected by how the company views the relative appeal of band segmentation. Absent reaching an operator-to-operator coordination agreement, a later entrant, for example, could potentially cause the earlier entrant to lose half of the spectrum during in-line alignment events over the U.S. territory if no coordination agreement is reached. This may cause an incentive for earlier-filed systems to coordinate in good faith with later-filed networks to avoid a band segmentation approach (cf. FCC, 2017c), balancing otherwise the coordination burden that falls on later-filed systems under the ITU regime. Conversely, these rules could provide the later entrant an advantage in coordination discussions, since the earlier entrant could stand to lose half of the bandwidth during beam alignments over U.S. territory if no coordination agreement is reached. Where negotiations and such incentives fail to yield a coordination agreement, national administrations may productively intervene; the ITU Radiocommunications Bureau also has the authority to convene multi-stakeholder coordination discussions, if requested by an administration, under ITU Resolution 602.

It should be noted that implementing satellite diversity as in Figure 6(a) above is feasible, since it is possible to predict accurately the position of satellites A and B in near real-time (some hours in advance) and exchange such information to provide both systems with the capability to avoid the other. Which system does the “avoiding” will ultimately depend on the coordination agreement between parties. In the case of geographic diversity, however, it can be much more complex. If the locations of system A or system B’s Earth stations are known, such as very large Earth stations (VLES; see ITU Radio Regulations, Article 9.7A) or specific Earth stations (feeder links or gateways), then the implementation is relatively straightforward. However, implementation becomes much more complex, or impossible, for ubiquitous user terminals. In addition to exchanging satellite ephemeris data, which can be done in near real-time, the two operators would need to also exchange beam location (Earth station location) in real-time. Coordinating two NGSO FSS systems using steerable spot beams to avoid mutual interference may be complex as it relies on real-time interference mitigation considering that: such satellite steerable spot beams can be moved every few milliseconds; satellite access by any typical (user terminal) Earth station is quasi-random; and it may be difficult for operators to exchange such information in real-time. Risk assessment could be helpful in indicating whether or when this will lead to an unacceptable reduction in quality of service.

A large satellite or Earth station beamwidth may complicate coexistence with other systems that operate co-frequency: higher gain antennas facilitate geographic diversity. Some cases where coordination may fail are illustrated in Figure 7.



(a) Satellite diversity failure due to low gain antenna at A_{earth} receiving interference from B, may force band splitting unless B has other satellites visible at B_{earth}

(b) Geographic diversity failure due to large spot size of A_{space} interfering with B_{earth}, which may force band splitting, unless B has other satellites visible to B_{earth}.

Figure 7. Potential scenarios in which failed coordination may force band splitting.

While it is true that a system which does not have the capability to implement satellite and geographic diversity makes sharing more difficult, it does not automatically lead to band segmentation. In fact, an NGSO system with satellite or geographic diversity could also impose band segmentation on smaller constellations given their large size. This may make band splitting a desirable outcome for that portion of their constellation which is in beam alignment with other systems; remaining satellites that are not in such a situation could use the entire bandwidth. As an example, a single or two-satellite highly elliptical orbit satellite (HEO) constellation does not have satellite diversity capability. If it cannot complete coordination with a LEO constellation that does have diversity, the latter would only suffer from half-bandwidth restriction for the one or two satellites in its constellation that may be aligned with the HEO satellites, while the rest of the LEO constellation can use the entire bandwidth. However, the HEO constellation (which is optimized for limited geographic coverage with a minimal cost implementation) may be forced to use only half the bandwidth all the time if there are enough satellites in the LEO constellation to cause constant beam alignment events (allowing the LEO system to operate on the full bandwidth).

As a result of the complexities just described, the best outcome can only be achieved through coordination between all parties in good faith, as reflected in both the FCC and ITU regimes respectively, and with the regulator's intervention where required.

2.2.3 Co-channel interference

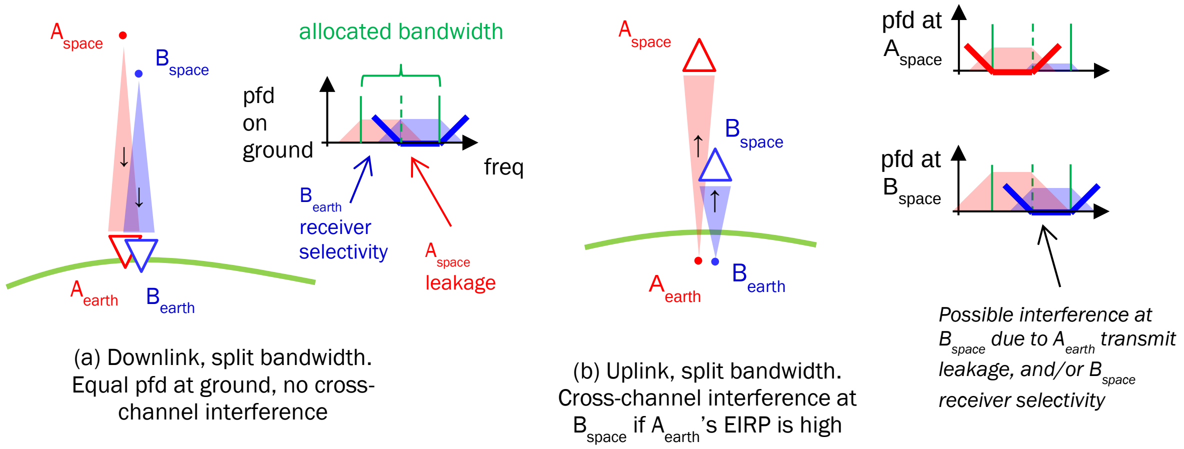
Co-channel interference can occur if coordination is not triggered when it should have been, or if appropriate mitigation has not been implemented in accordance with the coordination agreement. The degree of harm depends on the ratio of interfered to desired signal power, and the duration of the interference event.

2.2.4 Adjacent-channel interference

Under the new FCC rules, when the active space-ground links for two networks are aligned and coordination has not been successfully completed between the two satellite networks, band segmentation rules are applied above the ΔT/T trigger (FCC, 2017c). There is now concurrent transmit or receive in adjacent channels. This could cause adjacent-channel interference, in either uplink or downlink, as shown in Figure 8, depending on the relative power levels and the amount of filtering available.

