Recommendation ITU-R S.1503-4

(09/2023)

S Series: Fixed-satellite service

Functional description to be used in developing software tools for determining conformity of non-geostationary-satellite orbit fixed-satellite service systems or networks with limits contained in Article 22 of the Radio Regulations

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SA	Space applications and meteorology
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SM	Spectrum management
SNG	Satellite news gathering
TF	Time signals and frequency standards emissions
V	Vocabulary and related subjects

Note: *This ITU-R Recommendation was approved in English under the procedure detailed in Resolution ITU-R 1.*

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RECOMMENDATION ITU-R S.1503-4

Functional description to be used in developing software tools for determining conformity of non-geostationary-satellite orbit fixed-satellite service systems or networks with limits contained in Article 22 of the Radio Regulations

(2000-2005-2013-2018-2023)

Scope

This Recommendation provides a functional description of the software for use by the Radiocommunication Bureau of ITU to conduct examination of non-geostationary-satellite orbit (non-GSO) fixed-satellite service (FSS) system notifications for their compliance with the validation limits specified in the Radio Regulations.

Keywords

epfd, non-GSO, methodology

Abbreviations/Glossary

Alpha angle (α):	The minimum angle between the line to the non-GSO satellite and the lines to the GSO arc as seen at the earth station communicating with a geostationary-satellite orbit (GSO).
e.i.r.p. mask:	Equivalent isotropic radiated power mask used to define the emissions of the non-GSO earth station in the epfd(up) calculation or the emissions of the non-GSO satellite for the epfd(IS) calculation.
epfd:	Equivalent power flux-density, as defined in Radio Regulations (RR) No. **22.5C.1**, of which there are three cases to consider:
	epfd(down): emissions from the non-GSO satellite system into a GSO satellite earth station;
	epfd(up): emissions from the non-GSO earth station into a GSO satellite;
	epfd(IS): inter-satellite emissions from the non-GSO satellite system into a GSO satellite system.
pfd mask:	power flux-density mask used to define the emissions of the non-GSO satellite in the epfd(down) calculation.
WCG:	Worst Case Geometry, the location of the GSO earth station and GSO satellite that analysis suggests would cause the highest single entry epfd values for given inputs.

Related ITU Recommendations, Reports

Recommendation ITU-R BO.1443 – Reference BSS earth station antenna patterns for use in interference assessment involving non-GSO satellites in frequency bands covered by RR Appendix **30**

Recommendation ITU-R S.672 – Satellite antenna radiation pattern for use as a design objective in the fixed-satellite service employing geostationary satellites

Recommendation ITU-R S.1428 – Reference FSS earth-station radiation patterns for use in interference assessment involving non-GSO satellites in frequency bands between 10.7 GHz and 30 GHz

The ITU Radiocommunication Assembly,

considering

a)   that WRC-2000 adopted, in Article **22** of the Radio Regulations (RR), single-entry limits applicable to non-geostationary satellite orbit (non-GSO) fixed-satellite service (FSS) systems in certain parts of the frequency range 10.7-30 GHz to protect geostationary satellite orbit (GSO) networks operating in the same frequency bands from unacceptable interference;

b)   that these frequency bands are currently used or planned to be used extensively by geostationary-satellite orbit systems (GSO systems);

c)   that during the examination under Nos. **9.35** and **11.31**, the Bureau examines non-GSO FSS systems to ensure their compliance with the single-entry epfd limits given in Tables **22-1A**, **22-1B**, **22-1C**, **22-1D**, **22-1E**, **22-2** and **22-3** of Article **22** of the RR;

d)   that to perform the regulatory examination referred to in *considering c)*, the Radiocommunication Bureau (BR) requires a software tool that permits the calculation of the power levels produced by such systems, on the basis of the specific characteristics of each non-GSO FSS system submitted to the Bureau for coordination or notification, as appropriate;

e)   that GSO FSS and GSO broadcasting-satellite service (BSS) systems have individual characteristics and that interference assessments will be required for multiple combinations of antenna characteristics, interference levels and probabilities;

f)   that designers of satellite networks (non-GSO FSS, GSO FSS and GSO BSS) require knowledge of the basis on which the BR will make such checks;

g)   that WRC-19 adapted a methodology which assesses the impact of interference from non-GSO systems into GSO networks in the frequency range 37.5-51.4 GHz that utilises epfd statistics as an input;

h)   that such tools may be already developed or under development and may be offered to the BR,

recommends

that the functional description specified in Annex 1 should be used to develop software tools calculating the power levels produced by non-GSO FSS systems and the compliance of these levels with the limits contained in Tables **22-1A**, **22-1B**, **22-1C**, **22-1D**, **22-1E**, **22-2** and **22-3** of Article **22** of the RR.

