Technical Characteristics and Regulatory Challenges of Communications Satellite Earth Stations on Moving Platforms

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ABSTRACT

Earth stations on moving platforms (ESOMPs) are a new generation of satellite terminals designed to operate at the X-, C-, Ku-, and Ka-frequency bands and provide on-the-move broadband communication services to land vehicles, aircraft, and ships. Some of the distinguishing characteristics of ESOMPs are that they use very small antennas and require tracking systems to maintain accurate pointing to the target satellite. However, because they operate while on the move, there may be instances when antenna-pointing errors may result in increased interference to other co-frequency neighboring satellites or other radio systems. To account for pointing errors and other time-varying characteristics of a network of ESOMP terminals, it is necessary to use statistical approaches for interference analysis such that the resulting interference is not harmful to the victim network. The Johns Hopkins University Applied Physics Laboratory (APL) made significant technical contributions on these topics and is actively engaged in the development of international standards for ESOMPs. This article provides an overview of ESOMPs, their technical and operational characteristics, statistical approaches for interference analysis, and the standards and regulatory challenges that must be addressed for their successful operation.

INTRODUCTION

In recent years, owing to the growing user demand for on-the-move global broadband communications, a new type of satellite terminal has emerged, known as Earth stations on moving platforms (ESOMPs). ESOMP terminals use small antennas with tracking systems and advanced modulation and coding schemes that allow them to provide two-way, high-speed communications from aircraft, maritime vessels, trains, or land vehicles. Various types of satellite terminals have been used onboard vessels (maritime and air) since the 1980s. Initially operating over mobile satellite service (MSS) systems at the L-band, these terminals provided modest narrowband services (voice and low data rates). As very-small-aperture terminal (VSAT) systems became more established, the next generation of vessel terminals employed parabolic antennas (1.2–2.4 m) and some type of tracking or stabilizing system. They were designed to provide medium data rates over geostationary orbit (GSO) fixed satellite service (FSS) systems operating at the X-, C-, and Ku-frequency bands.

New technology capabilities, adopted by satellite designers and terminal equipment manufacturers, have allowed the development of more spectrally efficient, ultra-small terminals that can provide broadband communications (near or above 1.5 Mbps) to support voice, video, high-speed data, and access to the Internet. In addition to Ku-band implementations, work is being done in the Ka-band, with several Ka-band satellite operators and service providers developing systems that will carry ESOMP traffic over GSO and non-GSO FSS systems. FSS systems are preferred, as opposed to MSS, because FSS systems provide the geographic coverage, capacity, and bandwidth required to support broadband services. [Note: The ITU defines MSS and FSS from the point of view of the user terminal. The existing MSS systems provide primarily narrowband voice services and are not capable of supporting broadband data services. The emergence of ESOMPs highlights the need to redefine satellite services and adopt more flexible regulations. Some of the frequency bands used by communications satellites include L-band (1.6265- to 1.660-GHz uplink/1.525- to 1.559-GHz downlink); C-band (5.9- to 6.4-GHz uplink/3.7- to 4.2-GHz downlink); X-band (7.9- to 8.4-GHz uplink/7.25- to 7.75-GHz downlink); Ku-band (14.0- to 14.5-GHz uplink/11.7- to 12.2-GHz downlink); and Ka-band (27.5- to 31.0-GHz uplink/17.7- to 21.2-GHz downlink.] Figure 1 illustrates various types of ESOMP terminals operating with a GSO FSS system.

ESOMPs exhibit some technical and operational characteristics that are different from those of fixed (stationary) VSATs. One such characteristic is the small antenna size that is necessary to operate from a moving vehicle, aircraft, or maritime vessel. Another characteristic is the tracking system that is required to maintain accurate pointing to the target satellite at all times. However, as vehicles or vessels move, there is always a probability that antenna-pointing errors may occur for small fractions of time, thus leading to an increase of interference toward other co-frequency neighboring satellites or other radio systems. This possibility requires that systems be designed and operated rigorously to minimize interference and comply with established regulations. To properly account for the resulting time-varying interference impacts on other systems, it is essential to use statistical methods to analyze performance of these systems.[1–3] Statistical approaches are preferred because they provide the most efficient and effective method to account for interference compared with traditionally defined methods. More detail on the rationale and technical approach for statistical methods can be found later in this article.

Another important element for the successful deployment of ESOMPs is having appropriate standards and regulations. Service providers, operators, and regulators are beginning to address critical issues such as the use of FSS bands, interference considerations, and licensing procedures, among many others. The ITU and several national and regional telecommunication regulators have started the development of standards and regulations to ensure that ESOMP terminals can operate according to technical and operational guidelines,

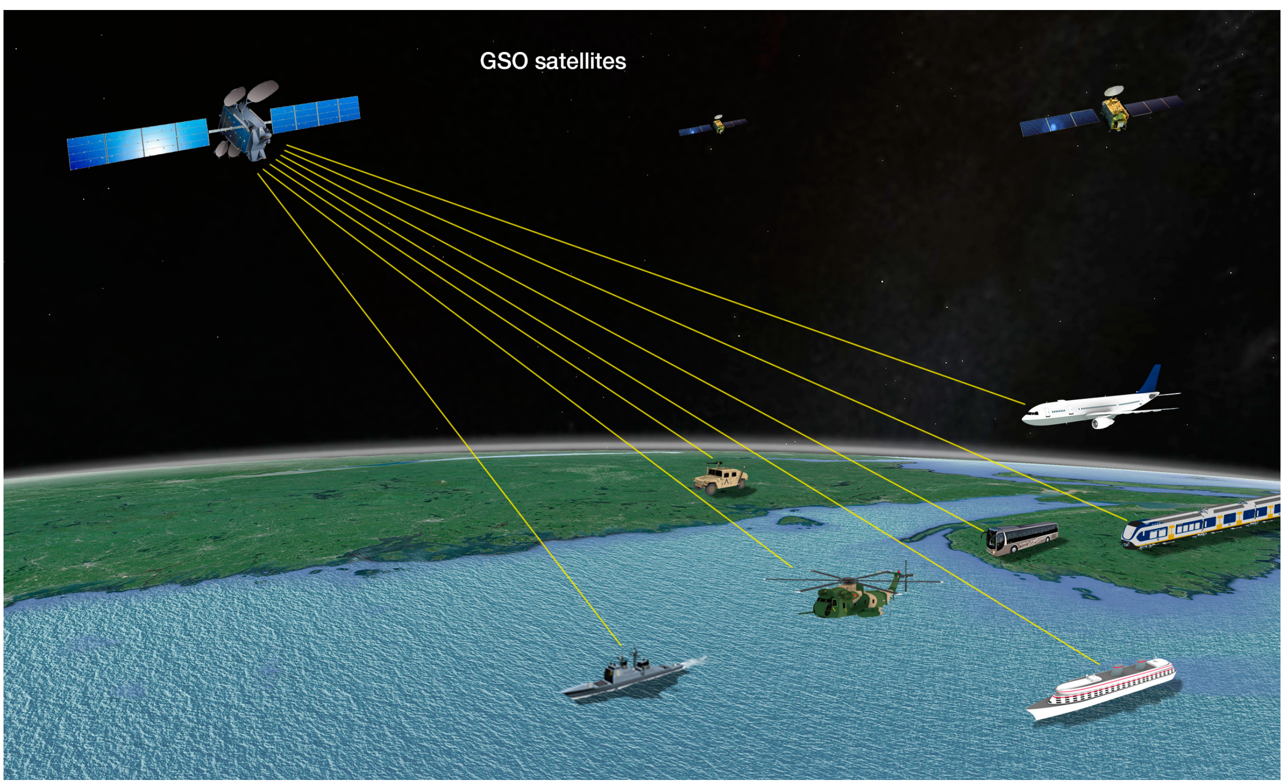

Figure 1. An ESOMP network enabled by a GSO FSS system.

which include interference mitigation considerations. APL made significant technical contributions on these topics, leading to the adoption of two ITU recommendations on interference analysis, and is actively engaged in the development of international standards for ESOMPs.