There are two modes in which cross-channel interference can occur:

1. *Out-of-band emission*: Signal power from transmitter A on the assigned channel A also overlaps onto adjacent channel B, causing adjacent-channel interference to receiver B – due to imperfect transmit mask (also known as leakage, splatter, etc.).
2. *Adjacent band interference*: Receiver B's front-end admits power transmitted by A but completely contained within channel A – due to imperfect receiver mask (also known as overload, desensitization, etc.).



Possible interference at B_{space} due to A_{earth} transmit leakage, and/or B_{space} receiver selectivity

(a) Downlink, split bandwidth. Equal pfd at ground, no cross-channel interference

(b) Uplink, split bandwidth. Cross-channel interference at B_{space} if A_{earth}'s EIRP is high

Figure 8. Band splitting scenarios with potential for cross-channel interference.

The two modes result from transmitter and receiver imperfections, respectively. Their effects can be evaluated using the following measures:

- Adjacent Channel Leakage Ratio (ACLR): The ratio of the transmitted power to the power measured after a receiver filter in the adjacent RF channel.

- Adjacent Channel Selectivity (ACS): Adjacent Channel Selectivity is a measure of a receiver's ability to receive a signal at its assigned channel frequency in the presence of a modulated signal in the adjacent channel.

Following 3GPP convention, we define Adjacent Channel Interference power Ratio (ACIR) as the ratio of the total power transmitted from a source to the total interference power affecting a receiver, resulting from both transmitter and receiver imperfections (Sesia, Toufik, and Baker, 2011, p. 485). ACIR, ACLR, and ACS are all power ratios and the relation between them is

$$ACIR \cong \frac{1}{\frac{1}{ACLR} + \frac{1}{ACS}}$$

In practice, satellite systems operate with sufficient satellite and/or geographic separation to make such interference scenarios all but negligible except in the cases described below. In fact, if two networks can be coordinated to resolve the case of co-channel interference, adjacent-channel interference would not be noticeable. That is because the amount of leakage from channel A (of system A) into channel B (of system B), and the filter selectivity of channel B reduce such interference levels to much below the desired signal. This is very different from the terrestrial "near-far" problem where the adjacent channel signal can be tens of dB's above the desired signal, due to the proximity of the interference source.

Adjacent channel interference in NGSO satellite sharing may need to be considered for the case of forced band segmentation. If two parties cannot resolve sharing during coordination, there is a possibility that system A's emissions could cause adjacent-channel interference into system B, as both systems would operate without mitigation techniques being employed. It may thus be necessary to assess the impact of band segmentation as a default measure, which we do next.

Characterizations of satellite ACLR are hard to come by. We will assume transmitter ACLR of -35 dBc which is reasonably easy to achieve. We do not expect problems due to OOBE on the downlink. Given power flux density rules, the signals arrive at the surface of the Earth with similar, or very comparable, levels (47 CFR 25.208). An ACLR around -35dBc will result in C/I around 35 dB, which is acceptable.

To explore the uplink, first consider a beam alignment event of two NGSO satellites at comparable altitudes (say, two LEO systems at around 1,200km), and assume that the two systems target similar C/N for their uplinks. Given the very comparable path losses, it is reasonable to assume that the Earth station EIRP (equivalent isotropic radiated power) are very similar, and thus resulting signal power at the space stations will be similar. If the two split the band during alignment, it follows that C/I will be around 35 dB, which is acceptable desensitization for C/N even as high as 20–25 dB.

Now assume an alignment between a LEO satellite at 1,200km and a MEO at 8,000 km. This gives a 16 dB difference in path loss. Assume that the two systems target similar C/N for their uplinks, and that the MEO system compensates for the additional path loss via increased EIRP in the Earth station. With the band splitting during the alignment event, the LEO has no impact on MEO (C/I = 35+16 = 51 dB at the MEO), while the C/I at the LEO is 35 – 16 = 19 dB. This is enough to cause some desensitization at the LEO, but probably not enough to cause significant signal degradation.

The situation is exacerbated with greater difference in altitude. An alignment between a LEO satellite at 1,200 km and a HEO at 42,000km gives a 31dB difference in path loss. With similar assumptions as the previous paragraph, the C/I at the LEO is 35 – 31 = 4 dB, which would cause significant desensitization, and could in reality lead to signal loss at the LEO satellite.

There are various ways to mitigate this uplink cross-channel interference, including better ACLR for Earth stations transmitting at higher EIRP, and requiring that all Earth stations transmit at comparable EIRP.[2] The latter measure may not be practicable since one of the

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[2] There are minimal limitations on uplink EIRP. 47 CFR 25.204 (e)(1): "transmissions from FSS Earth stations in frequencies above 10 GHz may exceed the uplink EIRP and EIRP density limits specified in the station authorization under conditions of …" The NGSO FSS Order (FCC, 2017c) is not proposing rules for EIRP levels associated with Earth station transmissions to NGSO FSS space stations. The One Web Authorization (FCC, 2017b) does not impose any EIRP limits, because the

main reasons for deploying LEO constellations is to permit the use of small and lower-power user terminals.

We were unable to obtain data on ACS. Since ACS is expensive in money and power consumption, it is probably no better than ACLR (for which 30–35 dB seems to be a reasonable guess), and it could be worse. In the absence of data, overall ACIR of ~ 30 dB seems a plausible working assumption. The impact of receiver selectivity is the same as for out-of-band emission, but with a reduced ACS as compared to ACLR, the effect is exacerbated.

2.3 *Mitigation*

A variety of factors and techniques can be used to mitigate or prevent harmful interference that might otherwise occur, e.g., when there is beam alignment between two systems. The mitigations chosen for a risk scenario will affect the outcome of the likelihood and consequence calculations in subsequent steps of the risk-informed interference assessment process. In fact, this will normally be incorporated into the analysis as an iterative process.

This section briefly describes some technical mitigations of NGSO-NGSO interference that could be adopted. The list is not exhaustive.

2.3.1 Leverage Satellite Diversity

Given sufficient redundancy in a constellation, operators can hand off traffic to satellites that avoid beam alignment, and therefore avoid interference. However, this does require that operators are able to predict beam intersections, and entails more satellites with the associated considerations of space safety and risk of orbital debris.