NOTE – The ITU-R agreed to continue working on a further revision of this Recommendation and has prepared a draft Workplan (in relation with this Recommendation) and a Working Document.

Annex 1

Functional description of software for use by the BR in checking compliance of non-GSO FSS systems with epfd limits

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PART A

Fundamental constraints and basic assumptions

A1 General

A1.1 Purpose

The software algorithm described in this Annex is designed for its application by the BR to conduct examination of the non-GSO FSS system notifications for their compliance with the limits contained in Tables **22-1A**, **22-1B**, **22-1C**, **22-1D**, **22-1E**, **22-2** and **22-3** of Article **22** of the RR.

The algorithm could also under certain conditions permit examination of whether coordination is required between non-GSO FSS systems and large earth stations under Articles **9.7A** and **9.7B** using the criteria in RR Appendix **5**.

The algorithm uses the parameters of the non-GSO system to derive statistics of epfd. These epfd statistics could be used as the input to other methodologies that assess interference from non-GSO systems into GSO network(s) in bands where there are no epfd limits in Article **22** of the RR.

The algorithm in this Recommendation was developed based upon a reference GSO satellite in equatorial orbit with zero inclination angle. The analysis to determine whether a non-GSO satellite system meets the epfd limits in Article **22** of the RR is made by calculating the epfd levels at the reference GSO satellite or at an earth station pointing towards it. A GSO satellite network operating with non-zero inclination angles could receive higher epfd levels than those predicted by this algorithm, noting that the analysis under RR Nos **22.5C**, **22.5D**, **22.5F** are conducted assuming zero inclination of the GSO satellite. Analysis under RR Nos. **9.7A** and **9.7B**, however, is to determine if coordination is required by comparing against the trigger level in Appendix **5** of the RR, and therefore in this case other methodologies, including those that assume non-zero GSO satellite inclination, could be acceptable alternatives.

A1.2 Software block-diagram

The block-diagram of the software algorithm described in this Annex is shown in Fig. 1. It comprises initial data and calculation for the notifying administration and the BR. The data section contains the whole set of parameters relevant to the notified non-GSO system, a set of reference GSO system parameters as well as epfd limits provided by the BR.

The calculation section is designed for estimations required to examine notified non-GSO systems compliance with the epfd limits. The calculation section is based on a concept of a downlink power flux-density (pfd) mask (see Note 1), an uplink effective isotropic radiated power (e.i.r.p.) mask (see Note 2) and inter-satellite e.i.r.p. mask (see Note 3).

NOTE 1 – A pfd mask is a maximum pfd produced by a non-GSO space station and is defined in Part C.

NOTE 2 – An e.i.r.p. mask is a maximum e.i.r.p. radiated by a non-GSO earth station and is a function of latitude and the angle from the boresight of the transmitting antenna main beam to a point on the GSO arc.

NOTE 3 – An inter-satellite e.i.r.p. mask is a maximum e.i.r.p. radiated by a non-GSO space station and is a function of latitude and the angle between the line to the sub-satellite point and a point on the GSO arc.

The pfd/e.i.r.p. masks are calculated by the filing administration as identified in Block 1 and then supplied with the other non-GSO system parameters in Blocks a and b. The BR supplies additional parameters, in particular the epfd limits in Block c.