This article presents an overview of the various types of ESOMPs, their technical and operational characteristics, and the standards and regulations that are being discussed. It describes the specific performance, spectral efficiency, and interference considerations. It identifies the regulatory challenges that must be addressed for operating ESOMPs over GSO and non-GSO satellites. Finally, it presents some spectrum-sharing concepts that could facilitate the use of ESOMPs in constrained scenarios.

CHARACTERISTICS OF ESOMPs

ESOMPs can be used to enable a wide range of applications, from voice or e-mail to high-definition video; thus, the terminal and network configuration depends on the specific platform used (aerial, ship, or ground vehicle) and the service offered. Typically, an ESOMP network may consist of a large number of terminals deployed over a wide geographical area. These terminals may operate with a range of aperture sizes and may require different transmit power levels, according to the location within the satellite footprint, the weather conditions, the type of modulation and coding used, and the maximum supported data rate. To use network resources efficiently, these networks may use time division multiple access methods and frequency division multiple access methods.

Ka-band ESOMP terminals use small, lightweight, high-efficiency antennas such as parabolic, low-profile, or phased-array antennas (phased-array antennas are beyond the scope of this article) with equivalent aperture sizes as small as 0.3 m. ESOMP terminals also include mechanical or electronic tracking systems with servo controllers and positioners to maintain accurate pointing to the target satellite. The tracking systems provide initial signal acquisition and instantaneous reacquisition after a signal loss due to signal obstructions, weather conditions, or antenna mispointing due to sudden turns.

To ensure that ESOMPs do not cause harmful interference on adjacent satellite networks, they must operate according to regulatory guidelines such as the off-axis effective isotropic radiated power (EIRP) spectral density (ESD) limits defined by the local regulators, or with other limits coordinated with neighboring satellite systems. Ensuring that the interference criteria are met with different co-frequency services is critically important for system designers. Designers must address the conflicting demands of ensuring the resulting interference is within acceptable limits, while at the same time providing an adequate ESD level that offers reasonable data rates that are acceptable to end users. These aspects are discussed in more detail in the *Compliance with Standards and Regulations* section of this article.

EVOLUTION OF STANDARDS AND REGULATIONS

To regulate the operation of broadband on-the-move terminals operating in the Ku-band, standards bodies adopted specific rules for each class of terminal. For example, in the United States, the Federal Communications Commission (FCC) adopted §25.222 for Earth stations on vessels (ESVs).[4] Similarly, in §25.226 new rules were adopted for vehicle-mounted Earth stations (VMESs)[5] and, more recently, in §25.227 for Earth stations aboard aircraft (ESAAs).[6] According to FCC rules, each of these types of terminals can operate within the United States as a primary application on specified frequencies over GSO FSS systems. Thus far, the FCC has not started the rule-making process to adopt specific rules for ESOMP terminals operating in the Ka-band. At the regional level, the European Telecommunications Standards Institute (ETSI) has adopted Ku-band standards for ESVs under European Norm (EN) 302 340, for VMESs under EN 302 977, and for aircraft Earth stations (AESs) under EN 302 186. More recently, ETSI has adopted EN 303 978, a new standard for ESOMPs transmitting toward GSO satellites operating in the 27.5-GHz to 30.0-GHz frequency bands.[7]

Table 1. Current regulatory status of ESOMPs

	Ku-Band			Ka-Band		
Terminal Type	USA (FCC)	Europe (ETSI)	International (ITU)	USA (FCC)	Europe (ETSI)	International (ITU)
Aeronautical: ESAA/AES/AMSS	§25.227	EN 302 186	RR No. 4.4 (ITU-R M.1643)	N/A	EN 303 978	RR No. 4.4
Maritime: ESV	§25.222	EN 302 340	RR No. 4.4 (ITU-R S.1587)	N/A	EN 303 978	RR No. 4.4
Terrestrial: VMES	§25.226	EN 302 977	RR No. 4.4 (ITU-R S.1857)	N/A	EN 303 978	RR No. 4.4

N/A, Currently, there are no FCC rules for ESOMPs.

The ITU has also considered the use of on-the-move terminals operating on FSS systems in the Ku-band. In 2003, it issued Recommendation (Rec.) ITU-R M.1643 for AESs of aeronautical MSS (AMSSs).[8] Then, in 2007 it issued Rec. ITU-R S.1587 for ESVs.[9] More recently, in 2010 it issued Rec. ITU-R S.1857, an interference methodology for VMESs.[10] The ITU granted secondary status to AMSSs, but ESVs and VMESs can only operate in FSS networks under RR No. 4.4. According to this ITU regulation, such stations shall not cause harmful interference to, and shall not claim protection from, interference caused by a station operating in accordance with ITU regulations. Table 1 summarizes these existing regulations on ESOMPs.

Because Ka-band ESOMP terminals are new and are under current international regulations, they can only operate under ITU RR No. 4.4. There is a desire from some service providers to elevate their status so that they can be officially recognized and thus enjoy the protection from interference produced by other co-frequency services. To this end, ESOMP proponents will have to develop spectrum-sharing studies to demonstrate that ESOMPs can operate without causing harmful interference to other services. Some initial steps toward this goal have already begun. For example, the ITU has developed two short reports that contain basic technical and operational guidelines for the use of ESOMPs. One report addresses ESOMPs on GSO FSS[11] systems while the other focuses on non-GSO FSS systems.[12] These reports were produced primarily to assist regulators in licensing these terminals within their countries. However, detailed technical studies are needed to address the interference criteria with other services and to create specific limits on ESD and interference within the specific bands of operation.

COMPLIANCE WITH STANDARDS AND REGULATIONS

In this section we examine the key requirements of applicable standards and regulations with which ESOMPs have to comply. Brief descriptions of the regulatory or standards requirements used in this section and in the subsequent sections are provided in Table 2.

Off-Axis Emission Constraints

To limit interference to adjacent GSO satellites, the ITU has established limits on the ESD of a transmit terminal in its off-axis directions. Because of the antenna beam characteristics, terminals with large-aperture antennas are not constrained by the main beam but by the side lobes; hence they can transmit higher ESD levels. However, because the main lobe of small antennas is wide, these terminals can be severely limited by the ESD in the boresight direction (the direction of the maximum gain of the antenna). These off-axis ESD limits are specified in Rec. ITU-R S.728-1 for Ku-band VSATs and in Rec. ITU-R S.524-9 for Ka-band terminals. These are shown as “Ku mask” and “Ka mask” in Fig. 2. Observe that the ESD constraints are applicable only for off-axis angles greater than 2° because the minimum orbital separation between adjacent satellites is usually 2°. This figure also shows the maximum off-axis ESD pattern obtained from typical parabolic antennas in the Ku- and Ka-bands. For example, in the Ku-band it can be seen that the maximum boresight ESD obtained from a 0.3-m-diameter aperture antenna is about 5.5 dB less than the corresponding boresight ESD obtained from a 0.5-m-diameter aperture antenna. Similarly, the boresight ESD of Ka-band antennas is limited by the corresponding off-axis ESD constraints, although smaller

Table 2. List of ITU, FCC, and ETSI requirements discussed

Regulatory or Standards Requirement	Brief Description of Specific Requirements
ITU RR No. 22.5C	Limits on equivalent PFD due to transmissions from non-GSO satellites in parts of Ka-band
ITU RR No. 22.5D	Limits on equivalent PFD due to transmissions from non-GSO Earth terminals in parts of Ka-band
ITU RR No. 22.32	Maximum off-axis emission limits in the 29.5- to 30-GHz frequency band
Rec. ITU-R S.524-9	Off-axis emission limits in the C-, Ku-, and Ka-bands
Rec. ITU-R S.728-1	Off-axis emission limits for VSATs in the Ku-band
Rec. ITU-R S.1323-2	Interference limits and time-varying interference methods for non-GSO systems
Rec. ITU-R S.1857	A statistical ESD mask to account for antenna-pointing errors and time-varying interference from a VMES terminal
Rec. ITU-R S.2029	Methods to estimate interference from a network of ESOMPs
FCC §25.138	Limits on the amount of increase of the effective isotropic radiated power to compensate for rain fading at the Ka-band
FCC §25.222	Antenna-pointing error and location accuracy requirements for ESVs in the Ku-band
FCC §25.226	Antenna-pointing error and location accuracy requirements for VMESs in the Ku-band
FCC §25.227	Antenna-pointing error and location accuracy requirements for ESAAs in the Ku-band
ETSI EN 302 977	Off-axis emission limits and antenna-pointing error requirements for VMESs in the Ku-band

