Radiocommunication Study Groups

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Annex 33 to Working Party 4A Chair's Report

WORKING DOCUMENT TOWARDS A PRELIMINARY DRAFT NEW RECOMMENDATION ITU-R S.[NON-GSO-MODELLING]

Working Party (WP) 4A has been working to develop a methodology for the assessment of interference from non-GSO FSS systems for sharing and compatibility. Several input contributions were received on this topic to the October 2024 meeting of WP 4A. Based on these input contributions and subsequent discussions during the meeting, it was decided to split the document into two separate documents: one document related to NGSO-Modelling Recommendation, one document containing all of the studies submitted under this topic, for consideration as the Recommendation is developed.

This document contains the work related to the NGSO modelling recommendation using as a baseline Annex 26 to Doc. 4A/128 and adding in coloured highlighting information from the following input contributions: Documents 4A/182, 215, 268 and 283.

Further contribution on this subject is encouraged.

Attachment: 1

ATTACHMENT

WORKING DOCUMENT TOWARDS A PRELIMINARY DRAFT NEW RECOMMENDATION ITU-R S.[NON-GSO-MODELLING]

Modelling and simulation of non-GSO FSS systems for use in sharing and compatibility studies

[Editor's note: a question was raised regarding the intended scope of this Recommendation and whether it is intended to provide elements for modelling NGSO systems or also a methodology]

considering

[*a)* that systems based on the use of non-geostationary-satellite orbit (non-GSO) FSS systems are capable of providing high-capacity and low-cost means of communication even to the most isolated regions of the world;

b) that the associated spectrum for the operation of non-GSO FSS constellations are valuable resources;

c) that Resolution **76 (Rev.WRC-15)** invites the ITU-R to develop a Recommendation on the accurate modelling of interference from non-GSO FSS systems;

d) that methodologies for the modelling and simulation of non-GSO FSS systems are needed to analyze compatibility between non-GSO FSS systems and systems in other services;

e)]that an accurate description of simulation of the transmissions of non-GSO FSS systems is required to realistically model non-GSO FSS systems in sharing and compatibility studies,

recognizing

a) that some technical parameters needed for ~~provisions governing the~~ operations ~~and regulatory restrictions~~ of non-GSO FSS systems within the regulatory requirements are contained in RR Appendix **4** parameters of non-GSO FSS system filings;

b) that Recommendation ITU-R S.1323 provides information on operational requirements and protection criteria that may be used in sharing studies;

c) that Recommendation ITU-R S.2131 provides ~~protection criteria~~a method for the ~~determination~~quantification of performance objectives for satellite ~~systems~~hypothetical reference digital paths utilizing adaptive coding and modulation (ACM),

recommends

that the modelling and simulation of non-GSO FSS systems ~~for use~~based on the information contained in Annex 1 may be used in sharing and compatibility studies ~~should be based on the methodology contained in Annex 1~~.

Annex 1

~~Methodology~~Information for modelling and simulation of non-GSO FSS systems for use in sharing and compatibility studies

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Page

1 Introduction

This Annex contains ~~a methodology~~information for modelling and simulation of non-GSO systems for use in sharing and compatibility studies. It describes ~~the appropriate~~some possible non-GSO models to be used for sharing and compatibility studies between non-GSO and other radio systems in various frequency bands.

[TBD]

2 Definitions and basic concepts

[TBD]

3 Simulation methodology

3.1 non-GSO FSS orbital parameters

Non-GSO systems operate in various orbits such as Low Earth Orbit (LEO), Medium Earth Orbit (MEO), and Highly Elliptical Orbit (HEO). The orbital parameters for non-GSO systems are crucial for determining their function and performance. The altitude of the orbit determines the time it takes for the satellite to complete one revolution around the Earth. The inclination of the orbit is the angle between the orbital plane and the equatorial plane of the Earth, which, in combination with altitude, determines the limits of the coverage area of the ~~satellite~~non-GSO system. The eccentricity of the orbit determines the difference between the minimum and maximum distances from the satellite to the Earth. The period of the orbit is the time it takes for the satellite to complete one full orbit around the Earth. The orbital parameters must be carefully chosen based on the mission requirements of the satellite system, such as coverage area, communication latency, and data transfer rate.

For ~~each~~ every ~~of the~~ non-GSO ~~satellites~~constellation, the following parameters are needed to define the location of the ~~constellation~~ each satellite within the constellation in any analysis:

– Orbital altitude (km) (Semi-major axis/apogee and perigee)
– Eccentricity of orbit
– Inclination of orbit (degrees)
– Longitude of ascending node of orbit (degrees)
– Right ascension of the ascending node (degrees)
– Argument of perigee (degrees).
– True anomaly (degrees)
– Type of the constellation
– Number of orbital planes
– Spacing between planes (degrees)
– Number of satellites per plane
– Initial phase of first satellite per each plane (degrees)
– Phase between satellites in same plane (degrees)
– Phasing of satellites between consecutive planes (degrees).