Stages in epfd verification – key logic blocks
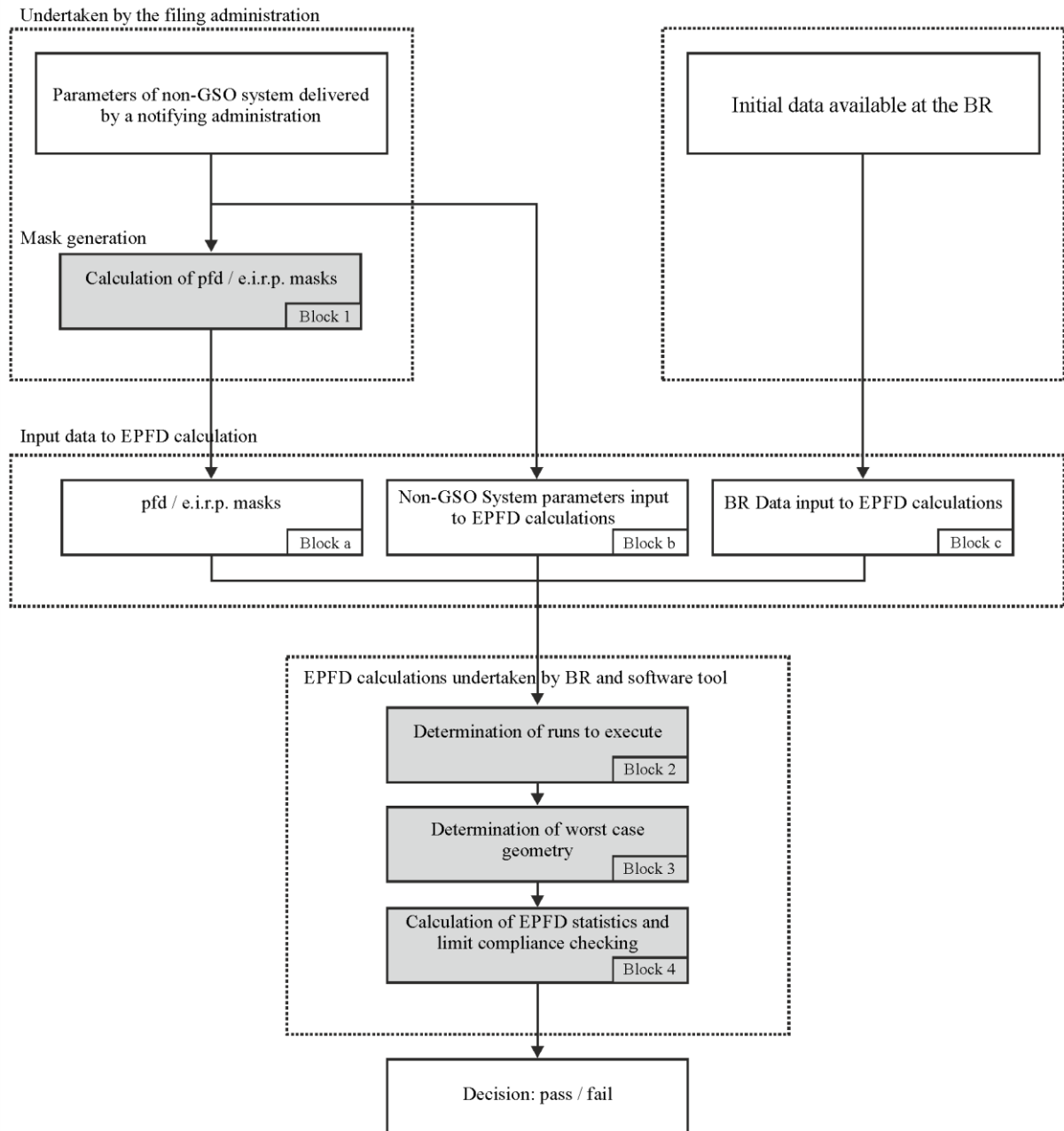
S.1503-01

A1.3 Allocation of responsibilities between Administrations and the BR for software employment

Taking into account significant complexity regarding specific features of different non-GSO system configurations in the software it would seem appropriate to impose some burden of responsibility relevant to testing for epfd limits on administrations notifying appropriate non-GSO systems. Therefore the examination procedure for meeting epfd limits would consist of two stages. The first stage would include derivation of a mask for pfd/e.i.r.p. produced by interfering non-GSO network stations. The mask would account for all the features of specific non-GSO systems arrangements (such as possible beam pointing and transmit powers). The first stage would be finalized by the delivery of the pfd/e.i.r.p. mask to the BR.

The second stage calculations would be effected at the BR. The second stage would feature the following operations:

–   Identification of the runs required for a non-GSO network taking into account the frequencies for which it has filed and the frequency ranges for which there are epfd limits in RR Article **22** (Block 2).

–   Definition of the maximum epfd geometry of a GSO space station and an earth station of that network (Block 3). It would ensure verification of sharing feasibility for a notified non-GSO network with any GSO network in the FSS and BSS.

–   epfd statistics estimation (Block 4).

–   Making a decision on interference compliance with appropriate epfd limits.

The estimations are based on the non-GSO system parameters (Blocks a and b) delivered by a notifying administration and the initial data (Block c) available at the BR.

Any administration may use software that uses the algorithms defined in this Annex together with data on the non-GSO networks to estimate statistics for interference into its own GSO networks and check for compliance with epfd limits. It would assist in solving probable disputes between the BR and administrations concerned.

The elements of the software block-diagram discussed are presented hereinafter in detail. The Parts are as follows:

Part A   –   Basic limitations and main system requirements for the software as a whole are presented.