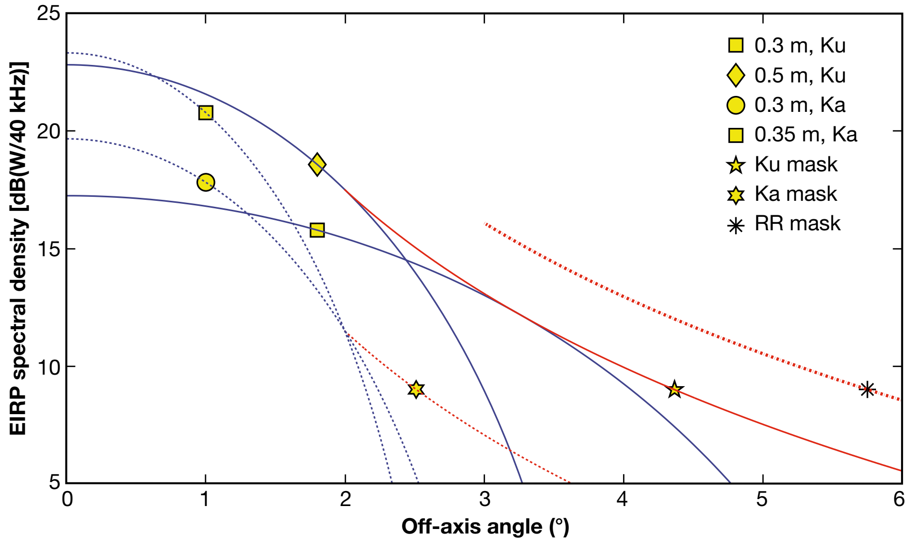

Figure 2. Off-axis ESD limits in the Ku- and Ka-bands. The legend denotes the antenna aperture diameter and the frequency band. EIRP, effective isotropic radiated power.

aperture sizes can be supported in the Ka-band. This figure also shows the off-axis ESD constraint established in RR No. 22.32 for the 29.5- to 30.0-GHz frequency band, which is significantly less restrictive than the corresponding Ka mask defined in Rec. ITU-R S.524-9.

Note that the Ku mask shown here is the ESD level established in Rec. ITU-R S.728-1 reduced by 8 dB as per note 1 of the recommendation to account for satellite spacing near 2°. The Ku-band off-axis ESD constraints established by the FCC for these terminals are similar to the above-described Ku mask but are effective for off-axis angles starting at 1.5°. On the other hand, the corresponding ESD levels adopted in ETSI EN 302 977 are 8 dB less restrictive than those of the Ku mask and are effective for off-axis angles starting at 2.5°.

Emission Constraints for Non-GSO Systems

The off-axis ESD limits discussed thus far are for GSO systems. Because of the recent deployment of a constellation of medium Earth orbit (MEO) satellites that operate in the Ka-band,[13] it is important to consider the emission constraints that are applicable to Earth terminals operating on MEO (non-GSO) satellites. To protect GSO satellites, the ITU, in RR No. 22.5D, has limited the equivalent power flux-density (EPFD) at any point in the GSO from all the Earth terminals in a non-GSO system to –162 dB(W/m2). The MEO satellite network, described in Ref. 13, orbits in the equatorial plane at a distance of 8000 km from Earth's surface. When the Earth terminal is located on the equator, its boresight points directly toward the GSO. In such cases, the boresight ESD is at the minimum allowed and is determined by the EPFD at the GSO, which is –162 dB(W/m^2). This is because when the Earth terminal is located to the north or the south of the equator its boresight is pointing away from the GSO; therefore, the boresight ESD for such cases can be larger than that for the preceding case.

Figure 3 shows the boresight ESD from Earth terminals operating on a MEO satellite constellation similar to that described above. The results shown are for antenna aperture sizes of 0.3 and 0.35 m and located at latitudes 5° and 8°. The x axis denotes the difference in longitude between the Earth terminal and the location of the satellite. As the satellite moves relative to the Earth terminal, the angles subtended at the Earth terminal between its boresight and directions to points on the GSO change. These angles determine the maximum boresight ESD. Note that because of the shorter distance to the MEO satellite orbit, for the same boresight ESD the PFD at the MEO satellite is about 13 dB higher than at a GSO satellite. Therefore, by comparing the boresight ESDs shown in this figure with those in Fig. 2, it can be concluded that the received signal level at the satellite is significantly better with MEO satellites.

In addition to the constraints on the emissions from Earth terminals discussed in the preceding paragraphs, the ITU has adopted limits on the emissions from non-GSO satellites. These limits are specified in RR No. 22.5C and are established to protect Earth terminal receivers of GSO systems.

Constraints on Antenna-Pointing Errors

Antenna-pointing errors are unavoidable in ESOMPs, but they can be controlled as required by applicable regulations and standards. (If not properly maintained and operated, antenna-pointing errors can also occur in VSAT systems, which tend to be less frequently checked for pointing accuracy and may drift in alignment over

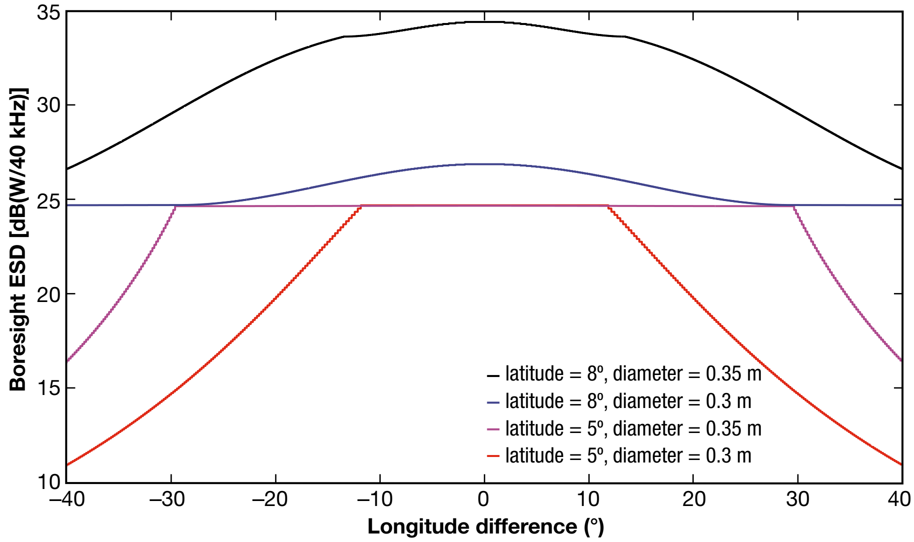

Figure 3. Boresight ESD from an Earth terminal of an MEO satellite network subject to RR No. 22.5D EPFD limits.

time.) The antenna-pointing error is defined as the angle between the boresight direction of the antenna and its intended direction, which is the direction toward its target satellite. According to the VMES rules adopted by the FCC (§25.226), the terminals are allowed to operate when they comply with one of the following constraints on the antenna-pointing errors:

(a) Antenna-pointing errors should be less than 0.2°. If they exceed 0.5°, emissions should cease within 100 ms and transmissions shall not resume until they are less than or equal to 0.2°.

(b) Antenna-pointing errors greater than 0.2° are allowed, provided that the peak value of these errors is declared and the ESD taking into account this peak value complies with the ESD constraints discussed in the preceding subsection. Moreover, transmissions should cease within 100 ms if the antenna-pointing errors exceed this declared value. Transmissions shall not resume until the errors are less than or equal to this declared value.

(c) The terminal may also operate in accordance with an off-axis ESD emission limit agreed with the satellite operator and coordinated with adjacent satellite operators. (Note that the *Limiting the Antenna-Pointing Errors* section in this article discusses how the antenna-pointing errors can be used to develop such an off-axis ESD emission limit.)