Predicting beam intersections is very difficult if treated as a problem that has to be solved across all locations; a paradigm shift to make it a set of uncoupled local problems could make it tractable. Simple heuristics could help: for example, learning from aviation practice where eastbound and westbound flight levels are odd and even thousands of feet. Pre-defined rules of the road for alignment events could help (e.g., two operators with a risk of beam alignment could look east vs. west from zenith, respectively) without knowing in detail where each beam is pointing.

If such simple approaches are inadequate, very dynamic, moment-to-moment scheduling could be required to re-plan beam locations and/or pick among coverage spots. This would put a heavy burden on the satellite control architecture. Furthermore, most of the time

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FCC is not authorizing associated Earth stations at this point. However, note 47 CFR 25.202(f)(4) “In any event, when an emission outside of the authorized bandwidth causes harmful interference, the Commission may, at its discretion, require greater attenuation than specified in paragraphs (f) (1), (2) and (3) of this section.”

operators will not know where another operator's beam is pointing; they will only know the satellite coverage. This potentially generates many false alignment events, i.e., where an operator has to assume potential interference, even though none exists. Addressing this would require data on beam pointing in real time, which operators may be unwilling to disclose.

Beam widths vary; the smallest are 0.3 to 0.5 degrees, but some are much wider. The footprint is also influenced by the minimum operational elevation. Thus, a service delivered from 1,000 km at 40º min. elevation will have a much smaller footprint than one from 8,000 km with 10º elevation. This complicates coordination when one system is low (e.g., LEO) and the other high (e.g., MEO) to assure that the burden does not fall unfairly on one party.

2.3.2 Separate users geographically

Steerable beams can avoid downlink and uplink in-line alignment events, provided Earth station locations are sufficiently well separated. However, separating Earth stations may be difficult, given pressure to collocate them and minimize impact on terrestrial services. Current rules place a limit on number of downlink Earth stations in Partial Economic Areas in 37.5–40 GHz; but maintaining and sharing the locations of all ground stations, including potentially mobile user terminals, may be problematic.

2.3.3 Employ adaptive links

Mechanisms like power control and adaptive coding can partially compensate for increased interference. However, adaptive coding leads to systems running closer to capacity limits, which means they may not have spare capacity to absorb reduction in throughput. This will depend on the number of services an operator is trying to support, and the service level agreements they have in place.

2.3.4 Reduce uplink EIRP

Given the current minimal rules for uplink EIRP, low/high systems could use different power levels. This can lead to a system with a high uplink EIRP (e.g., one with long path length) causing asymmetric interference to a system with a shorter path length; see the discussion about cross-channel interference in Section 2.2.4 above. Reducing uplink EIRP could mitigate this problem.

2.3.5 Align communication channels

As described in Section 4.1.5, the applications received in the FCC's current V-band processing round reflect quite a diversity of channel plans. Since the channel widths of some of the operators differ, interference may occur when one operator's channel overlaps another's. There may be benefit for the parties to harmonize their channel choices, or at least align their channel boundaries to an integer multiple of some common minimum width.

3 Second element: Define consequence metrics

A consequence metric quantifies the severity of an interference hazard, and is used to compare the impact of different scenarios, e.g., mitigations or rule choices. There are many potential consequence metrics, in three broad categories (FCC TAC, 2015c, Section 4):

- *Corporate metrics*: Examples include impact on the ability to complete a mission (particularly for government entities); and increased capital expenditure, loss in revenue or loss of profit (particularly relevant to the private sector).

- *Service metrics*: These measure the quality of the specific service that the radio link supports. Two broad sub-categories are availability (time period or time percentage of outage; number or percentage of receivers without service; etc.) and quality (bit error rates for data services, spectral efficiency in bit/s per Hz, etc.)

- *RF metrics*: Quantities observable in the radio frequency environment, such as changes in interference-to-noise ratio (I/N), signal to interference and/or carrier to interference plus noise ratios (SINR, $C/(N+I)$), absolute interfering signal level, receiver noise floor degradation, and so on.

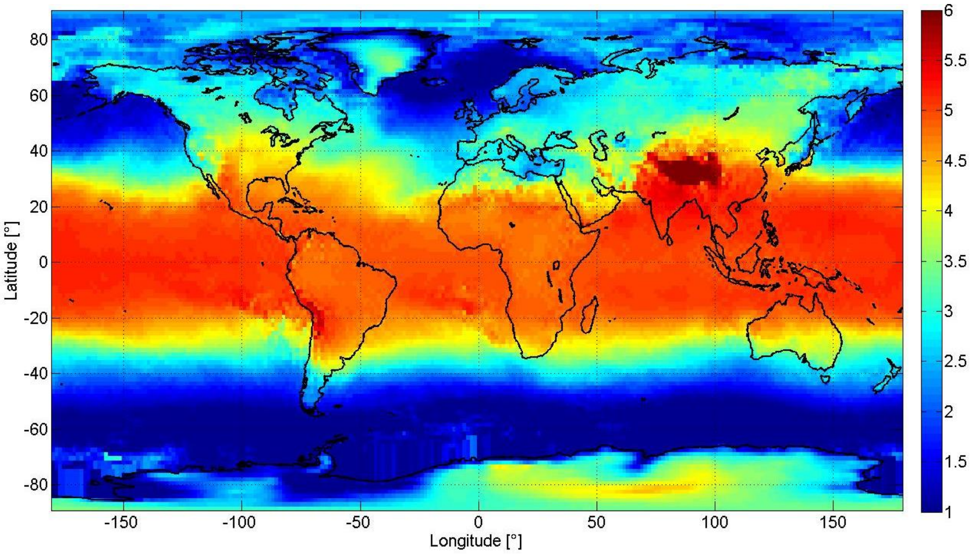
ITU-R WP4B has proposed that percentage degradation in throughput from a reference value (%DTp) be used as the new metric for satellite connections using adaptive coding and modulation rather than BER (ITU-R WP4B, 2017). This appears to be a plausible metric for NGSO-NGSO interference as well. It can be calculated based on the change in $C/(I+N)$ from a reference C/N value, or decrease in C/N expressed as $10 \log (1 + 10\ (^{I/N)/10})$.