Orbital altitude

The orbital altitude refers to the height of a satellite's orbit above the Earth's surface, typically measured in kilometers (km). Non-GSO networks can have orbits that are either circular or

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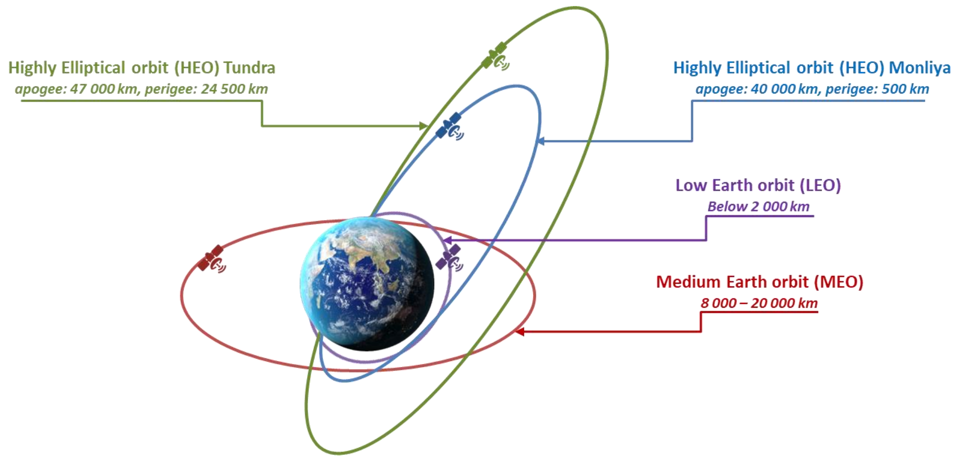
elliptical. For circular orbits, the altitude is consistent throughout, while for elliptical orbits, the altitude varies between the apogee (the highest point) and the perigee (the lowest point). The figure illustrates the various types of orbits used by non-GSO networks.

FIGURE 1

Types of non-GSO orbits



Semi-major axis

The longest radius of an elliptical orbit, extending from the center of the orbit to the farthest point on the ellipse. The semi-major axis can be calculated when knowing the values of apogee and perigee and can be expressed as follows:

$$a = \cancel{(h_{apogee} + h_{perigee})}(Ra + Rp)/2$$

where:

a: semi-major axis

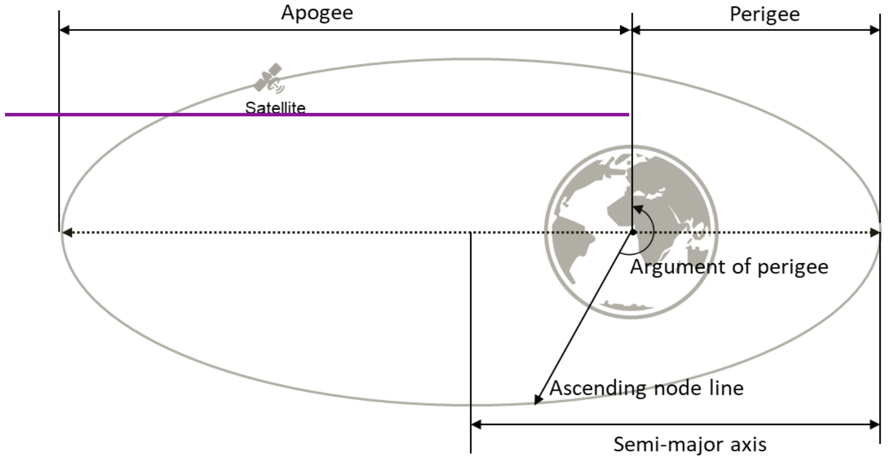
R_a: distance between the centre of the Earth and the space station at apogee

R_p: distance between the centre of the Earth and the space station at perigee.

The values of apogee, perigee and semi-major axis are shown graphically in Figure 2.

FIGURE 2

Semi-major axis, apogee and perigee representation



Eccentricity of orbit

A measure of how much an orbit deviate from being circular. An eccentricity of 0 indicates a perfect circle, while values closer to 1 indicate more elongated orbits. The eccentricity may be calculated knowing the values of apogee, perigee and the radius of Earth (6 378.1 km) and can be expressed as follows:

The eccentricity e is equal to: $e=(R_a-R_p)/(R_a+R_p)$

where:

R_a: distance between the centre of the Earth and the space station at apogee

R_p: distance between the centre of the Earth and the space station at perigee.

$$\cancel{e=\frac{h_{apogee}-h_{perigee}+2R_{Earth}}{h_{apogee}+h_{perigee}+2R_{Earth}}}$$

~~T~~

Inclination of orbit

The angle between the plane of the orbit and the equatorial plane of the Earth, measured in degrees.

Longitude of ascending node of orbit

The angle measured from a fixed reference direction (usually the vernal equinox) to the ascending node of the orbit, where the satellite crosses the equatorial plane from south to north.