The antenna-pointing error requirements for ESVs and ESAAs are established by the FCC in §25.222 and §25.227, respectively, and are similar to the above-described requirements.

The ETSI standard for VMESs in the Ku-band restricts the antenna-pointing errors similar to constraint (b) above. On the other hand, the Ka-band ESOMP standard is more flexible and allows use of a statistical basis to declare the peak value of the antenna-pointing error, instead of the actual peak value. As in constraint (b), the ESD, taking into account this declared value, should comply with the off-axis ESD emission limits.

Other Requirements

To assist in identifying and resolving sources of interference, FCC rules require that ESOMPs maintain a database of signal characteristics: location of the ESOMP, transmit frequency, channel bandwidth, and satellite used. The key requirement is the collection interval of the location data of the ESOMP: for VMESs in §25.226 this is at least every 5 min; for ESVs in §25.222 this is at least every 20 min; and for ESAAs in §25.227 this is at least every 1 min. ETSI standards require the ESOMPs to report their locations with at least 100-m accuracy.

A methodology to estimate the sensitivity of interference onto GSO satellite to the geographical location of Earth stations is presented in Ref. 14. The study shows that interference values of reasonable accuracy can be obtained by using approximated location values instead of the actual location values. Also, it demonstrates that the sensitivity is highest if the victim satellite receives the signal with a spot-beam antenna. Even in such a case, there is little change in the interference level for terminal location changes of a few kilometers.

SPECTRAL EFFICIENCY CONSIDERATIONS

The spectral efficiency of a communication link, which is the data rate transmitted in the link normalized with respect to the occupied bandwidth of the signal, is a key parameter that can be used to quantify the spectral use of that link. Shannon's well-known capacity formula demonstrates that the link spectral efficiency is proportional to the signal-to-noise ratio of the received signal. Additionally, as discussed in the previous section, the off-axis ESD constraints severely limit the transmit power in a given bandwidth for small-aperture terminals. Therefore, it follows that the spectral efficiency realized from a satellite link that uses a small-aperture transmit antenna can be low. Moreover, when a small-aperture antenna is used at the receiver, the link spectral efficiency can be very low because of the low antenna gain. Finally, the overall link spectral efficiency could be further degraded by adjacent satellite interference.

Figure 4 shows the spectral efficiency for a typical link from a small-aperture transmit terminal to a large-aperture receive terminal. In this example, the receive antenna aperture is assumed to be very large so that the overall link performance is dominated by the weak uplink. Because the uplink signal is weak, interference received at the satellite from co-frequency signals transmitting to adjacent satellites may have a significant effect on the overall link performance. The interference shown in this figure is due to terminals transmitting to adjacent satellites with their off-axis ESD emission pattern given by the Ku mask shown in Fig. 2. Using this Ku mask for the interferer, when the off-axis angle toward the adjacent satellite is 2.2°, the ESD of the interference signal is 16.4 dB(W/40 kHz), which is significant with respect to the boresight ESD of a small-aperture antenna.

To realize the low spectral efficiencies shown in Fig. 4, these communication links use spread-spectrum techniques in addition to coding and modulation schemes of variable rates. In this example, we used a combination of variable rate coding, modulation, and spread-spectrum schemes that support the multiple discrete spectral efficiency levels shown. Note that different terminals in a network of ESOMPs may use antennas of different aperture sizes and they may have to operate in a large area where the satellite antenna gain may vary significantly. In such cases, to support the varying spectral efficiency requirements, the communication link should support adaptive coding and modulation (ACM) schemes combined with variable gain spread spectrum schemes.

Spectral Efficiency from Ka-Band Links

Figure 2 shows that for the same antenna aperture size, higher boresight ESD levels can be achieved in the Ka-band. Although this is attractive when using small-aperture antennas, the signal attenuation due to rain can be considerably more at Ka-band frequencies. Because of this, to overcome the effects of rain fading, a significant portion of the transmit power has to be reserved for a link margin. This reduces the effective link spectral efficiency because the power reserved for the link margin could otherwise be used to enable higher-order modulation and coding rates and hence transmit higher data rates. The degradation of the received carrier-to-noise ratio (CNR) due to rain fading is shown in Fig. 5. This figure shows typical Ka-band links from Miami, Florida, to New York City (NYC), New York, and vice versa in the presence of rain fading in both links, in the uplink and the downlink, and only in the downlink. The CNR degradation in this figure is defined as follows. Satellite links are designed with a guaranteed link availability condition: the CNR should be better than CNR_{REQ} for p_{avail}% of time. To accomplish this objective, the CNR under nonfading (clear-sky) conditions should be greater

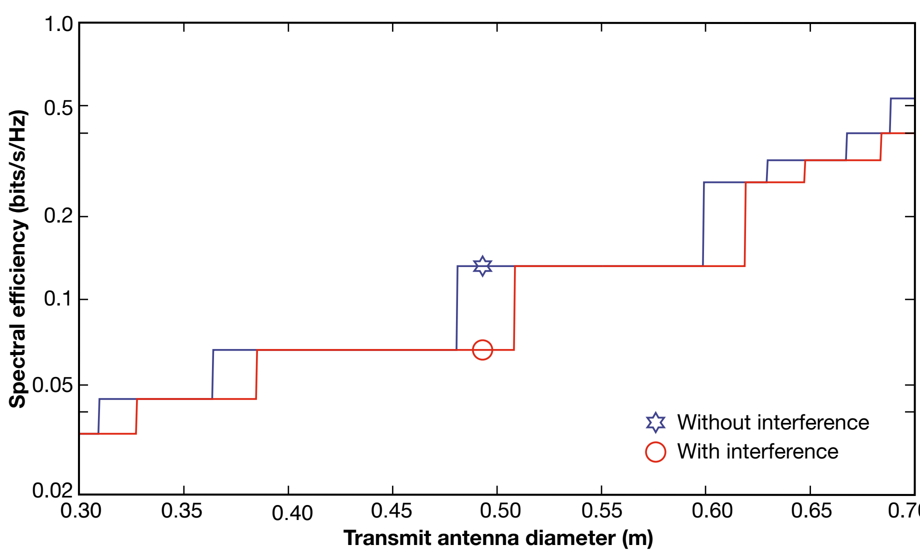

Figure 4. Spectral efficiency for a Ku-band link from a small-aperture transmit terminal to a large-aperture receive terminal.

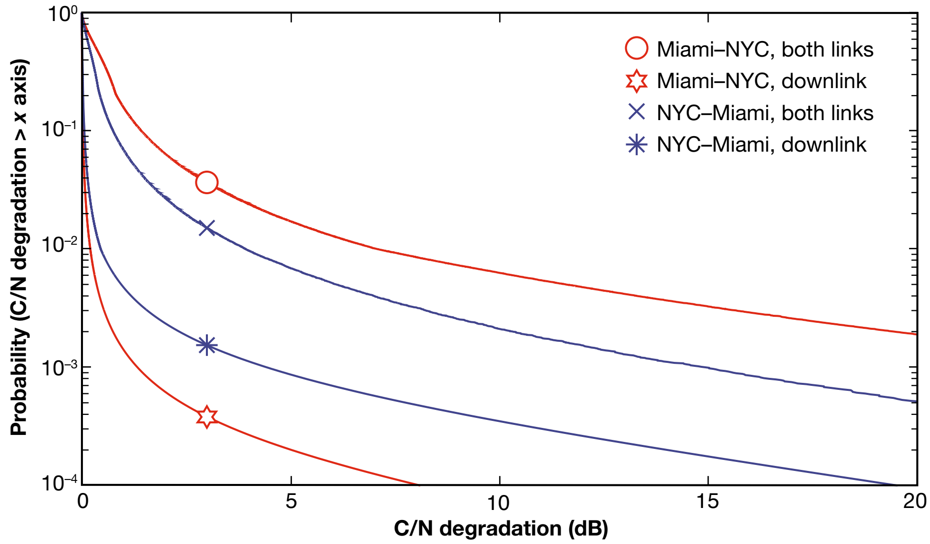

Figure 5. CNR ratio degradation due to rain fading.

than CNR_{REQ}. Then the CNR degradation is defined as Z (dB) = CNR_{CS} (dB) – CNR_{REQ} (dB), where CNR_{CS} is the CNR under clear-sky conditions. It follows that the link margin necessary to guarantee the required availability level is Z (dB).