As a guideline for judging the severity of degradation, ITU-R WP4B (2017) notes that a "1 dB reduction in C/N would be acceptable for all sources of external noise (inter-satellite interference, inter service sharing, etc.), and this 1 dB reduction results in 10% reduction in achievable throughput." We note that for GSO-NGSO interference the Commission adopted the ITU equivalent power flux density (epfd) limits in Ku-band (and proposes to do so for Ka-band) which were derived based on a 10% increase in unavailability according to ITU-R Recommendation S.1323 (ITU-R, 2002).

An unavailability metric might also be a possible way to evaluate the severity of degradation from NGSO-NGSO interference. ITU-R WP4A is considering such a metric (ITU-R WP4A, 2017b, Study #1, Section 4.3). As part of this metric, a recommendation is being considered for inter-satellite service sharing of percentage unavailability taking into account propagation impairments for the satellite link in the V-band.

Percentage degradation of throughput or unavailability needs to be calculated against a baseline value, e.g., at several representative locations with different baseline throughput/degradation (e.g., areas with low and high rain fade). For example, the baseline could be evaluated for a variety of locations with different rain heights. (Figure 9 is map of typical rain height from ITU-R Recommendation P.839.) A variety of link locations could be taken representing worldwide rain height.

Alternatively, or in addition, one could use a metric where the percentage degradation is weighted by the population density (as a proxy for user density) in locations with different baseline throughput. This amounts to adding an exposure-to-hazard dimension to the metric.



Source: ITU-R Recommendation P.839 (ITU-R, 2013a)

Figure 9. Typical worldwide rain heights.

With such consequence metrics, risk would be expressed as a probability distribution or exceedance function (i.e., a complementary cumulative distribution function) of the percentage degradation in throughput or unavailability.

Percentage degradation in throughput or unavailability may not be ideal performance proxies for all NGSO systems; for example, throughput may not be critical to remote sensing. However, either metric would seem to work at least in part for all V-band NGSO FSS applicants.

4 Third element: Calculate likelihood-consequence values

A risk-informed interference assessment is based on quantitative statements about likelihood and consequence—in this case percentage degradation in throughput or unavailability. For clarity, this section assumes that degradation in throughput is the metric used; the approach would be very similar for degradation in unavailability or other similar metrics.

First, the baseline situation must be analyzed. We recommend analyzing an illustrative system in the absence of any other constellations, but taking into account baseline degradation of the desired signal due to rain and cloud attenuation and atmospheric effects, and baseline noise temperature increase due to system electronics and atmospheric gases. It is unlikely that data on non-interference faults and failures will be available, but they should be included if possible.

With the baseline in place, the likelihood and consequence of different hazard scenarios can be analyzed. This means analyzing the percentage throughput or unavailability degradation relative to the baseline situation, with one or more additional constellations. Following De Vries, Livnat and Tonkin (2017), we recommend using Monte Carlo simulation to calculate distributions of throughput degradation, and plotting them as exceedance functions, i.e., complementary cumulative distribution functions (CCDFs).

The analysis will necessarily incorporate the effects of coordination between systems. (It is not necessary to consider all coordination options for all system permutations, since the high-risk combinations should be evident after some sample calculations.) The main options for coordination and associated mechanisms for throughput degradation are:

1. *No action*, i.e., all systems operate without attempting to coordinate: this leads to throughput degradation through co-channel interference.

2. *Band splitting*, i.e., systems operate in disjoint frequency ranges: this leads to throughput degradation through decreased bandwidth availability and the additional adjacent-channel interference when band splitting is triggered, and co-channel interference if band splitting is not triggered when it should be.

3. *Look-aside*, i.e., one or more systems use alternative beam paths when some threshold (e.g., $\Delta T/T > 6\%$) is exceeded for the default path: this leads to throughput degradation through increased system overhead and use of less-ideal (e.g., lower elevation) communication paths, as well as the decreased bandwidth availability and cross and co-channel interference associated with band splitting.

The coordination triggers, which determine the circumstances under which band splitting or look-aside occur, will have a critical effect on the overall percentage throughput degradation.

4.1.1 Harmful, actual, and potential degradation

Harmful interference is defined by the FCC in 47 CFR 2.1 as interference “which endangers the functioning of a radionavigation service or of other safety services or seriously degrades, obstructs, or repeatedly interrupts a radiocommunication service operating in accordance with [the ITU] Radio Regulations.” This is a regulatory, not an engineering, definition.

There have been many attempts to provide engineering proxies for the regulatory definition in 47 CFR 2.1. We can distinguish between three kinds of degradation (using “degradation” rather than “interference” to distinguish our terms from regulatory definitions):

- *Harmful degradation*: An unacceptable reduction in an end user quality of service metric caused by an undesired RF signal.
- *Actual degradation*: A reduction in a service metric or RF metric, exceeding a specified threshold, caused by an undesired RF signal. This may or may not constitute harmful degradation.
- *Potential degradation*: Given incomplete information, a situation where some values of the unknown variables lead to actual degradation of one of the systems involved.

To limit the amount of harmful degradation, spectrum management often focuses on eliminating or providing predictable bounds on the amount of potential degradation. This is acceptable if the gap between the amount of harmful degradation and the amount of potential degradation is small. When the gap is small, the efficiency penalty associated with focusing on potential degradation is also small.

In the case of coexisting NGSO satellite constellations, the gap between the potential level of degradation and the amount of harmful degradation is large. Contributors to the gap include the following factors:

- A satellite’s beam pointing direction is either proprietary and/or not predictable far in advance. With small spot beams, most of the satellite footprint is unused at any moment. Protecting the full footprint from potential degradation, when only ground terminals in the spot could experience actual degradation, results in significant lost communication opportunities.
- The beam pattern and pointing angle of ground terminals may also be proprietary and/or dynamically changing. With a narrow-beam ground terminal antenna, most of the potential directions of the ground terminal receiver sensitivity are unused at any moment. Providing the ground terminal receiver with full-arc full-elevation protection from potential degradation, when only emitters near the current antenna boresight angle and elevation could cause actual degradation, results in significant lost communication opportunities.

- Actual degradation events are often short (a few seconds) because they occur when two satellites in different orbits pass through a particular configuration that aligns them in the boresight of the same ground terminal.[3] A short actual degradation event may not lead to harmful degradation. For example, most systems can detect dropouts and retransmit the lost data as long as the dropout is shorter than a tolerance window. In such cases it may be inefficient to attempt mitigation. It is probably unnecessary to attempt mitigation for every alignment event that has occurred, and it may not be necessary if most inline events are shorter than the tolerance window.