Right ascension of the ascending node (RAAN)

Similar to the longitude of the ascending node, this is the angle from the vernal equinox to the ascending node of the orbit, expressed in degrees. It defines the orientation of the orbit in the equatorial plane.

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Argument of perigee

The angle from the ascending node to the perigee, measured in the orbital plane. It indicates the orientation within the orbital plane of the orbit's closest approach to Earth.

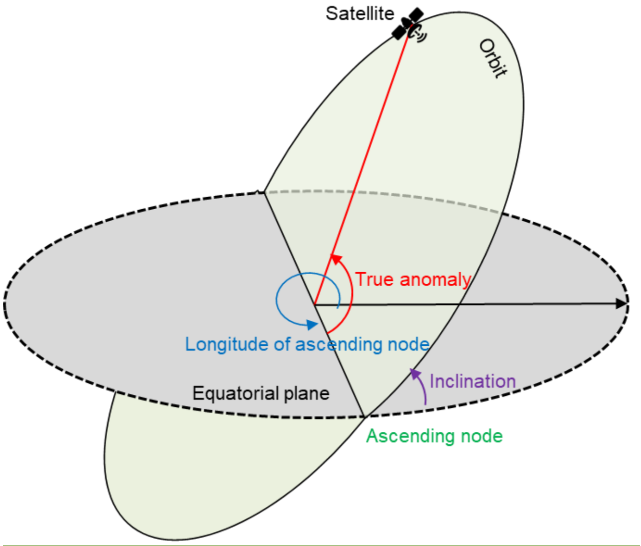
True anomaly

The angle between the direction of perigee and the current position of the satellite as it moves along its orbit, measured at the satellite's location.

The values of true anomaly, longitude of ascending node and inclination are graphically represented in Figure 3.

FIGURE 3

Graphical representation of celestial mechanics parameters



Phasing of Satellites between Two Consecutive Planes

The angular separation between satellites in adjacent orbital planes, measured in degrees. This is used to ensure proper spacing and coverage, particularly in constellations of satellites.

Type of the constellation

Type of the constellation is typically based on a Walker constellation which consists of a group of satellites that are in circular orbits and have the same period and inclination. The ascending nodes of the orbital planes of a Walker Constellation are also evenly spaced over a range of right ascensions (RAAN).

The pattern of the Walker constellation consists of evenly spaced satellites (s) in each of the orbital planes (p) specified so that a group of t=sp. Walker constellations are typically described using the notation:

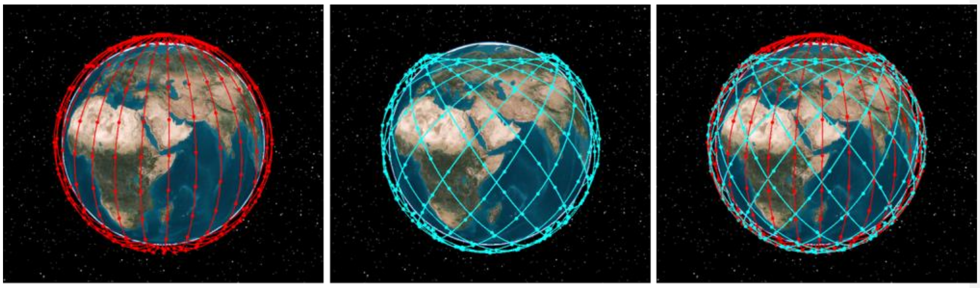
i:t/p/f

Where *i* represents the inclination of the orbital planes, *t* denotes the total number of satellites, *p* indicates the number of planes, and *f* is the interplane phasing parameter. The phase parameter (*f*) helps determine the relative along-track position of satellites in adjacent planes, with *f* being an integer from 0 to *p*-1. This parameter specifies the number of angular slots (360 degrees/*t*) by which one satellite leads another in the adjacent plane.

Walker constellations come in two primary types: Walker Delta and Walker Star constellations. The main difference between these two types lies in how the ascending nodes are distributed across the constellation's planes. In a Walker Delta constellation, the ascending nodes are spread out across a full circle of 360 degrees. In contrast, a Walker Star constellation distributes these nodes over 180 degrees.

FIGURE 4

Types of the orbit visualization



Walker Star   Walker Delta   Mixed

[US Note: the list of parameters above is an initial set of parameters. This list will be revised and will include explanation of each element in subsequent contributions.]

3.2 Non-GSO FSS system operating parameters

Non-GSO satellite systems typically consist of constellations of multiple satellites that are designed to provide global coverage for a variety of applications such as communication, navigation, and Earth observation. However, the operation of these systems is ~~more~~ complex and requires careful consideration of factors such as minimum elevation angle, satellite spacing, and ground infrastructure.

One of the key considerations for non-GSO system operation is the minimum elevation angle, which is the minimum angle between the satellite and the horizon as observed from a ground-based antenna. This angle determines the availability of visible of satellites from a specific location on the Earth's surface and affects the quality of the communication or data transmission.