For example, suppose the link is designed so that the CNR is greater than a required level CNR_{REQ} for p_{avail}% = 99% of the time, which is equivalent to saying that the CNR is degraded only 1% of the time. Then for the Miami to NYC link with rain fading in both uplink and downlink, the required link margin is 7 dB, which is significant. The corresponding link margin for the NYC to Miami link is only 3.9 dB. This margin is lower than in the previous case because of the higher rainfall accumulation rates experienced in Miami and because the path attenuation on the uplink frequencies is higher than on the downlink frequencies.

This figure also shows that in the presence of only downlink fading the required link margins are very low. This situation can be realized by using ideal uplink power control (UPC) in the presence of rain fading in the uplink, showing the benefit of using UPC. Observe that these results are applicable only when ideal UPC is used; the link margin has to be increased in a practical satellite link to account for estimation errors of the uplink fades. UPC has been extensively used in satellite links;[15] however, with small-aperture terminals, which have wide beamwidths and operate at ESD levels toward adjacent satellites that are close to their maximum allowed levels, UPC should be applied cautiously because of the potential to increase interference to adjacent satellites beyond their clear-sky levels.

The off-axis ESD constraints discussed in the previous section are applicable under clear-sky conditions. The relevant ITU-R recommendations and the ITU RRs recognize that uplink power may be increased to overcome rain fades, but they do not establish specific levels. On the other hand, in §25.138 the FCC specifies the ESD level that may exceed its off-axis ESD constraint when UPC is used. Specifically, to account for errors in UPC, it states that the amount of increase in the ESD in excess of the actual uplink fade is limited to 1.5 dB for 90% of time (this is a simplified statement of excess ESD specified in FCC §25.138). Denote the PFD at the wanted satellite under clear-sky and rain-fading conditions by P_{cs} (dB) and P_{ra} (dB), respectively. Then the above requirement can be expressed in the following form: $\Pr\{(P_{ra} - P_{cs}) \leq 1.5\} > 0.9$, which is equivalent to $\Pr\{(P_{ra} - P_{cs}) > 1.5\} < 0.1$. This expression shows that, in the presence of UPC, the wanted satellite could experience a PFD level that is higher than its clear-sky value—specifically, the PFD level in excess of its clear-sky value can be greater than 1.5 dB for less than 10% of the time.

ACM schemes could improve the spectral efficiency significantly in rain-fading conditions. To see this, refer to the above-described example in which a link margin of 7 dB was used to guarantee a 99% availability level for the Miami to NYC link. Unfortunately, because large link margins are necessary only under severe fading conditions and such periods occur only occasionally, this link margin is too large most of the time. During periods when rain fading is not severe, the additional link margin available could be used to send data at higher rates using ACM schemes. ACM schemes improve the overall spectral efficiency by estimating the channel conditions and sending data by using the appropriate coding and modulation scheme for that particular channel condition.

The focus of the preceding discussion was on GSO systems. Next, consider the MEO satellite network discussed in the previous section and the boresight ESD levels shown in Fig. 3. Clearly, these terminals must use UPC to realize the variable ESD levels available at different points along the path of the satellite. Furthermore, ACM techniques must be combined with UPC to achieve a spectrally efficient link.

LIMITING THE ANTENNA-POINTING ERRORS

The *Compliance with Standards and Regulations* section of this article presented regulatory constraints on antenna-pointing errors. This section examines these constraints in detail and presents a statistical approach to limiting antenna-pointing errors. Note that the antenna is usually tracked using the pointing errors in the azimuth and elevation directions[2] and these error components are available for analysis. The antenna-pointing error can be computed using these error components according to the expressions presented in Rec. ITU-R S.1857.

Because of antenna-pointing errors, the resulting ESD may exceed the off-axis ESD limits defined in ITU recommendations. Consider three general approaches for limiting the antenna-pointing errors. The first general approach for limiting the antenna-pointing errors is similar to that in constraint (a) described in the *Constraints on Antenna-Pointing Errors* section of this article: the antenna-pointing errors are constantly monitored, and when they exceed a specified level the carrier signal is shut off from the antenna. Key disadvantages of this approach are the difficulty of accurately monitoring the antenna-pointing error signal and how shutting off the carrier signal affects the user's applications.

The second general approach for limiting the antenna-pointing errors is similar to the approach described in constraint (b): the maximum antenna-pointing error is predetermined and the power spectral density at the antenna input is reduced so that under all antenna-pointing error conditions the resulting ESD satisfies the off-axis ESD constraints. Figure 2 illustrates that, in the presence of an antenna-pointing error, the off-axis ESD patterns must be shifted to the right. Thus, the off-axis ESD levels must be reduced because these shifted patterns exceed their off-axis ESD constraints. Figure 6 shows this reduction in ESD as a function of the maximum antenna-pointing error for the Ku-band, off-axis ESD constraints. As can be seen in the figure, the reduction in ESD could be significant for larger antenna-pointing errors, which tend to occur occasionally.

The above-described approach requires determining the maximum antenna-pointing error, which is unrealistic in many practical applications because large antenna-pointing errors are observed with a very small probability. Moreover, the maximum antenna-pointing error cannot be determined accurately because of measurement errors. The ETSI standard for ESOMPs effectively overcomes this problem by letting the ESOMP user define a peak pointing accuracy by using a statistical basis instead of the maximum antenna-pointing error.

Because antenna-pointing errors are random variables, the resulting ESD can also be considered a random variable. Recognizing this, Rec. ITU-R S.1857 has established a statistical technique to limit the ESD and, thus, the antenna-pointing errors. When the statistical characteristics of the antenna-pointing errors and the antenna characteristics are known, the probability that the ESD exceeds a given off-axis ESD constraint can be determined. Then a statistical ESD mask can be obtained by imposing an upper bound on this probability. Observe that this probability depends on the boresight ESD level; that is, to comply with this statistical ESD mask, antennas with larger pointing errors may require larger reductions of their boresight

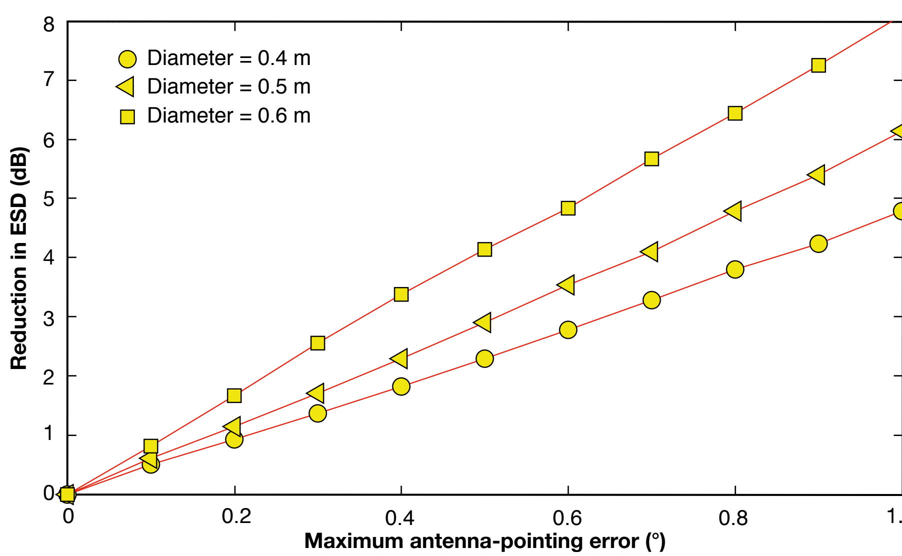

Figure 6. Reduction in ESD necessary to satisfy the Rec. ITU-R S.728-1 off-axis ESD constraints.