- Some system designs can dynamically adjust spectrum utilization to avoid noisy subchannels when usage is low. When usage is high, all subchannels in the allocated band are required. Protecting all subchannels from potential degradation when only some are vulnerable to actual degradation at a particular moment (depending on usage) results in lost communication opportunities.

These qualitative considerations could be quantified through a risk assessment.

4.1.2 Modeling approach

The number of potential interference scenarios is quite large since such a variety of systems have applied for authorization in the V-band. Given the uncertainty about network deployment, the first step would be to calculate order-of-magnitude risks for coexistence scenarios between generic operations, e.g.

1. Large LEO constellation (~3,000 satellites at ~1,000 km) in a combination of inclined and polar orbits (e.g., Boeing NGSO System, SpaceX).

2. Large MEO constellation (~1,000 MEO at ~8,000 km) in a combination of inclined and polar orbits (e.g., the MEO portion of OneWeb's hybrid system).

3. Medium LEO constellation (~100 spacecraft) LEO (~1,000 km) in polar orbit (e.g., Theia, portions of Telesat's and OneWeb's systems).

4. Small constellation (~3 spacecraft) MEO (~14,000 km) in circular equatorial orbit (modeling Audacy).

This is not an exhaustive list; for example, it focuses on LEO and MEO systems, but excludes very low Earth orbit (VLEO) satellites (~ 350 km) and HEO satellites.

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[3] A 1° full beamwidth corresponds to a patch 20 km wide at 1,200 km altitude directly overhead. Another satellite at the same altitude would cross this patch at right angles in about 2 seconds. For two satellites at 8,000 km, the corresponding time is about 20 seconds. These times can be significantly longer at lower elevation angles and non-right angle crossings.

Rough calculations can be done for each permutation to identify where the high-risk cases are likely to occur. Most of the analysis will focus on these high-risk cases.

Monte Carlo simulation is an obvious approach to calculation. Many satellite/Earth station configurations are generated; attenuation, e.g., due to rain fade, is sampled from a suitable distribution. A link margin, and thus throughput (see Section 4.1.3), is calculated for each configuration; this results in a distribution of throughput degradation.[4]

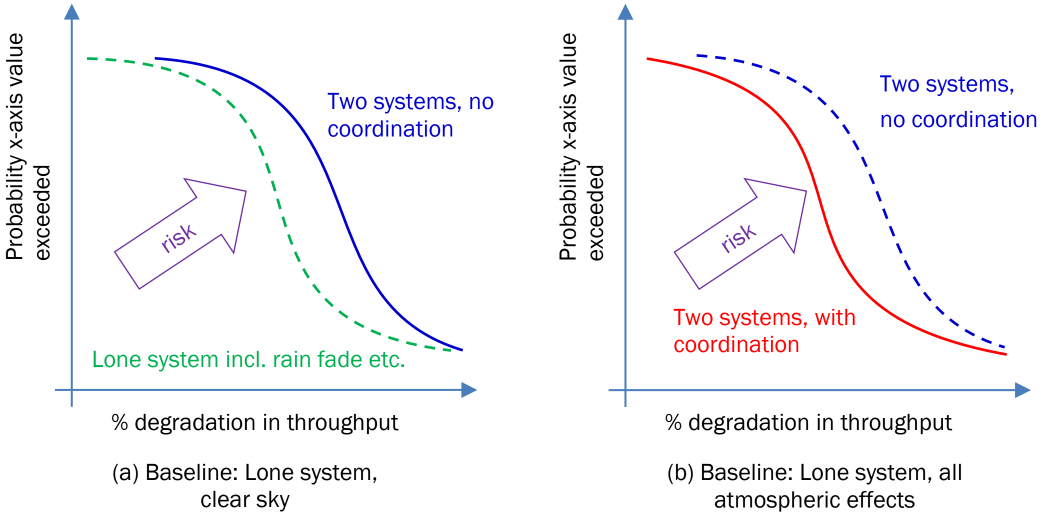

Figure 10. Schematic risk chart results.

The baseline against which throughput degradation is calculated can be the clear-sky situation, in which case even a lone constellation will show a distribution of throughput degradation due to atmospheric effects; or it can be the distribution of throughput (including atmospheric effects) for a lone constellation, in which case throughput degradation only occurs in the presence of additional constellations.

Figure 10 illustrates these two cases. In Figure 10 (a), the baseline is a single system, clear sky; the green dashed curve shows the percent degradation in throughput created by atmospheric effects, and the solid blue curve the additional risk created by adding an interfering system. Figure 10 (b) includes atmospheric effects in the baseline; the dashed blue curve is the risk when there another system is added without coordination, and the solid red curve shows the reduction in risk when coordination is included.

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[4] While the risk assessment terminology in this paper may be new to some, the techniques it uses are not. For example, the figures reported in Canada (2017, Annex 1 and 2) can be interpreted as risk charts. Each plots a complementary cumulative distribution of the probability that a given value of I/N, the consequence metric in this case, is exceeded.

4.1.3 Throughput calculation

The throughput for each case can be calculated given by a total link *C/(I+N)*. Schematically,

Link *C/(I+N)* = radiated power – attenuation + receive antenna gain
– thermal noise – interference

It can be assumed that the systems will use Adaptive Coding and Modulation (ACM), which allows communication systems to respond to a degradation of *C/(I+N)* by maintaining the connection but with reduced throughput.[5] Given the link margin, a combination of modulation type and forward error correction code is chosen to give the terminal the highest possible data rate that preserves enough operating margin to compensate for short term fluctuations. This data rate represents the throughput in the clear-sky case (i.e., no rain or cloud attenuation), as well as the throughput in the presence of atmospheric effects, interference, and other hazards.

These calculations require assumptions about system parameters, including channelization, antenna gain (main-beam gain, antenna pattern, etc.), transmit power, number of spacecraft visible simultaneously and ability to hand off, elevation angles while transmitting, and number of ground terminals (gateways and user terminals). This reflects not only RF issues but also system issues—i.e., whether the satellite and Earth station are even operating, and if so, whether their frequencies and antenna beams actually overlap for a given configuration. We briefly discuss inactive satellites, channelization, and antennas in the following three sections.