Many non-GSO systems also require complex ground infrastructure to track and communicate with the satellites as they move across the sky. This involves a network of ground stations that communicate with the satellites using antennas and sophisticated tracking systems.

[Editor’s note: Clarification is needed whether the below angle refers to the angle at the earth station location with two non-GSO satellites or the angle at the non-GSO satellites with two earth stations]

Additionally, the minimum angle between co-frequency Earth stations is the minimum angle that two non-GSO satellites must be separated by to prevent interference with each other's signals. [This angle is typically set at around 2 to 4 degrees, depending on the frequency band used and the specific non-GSO system.] These operational considerations ensure that non-GSO systems can operate effectively and efficiently while minimizing the risk of interference with other satellite systems.

Finally, in certain frequency bands, applications and scenarios non-GSO systems might need to employ mitigation techniques to avoid causing interference or receiving interference. Such techniques are including but not limited to employing fixed or dynamic exclusion zones, beam redirecting and etc.

The following items represent the set of parameters that help define a non-GSO system's operations.

– Exclusion Zone: In the frequency bands that is applicable, exclusion zone angle (degrees), as viewed from a location on the surface of the Earth within the beam, is the minimum angle to the GSO arc that the non-GSO systems would avoid.
– Minimum Elevation: Minimum elevation angle of the non-GSO earth station when it is receiving or transmitting (degrees) ~~by latitude and azimuth~~. It can vary by latitude and azimuth.
– Maximum Co-frequency tracked beams: Maximum number of tracked co-frequency~~ies~~ ~~tracked~~ non-GSO satellites transmitting with overlapping frequencies to a given location (N_{co}).
– Maximum Co-frequency receiving satellites: Maximum number of non-geostationary satellites receiving simultaneously with overlapping frequencies from the associated earth stations within a given cell.
– Minimum earth station angle: Minimum angle at earth station between active co-frequency non-GSO satellites.
– Minimum satellite angle: Minimum angle at non-GSO satellite towards two co-frequency earth stations.
– Maximum co-frequency satellite beams: Maximum number of co-frequency beams at each non-GSO satellite.
– Minimum/Average distance between co-frequency beams: Minimum/Average distance, in kilometres, between co-frequency cells.

4 Modeling non-GSO FSS systems

4.1 Satellite selection

The satellite selection strategy for non-GSO systems is an important aspect of designing and deploying such systems. In general, this strategy involves selecting a set of satellites from a larger constellation that will provide the desired coverage and connectivity for a particular region or application. This means that the other satellites, apart from this subset, will not contribute to providing services to the specific location, region or application.

There are several factors that need to be considered when selecting satellites for non-GSO systems, including:

1 Coverage: The selected satellites should provide coverage over the desired geographic region(s), and should have sufficient coverage overlap with neighboring satellites to ensure seamless handoff between satellites.

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2 Capacity: The selected satellites should have sufficient capacity to handle the expected traffic demand for the target application(s). This may involve selecting satellites with different bandwidths or frequency bands to provide the necessary capacity.

3 Latency: some /minimum track time, lowest latency, etc. and any combination of these strategies. [For a monte-carlo interference analysis, the serving satellite could also be randomly selected from the list of available satellites.]

The link-performance satellite selection strategies are usually suitable for conditions in which the other governing operational or regulatory conditions are not ~~constraining~~applicable. Highest elevation angle, or the shortest slant range are among these strategies. In the majority of the other cases satellite selection strategies are more complex and must take into account a handful of considerations in order to comply with system level objective as well as regulatory requirements~~constraints~~.

These regulatory ~~constraints~~requirements include but not limited to protection of ~~incumbent~~existing services from excessive emission levels, emission in certain angles, emission origination from certain orbital altitude, ~~and~~ etc. These conditions, together with the system level objectives to achieve the optimum performance, often render the satellite selection complex. These strategies ~~are best described~~may be defined using mathematical models.

In the following section most common tracking strategies and guidance on how to model them in sharing studies are described.

[Highest elevation angle

In this strategy the Azimuth and Elevation of all visible satellites to a point on the Earth is calculated. The resulting Azimuth/Elevation pair can be sorted and further consideration applied at the later stage.

$$\text{Sat\_loc} = \begin{bmatrix} S1x & S1y & S1z \\ S2x & S2y & S2z \\ \vdots & \vdots & \vdots \\ SNx & SNy & SNz \end{bmatrix}$$ Equation 1: satellites position matrix (1, N)

$$\text{Point\_loc} = Px \quad Py \quad Pz$$ Equation 2: test point position

$$\text{Az\_El\_SatfromPoint} = \begin{pmatrix} AzS1 & ElS1 \\ AzS2 & ElS2 \\ \vdots & \vdots \\ AzSN & ElSN \end{pmatrix}$$ Equation 3: calculated Azimuth and Elevation matrix for all satellites as viewed from the test point

The highest elevation satellite selection is a strategy that aims to choose the path with the lowest path loss for maximizing the received power.]