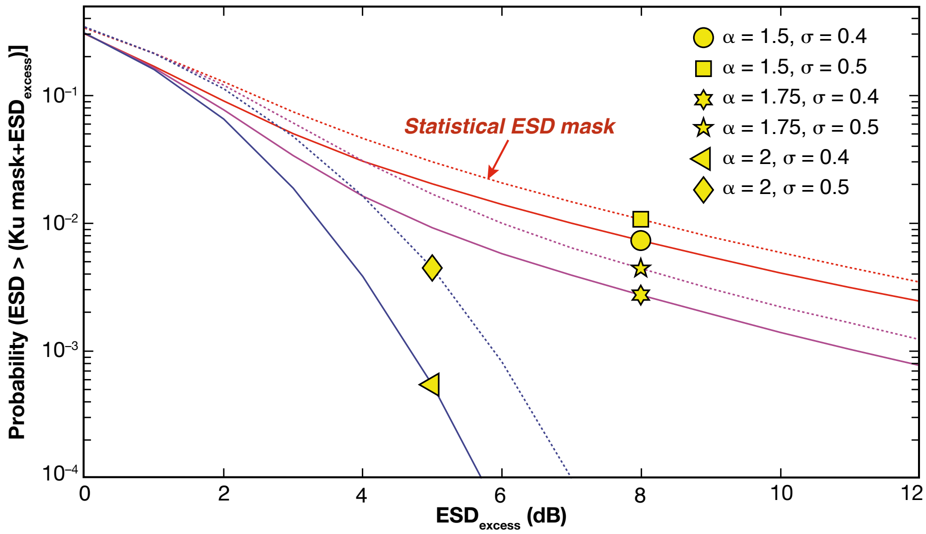

Figure 7. Probability of ESD exceeding the off-axis ESD constraints in Rec. ITU-R S.728-1.

ESD levels. The advantage of this technique is that a variety of antenna-pointing error characteristics can be accommodated without requiring the carrier signal to be switched off.

Figure 7 shows an illustrative statistical ESD mask and the probability of exceeding the Ku mask for different antenna-pointing error characteristics. Statistics of antenna-pointing errors are such that large antenna-pointing errors may occur with a very small probability. Therefore, for the results shown in this figure, the antenna-pointing errors in the azimuth and elevation directions are modeled using a symmetric α-stable distribution with stability parameter α and scale parameter $c = \sigma/\sqrt{2}$ (Ref. 10). Note that the normal distribution is a special case of this general distribution and is obtained when $\alpha = 2$ and the variance of this distribution is σ^2. Also, lower values of α result in longer tails, and higher values of c or σ result in larger errors. Therefore, as can be seen from this figure, the curves for lower α values result in higher excess ESD levels. Observe that these curves are a function of the boresight ESD level: increasing the boresight ESD increases the probability values shown on the *y* axis. The concept of a statistical ESD mask is useful to regulators and administrators because it can be used to establish an appropriate off-axis ESD mask, as in constraint (c), and the users can then adjust their antenna boresight ESD levels to comply with such a mask.

A statistical ESD mask that is tight or lax can be adopted depending on the probability of exceeding the underlying reference ESD mask. A tight statistical ESD mask results when this probability is very small, whereas larger probabilities give a lax statistical ESD mask. A VMES antenna can comply with the statistical ESD mask by reducing its boresight ESD appropriately, with the tight statistical ESD mask requiring a larger reduction of the boresight ESD. Figure 7 shows an illustrative statistical ESD mask for which the ESD is allowed to exceed the Ku mask as follows: 2 dB with probability 13%; 4 dB with probability 4.5%; 6 dB with probability 2%; and 8 dB with probability 1%. This is a lax statistical ESD mask and is satisfied by antennas with pointing error characteristics that correspond to long-tail distributions with a very small reduction in the boresight ESD level.

INTERFERENCE FROM A NETWORK OF ESOMPs

As seen in the discussions in the preceding sections, the technical characteristics of ESOMPs are different from those of conventional VSATs. Therefore, for efficient sharing of spectrum with other co-frequency users, it is important to be able to assess and quantify the interference from ESOMPs. A network of ESOMPs may use antennas of different aperture sizes and the terminals of the network may be located at different contours of the victim satellite's receive-antenna gain pattern. Because of this, when the network is using a time division multiple access protocol, the interference at the victim receiver is time varying. Moreover, antenna-pointing errors and mobility of the terminals introduce time-varying effects to the interference. In conventional point-to-point satellite links, interference is time invariant so the time variability of the interference from an ESOMP network must be investigated in detail. In conventional satellite systems, interference is quantified and limited using the $\Delta T/T$ ratio, where ΔT is the increase in the equivalent thermal noise temperature at the victim receiver due to the interference, and T is the noise temperature at the victim receiver. Because this is applicable to time-invariant interference, interference methodologies applicable to time-varying interference from ESOMPs were developed in Recs. ITU-R S.1857 and S.2029 (Rec. ITU-R S.1857 addresses time-varying interference from a single VMES terminal, whereas Rec. ITU-R S.2029 may be used to address time-varying interference from a network of ESOMPs).

To see the disadvantage of using the conventional $\Delta T/T$ ratio to assess the time-varying interference from ESOMPs, consider the following special case. Suppose the ESOMP is stationary and transmitting without antenna-pointing errors and the ESD level is such that the $\Delta T/T$ ratio at the adjacent satellite is at its maximum allowed level, which is denoted by $(\Delta T/T)_{max}$ and is usually 6%.[16] Now, introduce random antenna-pointing errors at the ESOMP. Observe that, because antenna-pointing errors occur in random directions, the $\Delta T/T$ ratio fluctuates about $(\Delta T/T)_{max}$ in both increasing and decreasing directions, and large fluctuations of the $\Delta T/T$ ratio may occur with a very small probability. By reducing the boresight ESD of the ESOMP, the peak value of the $\Delta T/T$ ratio may be limited to $(\Delta T/T)_{max}$. However, this requires an unreasonably large reduction of the boresight ESD. Moreover, adopting a criterion that limits the peak $\Delta T/T$ ratio to $(\Delta T/T)_{max}$ is not appropriate in this application because the peak $\Delta T/T$ ratio occurs with a very small probability. On the other hand, the average value of the $\Delta T/T$ ratio could be limited to $(\Delta T/T)_{max}$, and the fluctuations above this average $\Delta T/T$ ratio could be limited using separate interference criteria. This is the approach used in Recs. ITU-R S.1857 and S.2029.

Criteria to limit time-varying interference to GSO receivers caused by non-GSO satellite systems have been established in Rec. ITU-R S.1323-2. The approach adopted in this recommendation can be explained as follows: The performance objectives of a receiver may be specified in terms of the degradation time allowed for a particular metric, for example, the bit error rate (BER) or the CNR. The degradations in the link may occur because of propagation conditions, which include rain fading, and time-varying interference. According to this recommendation, 10% of the overall degradation time is allocated exclusively for time-varying interference, and propagation conditions cannot account for more than 90% of the overall degradation time. The link margin should be designed to satisfy both these conditions. For example, the performance objective of the receiver may be listed as $\Pr\{BER > BER_{max}\} < p_{out}$, where p_{out} is the outage probability. According to Rec. ITU-R S.1323-2, the link outages that occur only because of propagation impairments are limited to a probability of $90\% \times p_{out}$ and the remaining outage probability, $10\% \times p_{out}$, is allocated to outages only due to time-varying interference. This allocation of degradation time is shown in the top section of Fig. 8, where N_{sec} is the average number of seconds in a year and, in this example, $BER_{max} = 10^{-6}$ and $p_{out} = 0.01$. In this approach, it should be noted that the victim receiver's link margin is designed to accommodate some degradations due to time-varying interference, and limits are not explicitly imposed on the peak value of the time-varying interference.