4.1.4 Inactive satellites

Beam alignment does not lead to interference if satellites are inactive. This can happen in various scenarios.

For example, a large constellation with all spacecraft at (say) 53° inclination will tend to have a high density of stations at 53°; however, not all will be transmitting at the same time. Similarly, for “constellations [with] near-polar orbits, which result in a higher concentration of satellites over the poles … a significant number of satellites, or satellite beams, will likely be turned off when approaching northern latitudes” (LeoSat, 2017). Further, “NGSO constellations may only operate satellites at certain elevations above the horizon and may cease transmissions in certain zones of the sky for GSO arc avoidance or other reasons” (LeoSat, 2017). These are foreseeable occurrences, at least on a statistical basis, given that orbits are well-defined and predictable.

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[5] For a discussion of Adaptive Coding and Modulation (ACM) for satellite systems, see ITU-R (2014, Figure 32) and DVB (2015, Table 1).

4.1.5 Channelization

If a specific satellite–user terminal link (in either uplink or downlink) uses a single channel rather than the full allocated bandwidth, the risk of interference associated with beam alignment is significantly reduced.

The current V-band processing round applications reflect quite a diversity of channel plans (see Figure 11). Since channel widths of applicants sometimes differ, interference may occur when one applicant's channel overlaps partially with another's. There may be benefit for the parties to harmonize their channel choices, or at least align their channel boundaries to an integer multiple of some common minimum width.

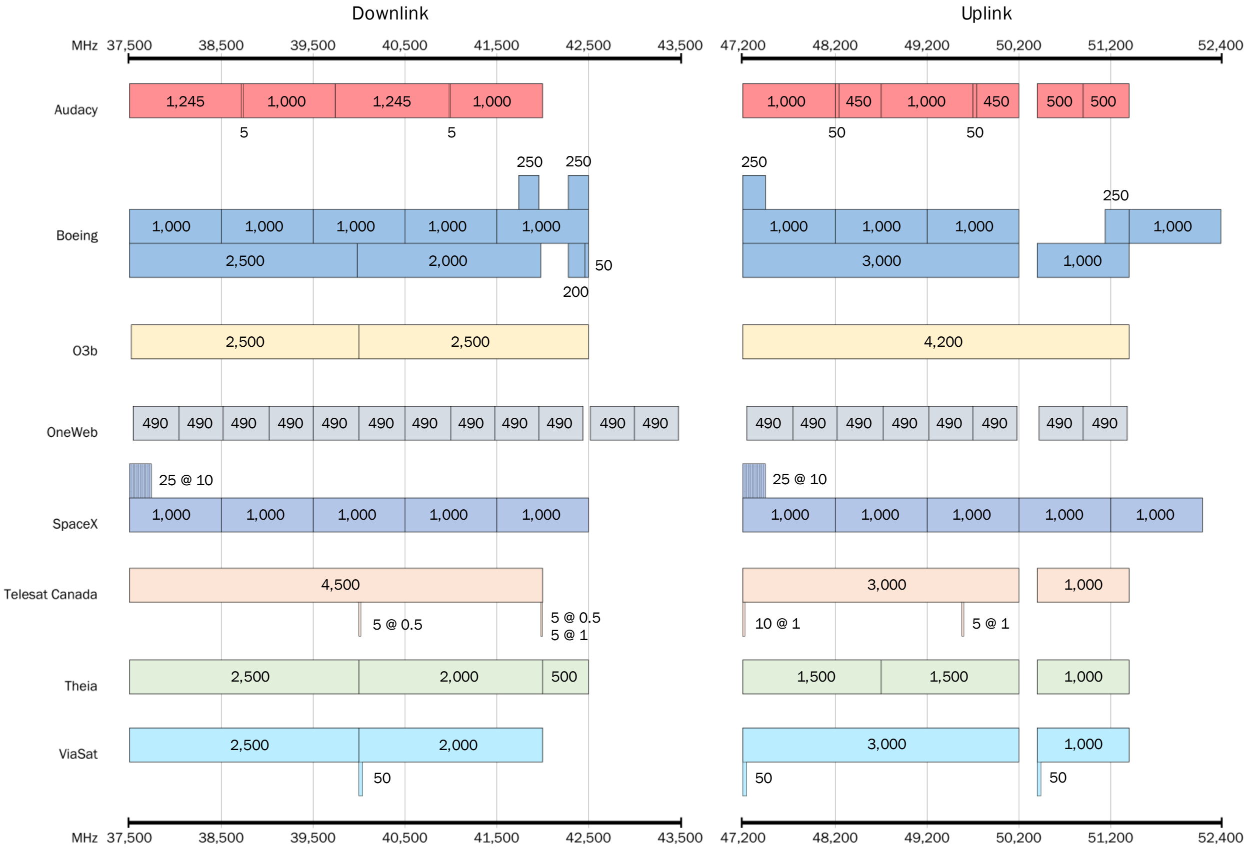


Figure 11. V-band channelization summary (FSS only).

4.1.6 Antennas

Antenna gain will influence the ease of coexistence. Generally, higher gain antennas will reduce the number and severity of beam alignments, although this generalization depends on various factors including the number of antennas and spacecraft. Antenna patterns vary significantly, not only within and among systems but also in real-time, allowing greater operational flexibility for each applicant's system. The difficulty is to predict the placement of one system's antenna beams at any instant in time, relative to anther system's beams. As a first-order simulation, a Monte Carlo approach can be used where beams are randomly placed within the satellites service area (area of coverage). However, results should be treated with caution since beam placements are not likely to be random in real life, but may spend "more time" in areas of greater demand.

For example, the LEO system proposed by Boeing can provide narrow spot beams for typical broadband services and larger beams for services such as low-rate multicast user data (Boeing, 2017). Proposed main-beam gains for V-band LEO applicants vary from as little as 36.2 dBi to more than 54 dBi, with the majority lying between 40 and 46 dBi. The antenna patterns proposed for MEOs are generally narrower, with main-beam gains of 48 dBi or more.

Since the current V-band processing round addresses market access and space station licenses, essentially no information is on the record about Earth station antenna performance. However, it can be expected that their main-beam gains will be similar to those in the ITU Radio Regulations Appendix 8 (for less expensive user terminals) or similar to the FCC Earth station antenna patterns (particularly for gateways).