Part B   –   Non-GSO networks parameters and initial data for Blocks a and b are discussed.

Part C   –   Definitions and estimation algorithms for pfd/e.i.r.p. masks relative to non-GSO network earth and space stations are presented. Specifics of those masks applying in simulation is also discussed (Block 1).

Part D   –   This Part deals with general requirements on the software related to examination of non-GSO networks notifications, algorithms to estimate epfd statistics, and the format for output data presentation. Part D covers issues of Blocks 2, 3 and 4.

Parts E, F – These Parts define requirements on the software related to valuation of delivered software and to verification of the software output on validity.

A2   Fundamental assumptions

A2.1   Units of measurement

To provide for adequate simulation results and to avoid errors a common measurement units system is used in Table 1 for the software description. The list of measurement units for the basic physical parameters is shown in Table 1.

TABLE 1

**The system of measurement units for basic physical parameters used
for the software performance description**

Parameter	Units
Distance	km
Angle	degree
Time	s
Linear rotation velocity	km/s
Angular rotation velocity	degree/s
Frequency	MHz
Frequency bandwidth	kHz
Power	dBW
Power spectral density	dB(W/Hz)
pfd	$dB(W/(m^2 \cdot BW_{ref}))$
Average number of co-frequency non-GSO earth stations per unit area	$1/km^2$
epfd↓, epfd or epfd$_{is}$	$dB(W/BW_{ref})$
Antenna gain	dBi
Geographical position on the Earth's surface	degrees

A2.2 Constants

The functional description of the software for examination of non-GSO networks notification at the BR uses the constants shown in Table 2.

TABLE 2

Constants to be used by software

Parameter	Notation	Numerical value	Units
Radius of the Earth	R_e	6 378.145	km
Radius of geostationary orbit	R_{geo}	42 164.2	km
Gravitational constant	μ	$3.986\ 012 \times 10^5$	km^3/s^2
Speed of light	c	$2.997\ 924\ 58 \times 10^5$	km/s
Angular rate of rotation of the Earth	ω_e	$4.178\ 074\ 582\ 3 \times 10^{-3}$	degree/s
Earth rotation period	T_e	86 164.090 54	s
Factor of the Earth non-sphericity	J_2	0.001 082 636	–

A2.3 The Earth model

The force of the Earth attraction is the main factor to define a satellite orbital motion. Additional factors include:

– orbit variations due to the Earth's oblateness and its mass distribution irregularities;

– solar and lunar attraction;

– medium drag for satellite;

– solar radiation pressure, etc.

The function description of software in this Annex accounts orbit perturbations only due to the Earth oblateness. It is motivated by the fact that effect of other perturbing factors is significantly less. The Earth's oblateness causes secular and periodic perturbations of ascending node longitude and orbit perigee argument. Section D6.3 describes expressions to account the Earth's oblateness effect.

The orbits of some repeating ground tracks can be very sensitive to the exact orbit model used. Administrations could also provide the BR with their own independently determined average precession rates that could be used by the software instead of the values calculated using the equation in § D6.3.

A2.4 Constellation types

The algorithm in this Recommendation has been developed to be applicable to at least the non-GSO satellite systems shown in Table 3.

Constellations can contain sub-constellations with different orbit parameters and shape, but all sub-constellation within a constellation have to be either repeating or non-repeating. If the constellation is repeating then the repeat period specified must be appropriate for all non-GSO satellites, including all sub-constellations.

TABLE 3

Orbit type classification

Type	Orbit shape	Equatorial ?	Repeating ?
A	Circular	No	Yes
B	Circular	No	No
C	Circular	Yes	n/a
D	Elliptical[(1)]	No	Yes
E	Elliptical[(1)]	No	No

[(1)] Assuming that the elliptical system has perigee and apogee at the extrema in latitude, i.e. with active arc at highest or lowest latitude.

A3 Modelling methodology

The approach described in this Annex involves time simulation in which interference levels are evaluated on a time step by time step basis. Section D4 defines the method to calculate the size of time steps and the total number of time steps to be used. That section also identifies an optional dual time step approach to reduce run times without altering the resulting decision.

PART B

Input parameters

B1   Introduction

B1.1   Background

Certain parameters for a non-GSO network and other data must be specified in order to accomplish the requisite software functions:

–   *Function 1*: Provide the pfd masks for the non-GSO satellites (downlink) and the e.i.r.p. mask for the earth stations transmitting to those satellites (uplink) or non-GSO satellite (intersatellite).

–   *Function 2*: Apply the pfd/e.i.r.p. mask in the calculation of downlink epfd↓, uplink epfd↑ and/or intersatellite epfd levels (cumulative time distributions of epfd).