[Shortest slant range ~~(optimum latency)~~

In this strategy the slant range to all visible satellites from a point on the Earth is calculated. The resulting array of slant range length can be sorted and further consideration applied at the later stage.

$$\text{Sat\_loc} = \begin{bmatrix} S1x & S1y & S1z \\ S2x & S2y & S2z \\ \vdots & \vdots & \vdots \\ SNx & SNy & SNz \end{bmatrix}$$ Equation 4: satellites position matrix (1, N)

$$\text{Point\_loc} = Px \quad Py \quad Pz$$ Equation 5: test point position

$$\text{Slant\_PointtoSat} = \begin{pmatrix} LS1 \\ LS2 \\ \vdots \\ LSN \end{pmatrix}$$ Equation 6: calculated slant range length from the test point to all satellites

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[Longest / Maximum **Hold Time** / **Track duration** ~~(optimum handover time)~~

[TBD]

[

This satellite selection method prioritizes choosing satellites that will be in view of a given location, such as a gateway, for the greatest amount of time. This allows for maximum usage of the resources of a given site that would contain multiple earth station antennas.

Some constellations try to reduce the number of handovers between satellites by selecting a satellite that is in view of~~heading towards~~ an earth station and then tracks it for as long as possible in order to maintain continuity of the link.

In this strategy the Earth station locks to the first satellite and remains locked until it is no longer in view (or in view above a minimum specified elevation angle). When choosing between multiple satellite, the station tracks the one with the longest possible hold time at the simulation stage. The primary objective of this strategy is to maximize the duration of continuous communication, thereby minimizing the frequency of handovers between satellites.

During the hold time, based on the change of the slant range (the distance between the satellite and the Earth station) and the signal quality, a~~A~~djustments to the link parameters (like power control) may be made to ensure minimum required link performance.

In this strategy, the duration of the visibility of the satellites are taken into account. The goal is to maximize or define~~d~~ a minimum duration for which the selected satellite must be eligible.

$$\text{Sat}_{\text{loc}}(t) = \begin{bmatrix} S1x & S1y & S1z \\ S2x & S2y & S2z \\ \vdots & \vdots & \vdots \\ SNx & SNy & SNz \end{bmatrix}$$ Equation 4: satellites position matrix (1, N) for $t \in [t_1, t_n]$

$$\text{Point\_loc} = Px \quad Py \quad Pz$$ Equation 5: test point position

$$\text{Duration of visibility} = \begin{pmatrix} LS1 \\ LS2 \\ \vdots \\ LSN \end{pmatrix}$$ Equation 6: calculated the duration of visibility for each satellite

This strategy can be combined with the highest elevation and shortest slant range depending on the need of the constellation, for example keeping the mean highest elevation.

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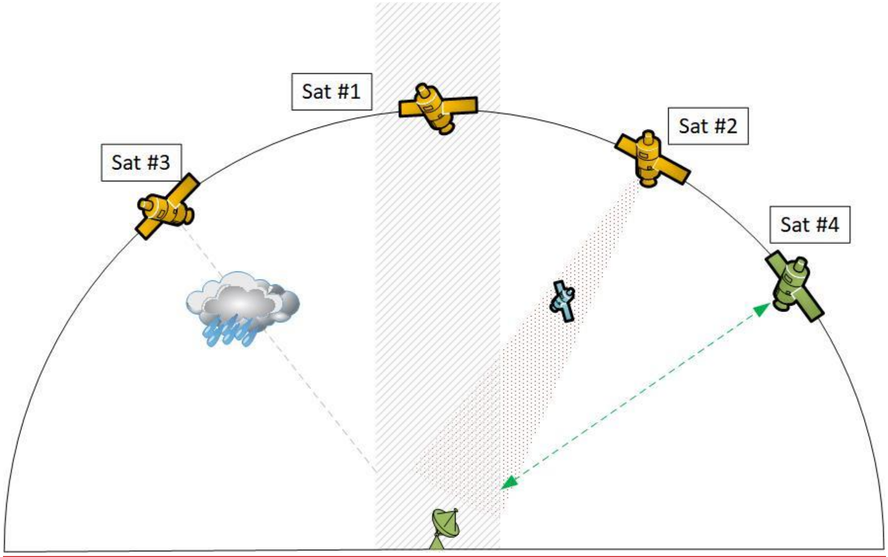
Other considerations

These performance-based tracking strategies are geared towards considering a subset of satellites that are eligible for providing services to a point on the Earth. For the next step of making the final selection of satellite(s) to serve that point, there are a number of other factors that need~~s~~ to be considered. Some of these factors are related to beam planning, which could be a function of service demands. Another factor that dictates the selection is the regulatory regiment, which in some cases could establish an exclusion zone or avoidance requirement. Finally, it is important to note that the link performance is a critical aspect of a satellite selection strategy, as environmental conditions will determine whether a link could practically perform as the system goals require or not.