A risk assessment would have to consider that the same network may deploy terminals from different vendors with different characteristics, and thus different throughput degradation behavior. This should be reflected in the sensitivity analysis that accompanies the results (cf. De Vries, Livnat & Tonkin, 2017, Section VIII). We believe that the consequence metrics described above—percentage degradation in throughput or unavailability—will be relatively robust to inter-device variation compared to absolute throughput. If industry does risk assessment collectively, it may choose to use the approach taken by 3GPP, where vendors share models of device performance along various dimensions (e.g., average throughput, 5% and 95% CCDFs, capacity loss), and then the group collectively decides on the requirements for the standard, or in this case, assumptions for a risk assessment (3GPP, 2016).

5 Fourth element: Aggregate results

With results in hand from a representative set of hazard scenarios, a risk analyst could compare interference management options.

As a first step, a risk chart that shows the most hazardous scenarios would shed light on whether coordination is likely to be workable. As the FCC has recognized, using ΔT/T as a coordination trigger "will be a complex calculation" (FCC 2017c, para. 49); any method to implement it will produce false positives and false negatives, perhaps many of them.

Further, the calculation will require disclosure of sensitive information like user terminal location (when known), beam pointing (where possible to define), and local channel use. If the risk of interference is sufficiently low, the cost of implementing real-time ΔT/T coordination may outweigh the benefits.

Nevertheless, the ΔT/T calculation method can be used without detailed knowledge of the other NGSO system's beam pointing information, when one NGSO system employs geographic diversity in order to achieve coordination. For example, if system A only has gateway operations in part of the band, even if it has no knowledge of system B's satellite beam location, it can nevertheless employ geographic diversity to avoid any potential interference to system A's Earth stations (wherever they are located) by ensuring that its own beam points well away from the geographic area where in-line alignment events would occur. System A would achieve this by moving its beam towards an area where the two satellites are not in beam alignment, through gateway diversity.

As a second step, assuming a high enough risk of interference, comparative risk curves would allow one to explore comparative risk scenarios, and validate engineering intuition. For example:

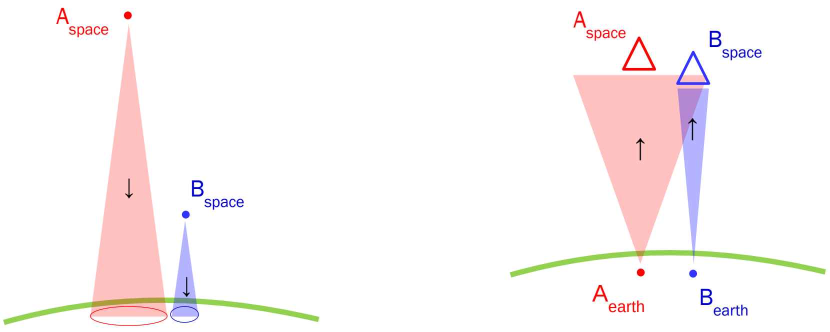
- The most significant risk is likely to be a MEO or inclined NGSO uplink interfering with a LEO satellite, given the likely difference in transmit power. Since power reaching the ground is likely to be similar for MEO and LEO (to protect GEO), this is not a major issue with the downlink.

- Given the dynamics of the MEO and LEO constellations, a risk calculation would provide insight into the relative risks of MEO-MEO and LEO-LEO interference.

- Differences in antenna gain could cause problems, e.g., a low-gain Earth station antenna could receive downlink interference from another system at a wide angle. However, calculation would be required to assess the significance of this risk, as small sized antennas are very desirable for user terminals.

- For comparable antenna gain, MEO downlinks will deliver energy to a wider area than LEO given the higher altitude, and thus impact more possible receivers. How significant is this risk?

- Many operating parameters have an impact on the likelihood and severity of interference, including EIRP, antenna gain, out-of-band emission, and receiver selectivity, etc. Risk calculations, even preliminary order-of-magnitude ones, should shed light on which parameters are the most important ones.



(a) With same antenna gains (i.e., beamwidth), a higher transmitter interferes over a wider area than a lower one

(b) Low gain uplink antenna at A_{earth} causes interference at B_{space}; high gain antenna at B_{earth} does not interfere with A_{space} for a given separation angle between satellites

Figure 12. Some asymmetric risk scenarios.

6 Conclusions

A risk-informed interference assessment (RIIA) may help the FCC and industry to explore questions regarding NGSO-NGSO coexistence, such as the likelihood and consequence of service degradation under various assumptions regarding the types of coexisting systems, and interference mitigation techniques. It could assist in identifying approximate boundaries between acceptable and unacceptable risk, and focus attention on those interference mitigation measures that are likely to be most effective. We recommend that the FCC consider using, and encouraging the use of, RIIA (among other methods) in the analysis of NGSO-NGSO coexistence.

This paper deals only with technical methods to assess interference hazards. Such analysis (whether using RIIA or other methods) is necessary but not sufficient for effective spectrum management. The FCC, industry and/or researchers could explore the use of economic and environmental analysis to complement the engineering analysis described here, such as performing a cost-benefit analysis of various mitigation strategies. By analogy to the efficient frontier in portfolio theory, economic analysis coupled to RIIA could help find the optimal balance of risk and return.

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Appendix for discussion: Triggering coordination by observed degradation

This appendix describes a hypothetical approach to spectrum management and coexistence that may be beneficial for NGSO-NGSO interference risk management. The approach would trigger coordination based on observed degradation, rather than on a predictive measure such as ΔT/T or beam alignment. This approach is applicable to bands where sharing is built in from the start, and systems have been designed to share, e.g., as outlined below.

Section 4.1.1 introduced the concepts of harmful degradation (an unacceptable reduction in quality of service), actual degradation (a reduction in service exceeding a specified threshold), and potential degradation (a situation where actual degradation may occur). Determining what level of actual degradation constitutes harmful degradation depends on numerous factors, and system operators are best placed to determine this through studies. However, there appears to be a large gap between potential and harmful degradation in the NGSO-NGSO application, as discussed in Section 4.1.1. Therefore, satellite operators should be able to realize significant economic benefits by adopting an interference mitigation approach that does not attempt to prevent all potential degradation. The potential economic benefits arise because each operator may realize significantly increased access to the limited amount of available spectrum. This becomes a good incentive to include the design features in the systems required to support the new approach.