The methodologies established in Recs. ITU-R S.1857 and S.2029 are based on the above-described concept of accommodating time-varying interference; however, there is a key difference in these methodologies.[17] The total time-varying interference from an ESOMP can be considered to be the sum of its average interference and the time-varying part of the interference. Technical characteristics of a stationary ESOMP can be considered to be the same as that of a VSAT operating in the FSS bands so the $\Delta T/T$ ratio measure should be used to limit the interference from a stationary ESOMP. The average interference is similar to the interference from a stationary ESOMP so the $\Delta T/T$ ratio measure is used to limit this component. The difference in the interference between an ESOMP and a VSAT is because of the time-varying part of the interference due to antenna-pointing errors and motion of the ESOMP. Therefore,

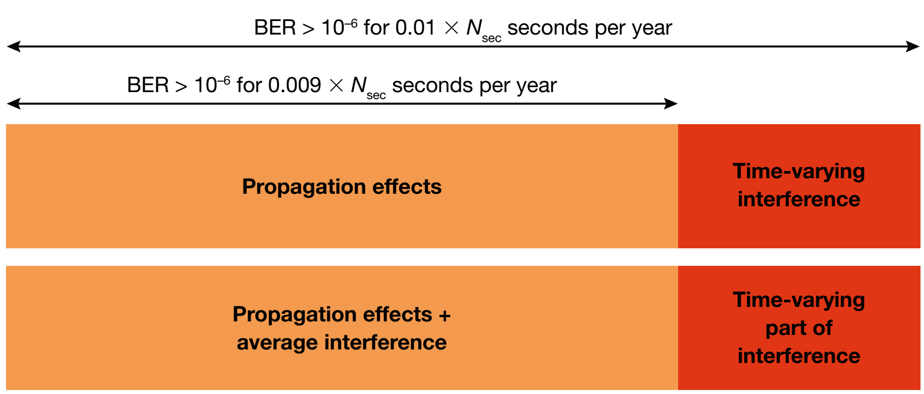

Figure 8. Illustrative examples of allocation of the overall BER degradation time for time-varying interference in Rec. ITU-R S.1323-2 (top section) and Recs. ITU-R S.1857 and S.2029 (bottom section).

only the time-varying part of the interference, instead of the total interference as in the non-GSO application, is allocated a small fraction of the total degradation time specified in the performance objectives of the victim receiver. The bottom section of Fig. 8 shows the allocation of degradation time to the time-varying part of the interference. As shown, the average interference is combined with the propagation effects and is allocated a maximum of 90% of the allowed degradation time. Note that the link margin is designed so that the total interference, which is the sum of the average interference and the time-varying part of the interference, has to comply with the overall performance objectives of the receiver. Also, note that in Recs. ITU-R S.1857 and S.2029, the allocation of the degradation time is given in parametric form instead of the 90% and 10% partition as shown in Fig. 8.

Figure 9 shows the relative increase of the degradation time due only to the time-varying part of the interference from a VMES with antenna-pointing errors. The antenna-pointing errors are modeled so that their error components in the azimuth and elevation directions are zero-mean normal random variables with the standard deviation as shown in the *x* axis. The required availability levels, which are given by $(1 - p_{out}) \times 100\%$, of these links are also shown in this figure. As the variance of the antenna-pointing error increases, the percentage of the degradation time due only to the time-varying part of the interference also increases. Note that, in this example, the maximum allowed for relative increase in the degradation time is 10%. It is seen that larger antenna-pointing errors can be tolerated by links with higher availability levels. This is because higher link availability levels yield larger link margins that in turn accommodate larger antenna-pointing errors.

The interference assessment techniques discussed above are limited to FSS GSO networks. As discussed in the next section, ESOMPs may share the spectrum with other services and this will require development of interference assessment techniques suitable for such spectrum-sharing applications.

TECHNIQUES FOR EFFICIENT SHARING OF SPECTRUM

ESOMPs operate in the FSS bands and share the spectrum with other FSS applications and other services such as fixed service (terrestrial service) and non-GSO systems. ESOMPs can use spectrum-sharing techniques that will help them to gain access to additional bands and share them with other services without causing harmful interference. Spectrum sharing using cognitive radio techniques has been examined for the terrestrial frequency bands in the past, and more recently by CoRaSat (http://www.ict-corasat.eu) for satellite frequency bands. CoRaSat is a European Commission project aimed at studying and developing cognitive radio techniques in the frequency bands allocated for satellite communications. In this section, we consider two specific examples in which the ESOMPs can use dynamic spectrum access techniques in an effective manner. A network of ESOMPs is usually scattered over a large geographical area so the ESOMPs can dynamically monitor the spectrum for unused spectrums, estimate the interference at the victim receiver, and coordinate with other co-frequency users of the spectrum before transmitting.

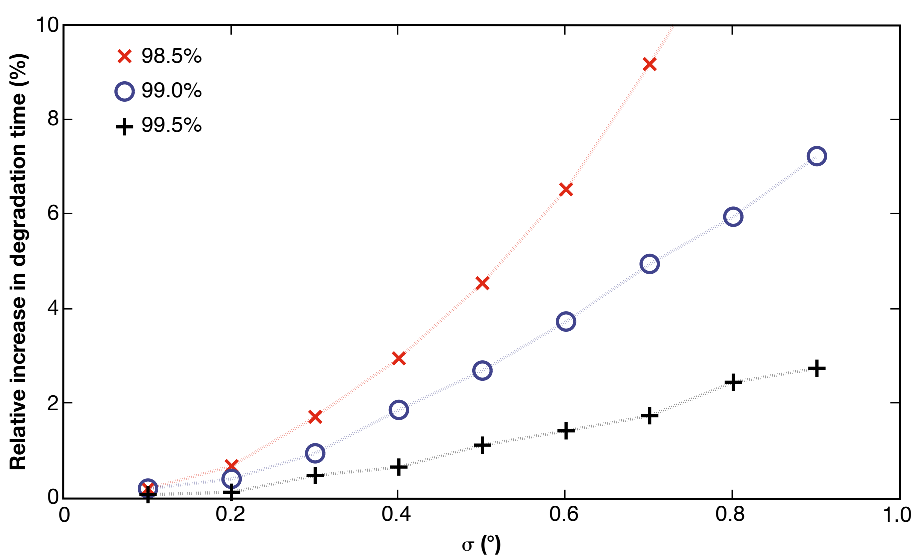

Figure 9. Relative increase in the degradation time for the time-varying part of the interference. Legend denotes the link availability level.