FIGURE 4.1.1

Example of conditions impacting satellite selection strategies



Sat #1: Falls into an area ~~the~~where operation is not allowed or another servi~~v~~ce is protected

Sat #2: Falls into an area ~~that~~where operation is limited in order to protect another service

Sat #3: Propagation fading is impacting the link quality

Sat #4: First available satellite with acceptable link performance

The compound impact of considering all of these conditions is a computational ~~burden~~complexity for every system, but it is an operational necessity for ~~navigating~~complying with the regulatory requirements and environmental constraints while maintaining optimum link performance. In those cases when simulation requires modelling of systems with a very large number of satellites, the direct implementation of the modelling described above may be ~~excessively~~ time-consuming. [In those cases, statistics of the satellite selection could be modelled and collected from a representatively large system. The collected statistics from this system may then be used to calculate the mathematical models that have equivalent characteristics. It should be emphasized that any simplification, by the way of using mathematical implementation, should not lead to deviation in the selection strategy statistics compared to direct application of this methodology.

Below, description of some of these models and guidance on how to implement them in sharing studies is provided.]

[Random selection

Utilizing a random selection model in a simulation executes a [mathematical][statistical] model that is suitable for long simulations involving systems with a large number of satellites with complex selection strategies. This tracking strategy is usually chosen to reduce the level of specific detail of modelling an exact selection mechanism while still mimicking the operation of such satellite systems.]

[TBD]

4.2 Satellite characteristics

There are several factors that need to be considered when modelling satellites for non-GSO systems, including:

1 Peak antenna gain (dBi) and its 3-dB beam width (degrees)

2 Antenna pattern

3 Maximum PFD on Earth's surface (dB(W/(m²·*RefBW*))) per beam

4 Maximum EIRP (dBW) and/or ~~its~~ Maximum EIRP density (dBW/Hz) per beam

4.3 Earth station characteristics

There are several factors that need to be considered when modelling earth stations for non-GSO systems, including:

1 Peak antenna gain (dBi) and its 3-dB beam width (degrees)

2 Antenna pattern

3 Maximum transmit power (dBW) and/or its density (dBW/Hz) at antenna input

5 Implementation of antenna pattern

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5.1 Parabolic antennas

5.1.1 Background

The parabolic dish is one of the classic types of antennas, commonly used in different types of satellite communication systems. This type of antenna effectively demonstrates key concepts related to antenna gain patterns.

The peak gain of a parabolic antenna is determined by its area compared to the effective area of an isotropic antenna. For a circular dish antenna with a diameter D and efficiency η, the effective area Ae is calculated as follows:

$$A_e = \eta \frac{\pi D^2}{4}$$

Observe how the peak gain of an antenna increases with both the diameter of the dish and the frequency. Typical antenna efficiency of the satellite services is from 0.55 to 0.65.

The peak gain G is then the ratio of this area to the effective area of an isotropic antenna expressed in dB, as described in the following equation:

$$G = 10log\left(\eta\left(\frac{\pi D}{\lambda}\right)^2\right)$$

It can be observed that the peak gain of an antenna increases with both the diameter of the dish and the frequency.

An ideal~~perfect~~ parabolic dish antenna is analogous to a circular aperture in an infinite metal plate and is characterized by a Bessel function as follows:

$$G_{rel}(\theta) = 20log\left[\left(\frac{2j_1(x)}{x}\right)^2\right]$$

where x can be expressed as follows:

$$x = \frac{\pi D}{\lambda}sin\,\theta$$

5.1.2 Modelling the parabolic antenna patterns

It is not common practice though to use theoretical antenna gain~~s~~ models for sharing and compatibility studies, instead empirical models~~approximations~~ based on the ITU-R Recommendations can be used. For non-GSO modeling the most commonly used antenna patterns for the satellites are based on the Recommendation ITU-R S.1528. In the case of Earth stations, it's common to use the antenna patterns based on Recommendation ITU-R S.465 and Recommendation ITU-R S.580.

5.2 Phased array antennas

5.2.1 Background

Typically, a phased array antenna is an advanced antenna system (AAS) that employs a beamforming technology. The operation of an AAS is based on an antenna array, where beamforming is used to electronically steer directional beams. The antenna array is designed such that individual elements combine constructively to form a main lobe which transmits energy in a given direction, with the overall gain of the system dictated by the number of elements in the array. The RF signals to be transmitted are individually pre-coded, with phase and amplitude shifts, before being applied to the individual array elements - enabling them to be steered in the desired direction.

The technology utilized in phased array antennas used in non-GSO systems, for both space stations and earth stations, is similar to that used for other communications systems.