The high-level principles enunciated in FCC TAC (2015b) are relevant here:

- *Principle 1*: Harmful interference is affected by the characteristics of both a transmitting service and a nearby receiving service in frequency, space or time.
- *Principle 2*: All services should plan for non-harmful interference from signals that are nearby in frequency, space or time, both now and for any changes that occur in the future.
- *Principle 3*: Even under ideal conditions, the electromagnetic environment is unpredictable; operators should expect and plan for occasional service degradation or interruption.
- *Principle 4*: Receivers are responsible for mitigating interference outside their assigned channels.
- *Principle 5*: Systems are expected to use techniques at all layers of the stack to mitigate degradation from interference.
- *Principle 6*: Transmitters are responsible for minimizing the amount of their transmitted energy that appears outside their assigned frequencies and licensed areas.

- *Principle 7*: Services under FCC jurisdiction are expected to disclose the relevant standards, guidelines and operating characteristics of their systems to the Commission if they expect protections from harmful interference.
- *Principle 8*: The Commission may apply Interference Limits to quantify rights of protection from harmful interference.
- *Principle 9*: A quantitative analysis of interactions between services shall be required before the Commission can make decisions regarding levels of protection.

Design margin and the rate of actual degradation events

The design margin of an NGSO system and the rate of actual degradation events are closely linked. All RF systems have design margins to accommodate effects such as weather and other propagation impairments, imperfectly aligned antenna beam direction, solar noise, co-channel interference from other users of the same system, out-of-band energy from adjacent systems, etc. As long as undesired signals from coexisting independent systems are below the design margin of the affected system, actual degradation will not turn into harmful degradation.

However, the design margin has a high cost: it directly reduces the end user service capacity of the system for a given hardware investment. If actual degradation from coexisting NGSO systems occurs on top of all the other impairments, additional costly design margin is needed.

Consider a situation where the automatic retransmission subsystem of a space-to-Earth link has sufficient tolerance window for the short period of actual degradation caused by beam alignment with a satellite in a non-coincident orbit. If the beam alignment events occur frequently, statistically there will be a non-trivial rate of situations with harmful degradation: that is, end-user throughput reduction or data loss. For example, harmful degradation events might occur when a beam alignment event combines with a long noise burst to exceed the automatic retransmission subsystem tolerance window. Designers observing this statistical probability might have to reduce system capacity to increase noise tolerance, in order to reduce the rate at which these harmful degradation events occur.

Stated another way, the problem for an affected system is not individual events of actual degradation, or even occasional events of harmful degradation (with the important exception of safety critical links, which are excluded from this discussion). The problem occurs when the rate of actual degradation events rises to a level where system designers must add costly design margin to achieve an acceptable end user quality of service.

Coexistence management via rate of observed actual degradation events

When the issue of concern is the rate of actual degradation events rather than the existence of individual events, there is the potential to manage interference by triggering coordination based on the observed actual degradation event rate rather than predicted potential interference. As described earlier, this is valuable because coordination will occur far less frequently than if it is based on predictions, which are necessarily associated with the much more frequent potential degradation events.

We assume that each NGSO system has the following capabilities:

- Sufficient design margin to operate effectively in the absence of coexistence degradation (i.e., no change from today in this costly design aspect).
- The ability to monitor and report actual degradation events.
- The ability to transmit device identifiers (IDs) complying to a modulation, framing and repeat interval specified in an industry-agreed standard (it would likely differ from the modulation and framing used for the system's user and control data).[6]
- Optionally, the ability to activate and deactivate device ID transmissions according to geospatial or temporal criteria: for example, satellites could be commanded to transmit device IDs only when their spot beams intersect with a specified geographical area (reducing the impact on the constellation's capacity compared to transmitting device IDs all the time).
- The ability to receive device ID transmissions from other constellations at satellites and ground terminals.[7]

In this proposed spectrum management approach, operators need not fully coordinate in advance of operation in the shared spectrum band. Rather, in cases where coordination is deferred, the Network Operation Center (NOC) for each system looks for actual degradation event rate spikes that exceed acceptable levels.[8] Operators coordinate with each other as

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[6] The DVB Carrier ID technology could be a candidate for this ID system (DVB 2016). According to http://satirg.org/working-groups/carrier-id/, it is "an embedded code containing contact information, which enables the satellite operators to quickly and easily identify the source of an interfering transmission. The latest version, DVB-CID, adds a low power spread spectrum carrier on top of the carrier, meaning that the correct transmission doesn't need to be interrupted to identify the interfering carrier, this minimising impact."

[7] The ability to decode these transmissions locally is not required, only the ability to identify them and forward raw data to the network operation center for further analysis.

[8] In general, actual degradation event rate spikes will be location- and time-varying. Correlation with known ephemeris and/or ground terminal location data may identify the responsible constellation. If not, system operators can request others to activate device ID transmissions for the minimal time and spatial region required to enable identification of the responsible correlation.

required to mitigate spikes in the actual degradation event rate. An example would be an agreement to look-aside when satellites of the two constellations pass in a particular alignment over a particular geography.

Normally, reaching a mitigation agreement requires negotiation and agreement between organizations, something which takes days to weeks. If faster mitigation is required, technical mechanisms can be specified and agreed among the operators in advance. Such mechanisms would be automatically activated when degradation rate spikes are observed. They would likely result in higher compliance costs (e.g., greater capacity reduction than is truly necessary to mitigate the actual degradation) in the period until a more optimal agreement can be negotiated.

The regulator acts as the backstop to impose a solution in cases where operators cannot reach agreement, either bilaterally or otherwise. Since a regulatory solution will likely be coarse and result in significant loss of spectrum access compared to peer coordination, operators have strong incentive to work out a local solution. The FCC can also support the process by encouraging experimentation.

Looked at more abstractly, in this approach degradation due to coexistence effects is mitigated by a control loop that passes through the NOC and the coordination mechanism, rather than mitigated by design margin in the communications stack. It seems plausible that this will achieve the desired end user quality of service for coexisting satellite systems at lower cost than either design margin in the communications stack or spectrum management approaches that strictly limit potential interference.