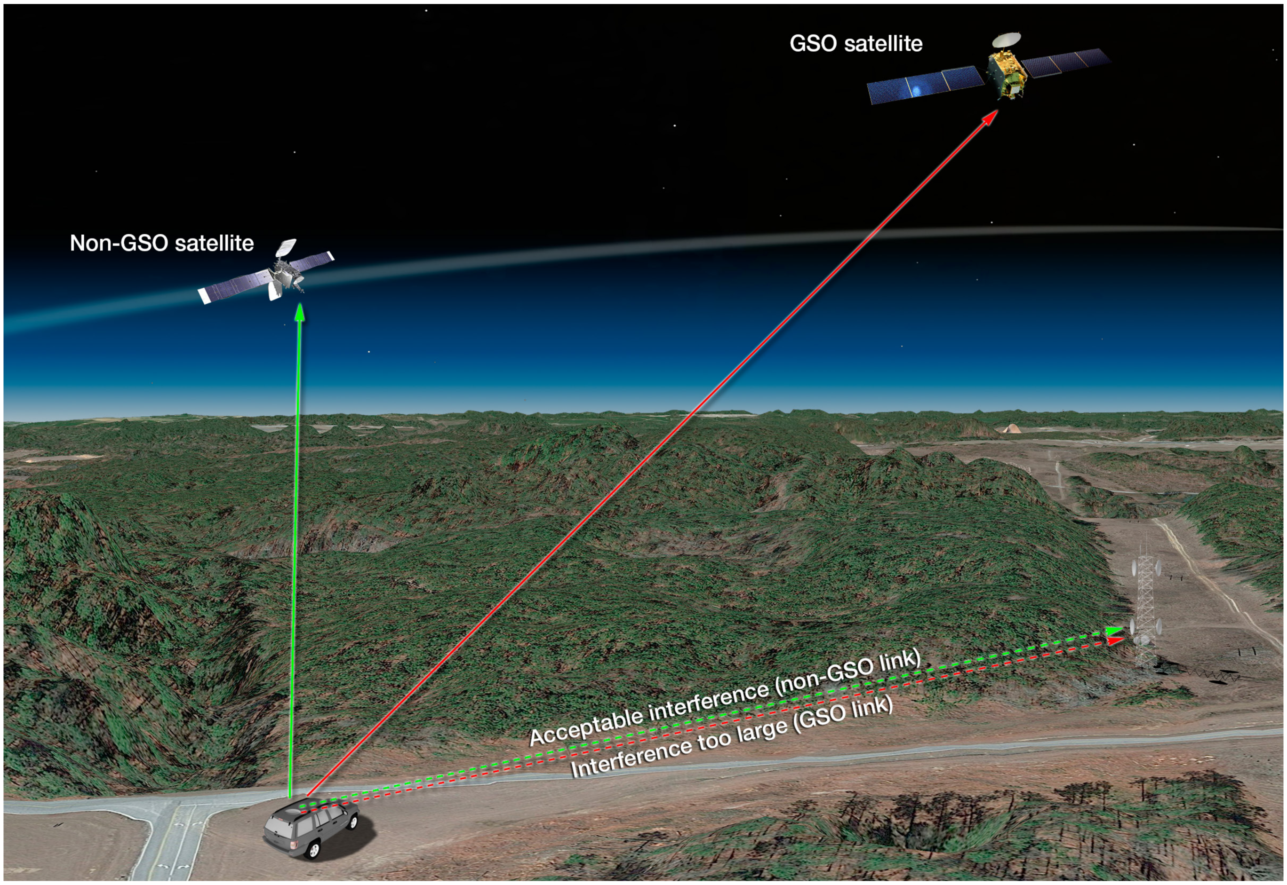

Figure 10. Example of an ESOMP (VMES) sharing the spectrum with a terrestrial station.

Figure 10 shows the case of an ESOMP transmitting to a GSO satellite and sharing the spectrum with a terrestrial station in fixed service without causing harmful interference to the terrestrial service station. The ESOMP can transmit to either the GSO or the non-GSO satellite. Using *a priori* knowledge of the location of the terrestrial station and making use of the link calculations established in ITU-R recommendations for interference levels,[18–19] the ESOMP can dynamically estimate the interference level received at the terrestrial station. In the example shown in this figure, the ESOMP switches its transmission from the GSO satellite to the non-GSO satellite to maintain its interference at acceptable levels. The non-GSO satellite is located in a direction opposite to the terrestrial station so the directive antenna of the ESOMP reduces interference at the terrestrial station. Additionally, the ESD levels transmitted to the non-GSO satellites are substantially lower than those for GSO satellites. Both of these factors help to reduce the interference level at the terrestrial station.

The second example considered is shown in Fig. 11, where the ESOMP is using antenna beamforming techniques to limit its interference level in the directions of the terrestrial stations in fixed service while transmitting to its target satellite in the GSO. Observe that the use of a phased-array antenna is advantageous in this application because of its ability to form multiple nulls in directions toward terrestrial stations. As in the previous example, the ESOMP can dynamically estimate the interference level at the terrestrial stations and adjust its ESD level so as to comply with all the applicable interference requirements.

It should be stated that some ITU-R recommendations[20] specify a minimum distance from the shoreline, which is 125 km in the Ku-band, for ESVs to operate without causing unacceptable interference to the terrestrial service. This minimum distance requirement is not reasonable because it does not account for the dynamics of the ESV and thus prevents efficient use of the spectrum. Additionally, this distance requirement may be too stringent and unduly limit ESV operations because it does not represent the actual interference level at the victim terminal.

Because of widespread use of ESOMPs, there are many applications for which spectrum sharing is advantageous for ESOMPs as well as other services. To facilitate the spectrum-sharing concepts presented here, it is necessary to develop statistical methods for interference assessment and criteria for spectrum sharing among different services and applications.

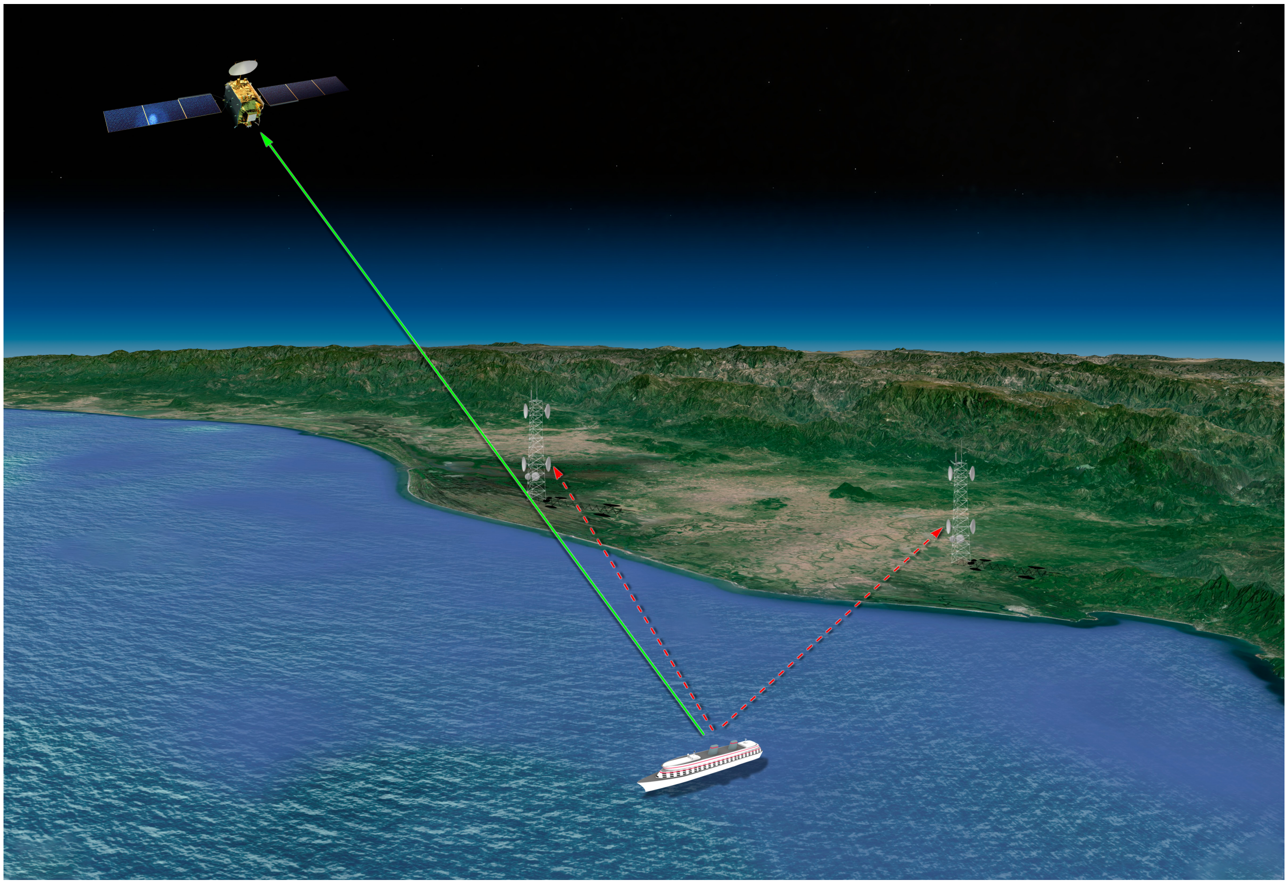

Figure 11. Example of an ESOMP (ESV) sharing the spectrum with terrestrial stations.

CONCLUSION

The user's demand for broadband satellite communications while on the move can be met with ESOMPs. This new type of Earth terminal has emerged from recent technology capabilities adopted by satellite designers and terminal equipment manufacturers. Today's ESOMPs are more spectrally efficient, use ultra-small antennas with multi-axis stabilizers and tracking systems, and can provide broadband communications to support voice, video, and high-speed data. However, to successfully deploy ESOMPs worldwide, it is imperative to have appropriate standards and regulations to enable proper operation of these terminals. To meet this goal, several technical and regulatory challenges will need to be addressed by the standards and regulatory bodies and by the satellite community. This article has outlined the need to use statistical approaches to address the time-varying characteristics of ESOMPs and to develop future frequency sharing studies. Also, it has described some technology innovations and new concepts that could facilitate the use of ESOMPs on constrained scenarios. The technical community will need to address these challenges and develop solutions that enable on-the-move users with broadband satellite services and with seamless operations.

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