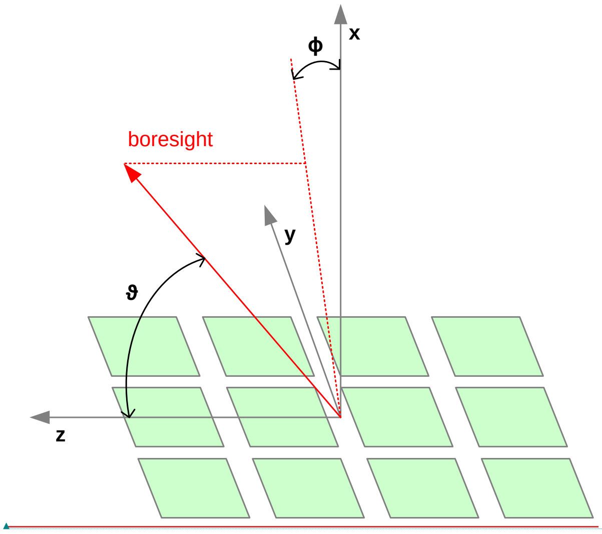
5.2.2 Modelling the Phased Array Antenna Pattern

A phased array antenna consists of a number of radiating elements located in the z-y plane with a fixed separation distance (usually a fraction of the wavelength at which the antenna is operated). Typically, all elements have identical radiation patterns and "pointing" (having maximum directivity) along the x-axis. The radiation elements are typically placed uniformly along a Cartesian coordinate system plane, for instance the z- and y-axis in the illustrated Figure 1 below. The z-y plane denotes the horizontal plane and the x axis, perpendicular to the z-y plane, denotes the antenna zenith (or nadir). The elevation angle of the direction of the antenna boresight is denoted as θ (defined between 0 deg and 180 deg, with 90 deg representing the direction perpendicular to the array antenna aperture). The azimuth angle of the direction of the antenna boresight is denoted as φ (defined between −180 deg and 180 deg, with −90 deg ≤ φ ≤ +90 deg indicating the half plane opposite on the structure to which the antenna is mounted~~on~~). A [weighting] function is used to steer the beam in various directions. The total antenna gain is the sum (logarithmic scale) of the array gain and the element gain when pointed along the x-axis.

[US Note: Further consideration should be given to the usage of similar terminologies for earth centric coordinate system when it comes to elevation and azimuth of the antenna pointing.]

FIGURE 1

Geometrical description of a phased array antenna and its radiating elements



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The phased array antenna model is determined by array element pattern, array factor and signals applied to the array system, amongst other things. The satellite systems may employ rectangular, circular and hexagon shape arrays. The element pattern and composite antenna pattern for rectangular shape antenna are described in Tables 1 and 2 below.

TABLE 1

Element pattern

Azimuthal radiation pattern	$\cancel{TBD}A_{Az}(\varphi) = -\min\left[12\left(\frac{\varphi-90}{\varphi_{3dB}}\right)^2, A_m\right]$ dB
Element azimuthal 3-dB beam width, element deg φ_{3dB}	Input parameter
Front-to-back ratio: A_m and SLA_v	Input parameter
Elevation radiation pattern	$\cancel{TBD}A_{El}(\theta) = -\min\left[12\left(\frac{\theta-90}{\theta_{3dB}}\right)^2, SLA_v\right]$ dB
Element elevation 3-dB beam width of single deg θ_{3dB}	Input parameter
Single element pattern	$\cancel{TBD}A_{Az}(\varphi,\theta) = G_{Emax} - \min\left\{-\left[A_{E,H}(\varphi) + A_{E,v}(\theta)\right], A_m\right\}$

Element gain (dBi), $G_{E,max}$	Input parameter

Table 2 illustrates the derivation of the composite antenna pattern, $A_A(\theta, \varphi)$. $A_A(\theta, \varphi)$ is the mathematical results of logarithmic sum of the array gain and the element gain $A_E(\theta, \varphi)$.

The resulting antenna pattern is a logarithmic summation of the array gain using the following expression:

$$A_A(\theta,\varphi) = 10\log\left(\left|\sum_{m=1}^{N_n}\sum_{n=1}^{N_r} w_{i,n,m} v_{n,m}\right|^2\right)$$

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[Editor's Note: The antenna pattern information below was not reviewed in detail and may need to be revisited at a future WP 4A meeting.]

TABLE 2

Composite antenna pattern

Configuration	Multiple columns ($N_V \times N_H$ elements)
Composite array radiation pattern in dB $A_A(\theta, \varphi)$	~~TBD~~ $A_{A,Beam}(\theta,\varphi) = A_E(\theta,\varphi) + 10log_{10}\left(\left\lvert\sum_{m=1}^{N_{Az}}\sum_{n=1}^{N_{El}} w_{i,n,m}\, v_{n,m}\right\rvert^2\right)$ The superposition vector can be derived from the following: $v_{n,m} = \exp\left(\sqrt{-1}\,2\pi\left((n-1)\frac{d_v}{\lambda}\cos(\theta) + (m-1)\frac{d_H}{\lambda}\sin(\theta)\sin(\varphi)\right)\right)$ n = 1,2,… N_{El} ; m = 1,2,…N_{Az}; The weighting can be expressed as follows: $w_{i,n,m} = \frac{1}{\sqrt{N_{Az}N_{El}}}\exp\left(\sqrt{-1}\,2\pi\left((n-1)\frac{d_v}{\lambda}\sin(\theta_{i,etilt}) - (m-1)\frac{d_H}{\lambda}\cos(\theta_{i,etilt})\sin(\varphi_{i,escan})\right)\right)$
Antenna array configuration (Row x Column)	Input parameter
Radiating element spacing d/λ	Input parameter
Tapering function	Input parameter

[USA Note: Definitions to be provided for parameters in Table 1 and 2 at a subsequent meeting.]

5.2.3 Example input parameters for non-GSO FSS phased array antenna

This section provides a few sets of input parameters to obtain the antenna pattern using the mathematical model described in Section 5~~above~~. Each of these cases corresponds to a particular use case.

To obtain a composite~~an~~ antenna pattern, it is required to have the information on the element antenna gain, azimuth element spacing, elevation element spacing, azimuth element 3 dB beamwidth, elevation element 3 dB bandwidth, front-to-back ratio expressed in dB.

5.2.4 Example phased array antenna gain patterns

~~TBD~~

Example of composite antenna pattern for 40 × 40 rectangular antenna array with 0.5 element spacing, 6.4 dBi element gain, 65 degrees elevation and azimuth 3 dB beamwidth ~~and front-to-back ratio 30 dB~~ presented in Figure 7.

FIGURE 7

Geometrical description of a phased array antenna and its radiating elements

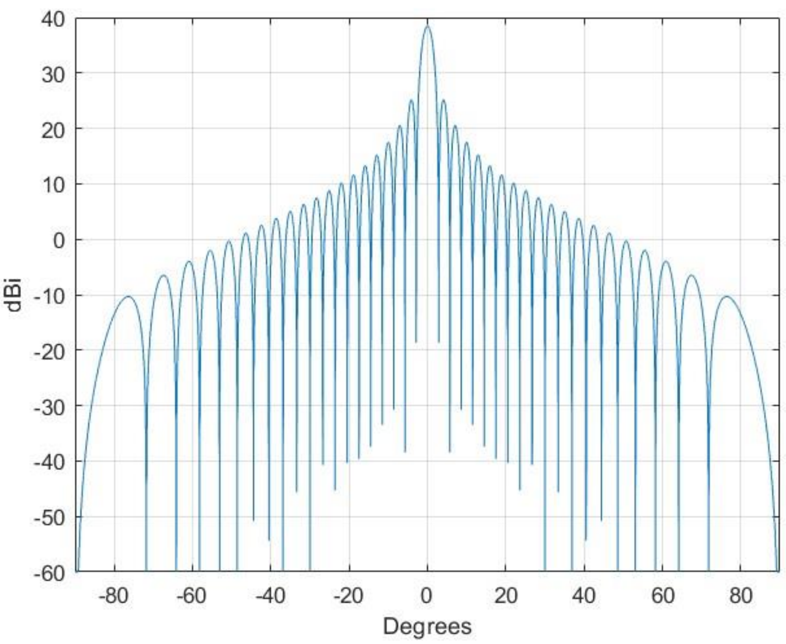
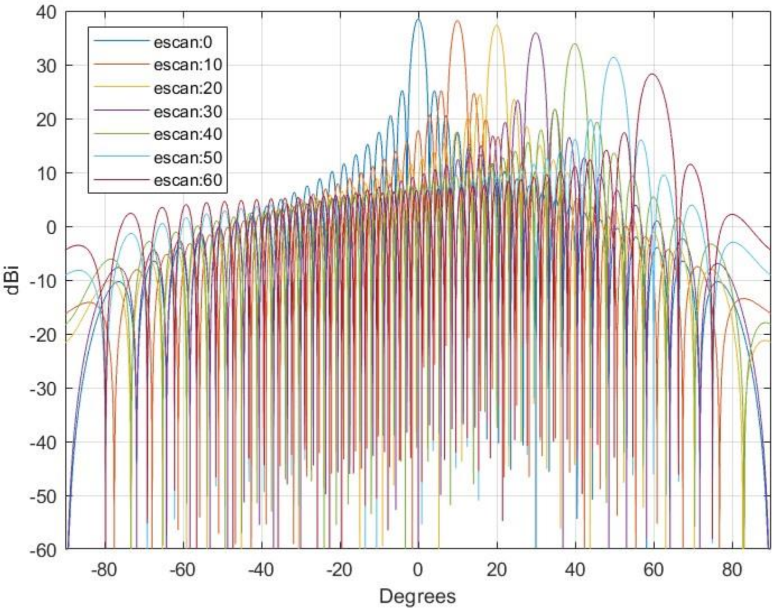


Figure 8 presents the above antenna pattern for different escan angles (10 degrees, 20 degrees, 30 degrees, 40 degrees, 50 degrees and 60 degrees).

FIGURE 8

Geometrical description of a phased array antenna and its radiating elements



It is important to note that the antenna pattern can be steered without any mechanical adjustments, a feature that makes phased array antennas particularly well-suited for megaconstellations, where frequent handovers are required. However, it should also be noted that as the scan angle increases, there is a corresponding reduction in maximum gain.