–   *Function 3*: Determine whether the pfd/e.i.r.p. mask levels are consistent with basic transmission parameters of the non-GSO network, only in the case of dispute.

The roles of the administration of the non-GSO network and the BR are discussed in § A1.3.

Detailed parameters are needed by the BR in support of Function 2 and so this section focuses on the parameters needed to fulfil that requirement.

The parameters provided should be consistent, so that if the administrations modify its network (e.g. if there are changes to the constellation) so that the pfd/e.i.r.p. changes then a new mask would need to be supplied to the BR.

B1.2   Scope and overview

This section identifies inputs to the software in four main sections:

–   Section B2 defines the inputs from the BR;

–   Section B3 defines the inputs from the non-GSO operator excluding the pfd/e.i.r.p. masks;

–   Section B4 defines the pfd/e.i.r.p. masks.

–   An Attachment to Part B then maps the parameters to the SRS database tables.

Note that in the following tables, square brackets in variable names indicate an index for that variable and not tentative text.

B2   BR supplied parameters to software

The BR supplies two types of data, firstly the type of run to execute:

RunType	One of {Article **22**, **9.7A**, **9.7B**}
SystemID	ID of system to examine (either non-GSO or large earth station)

The second data is to provide the threshold epfd levels to use as the pass / fail criteria. These are accessed by the software when generating the runs and consists of a series of records as follows:

epfddirection	One of {Down, Up, IS}
VictimService	One of {FSS, BSS}

StartFrequencyMHz	Start of frequency range for which epfd threshold applies
EndFrequencyMHz	End of frequency range for which epfd threshold applies
VictimAntennaType	Reference code for antenna pattern to be used in calls to ITU supplied antenna gain pattern DLL
VictimAntennaDishSize	Dish size of victim antenna pattern to be used in calls to ITU supplied antenna gain pattern DLL
VictimAntennaBeamwidth	Beamwidth of victim antenna pattern to be used in calls to ITU supplied antenna gain pattern DLL
RefBandwidthHz	Reference bandwidth in Hz of epfd level
NumPoints	Number of points in epfd threshold mask
epfdthreshold[N]	epfd level in dBW/m^2/Reference bandwidth
epfdpercent[N]	Percentage of time associated with epfd threshold

B3 Non-GSO system inputs to software

These are split into constellation parameters, orbit parameters for each space station and one or more sets of system operating parameters.

B3.1 Non-GSO constellation parameters

N_{sat}	Number of non-GSO satellites
H_MIN	Minimum operating height (km)
DoesRepeat	Flag to identify that constellation repeats using station keeping to maintain track
AdminSuppliedPrecession	Flag to identify that the constellation orbit model precession field is supplied by the admin
W_{delta}	Station keeping range (degrees)
ORBIT_PRECESS	Administration supplied precession rate (degrees/second)

B3.2 Non-GSO space station parameters

For each of the non-GSO satellites, the following parameters to define the location of the constellation at the start of the simulation:

A[N]	Semi-major axis of orbit (km)
E[N]	Eccentricity of orbit
I[N]	Inclination of orbit (degrees)
O[N]	Longitude of ascending node of orbit (degrees)
W[N]	Argument of perigee (degrees)
V[N]	True anomaly (degrees)

B3.3 Non-GSO system operating parameters

These represent the set of parameters required to define the non-GSO system's operations. There could be different sets of parameters at different frequency bands, but only one set of operating parameters for any frequency band used by the non-GSO system.

Freq_Min	Minimum frequency for which this set of parameters applies
Freq_Max	Maximum frequency for which this set of parameters applies
MIN_EXCLUDE[Latitude]	Exclusion zone angle (degrees), the minimum angle to the GSO arc at the non-GSO ES at which the non-GSO system can provide a service to that location, defined at the ES (α angle) by latitude. The MIN_EXCLUDE at a specific latitude will be derived using linear interpolation between data points. This field could vary between non-GSO system orbit planes via the orb_id field. If the orb_id field equals 0 then the data exclusion zone data applies to all orbit planes
MIN_ELEV[Latitude][Azimuth]	Minimum elevation angle of the non-GSO earth station when it is receiving or transmitting (degrees) by latitude and azimuth. The nearest latitude to that in the table will be used and then linear interpolation in azimuth
MIN_DURATION[Latitude]	Minimum satellite tracking duration at latitude (seconds): the nearest latitude to that in the table will be used
MAX_CO_FREQ[Latitude]	Maximum number of co-frequency tracked non-GSO satellites by latitude: the nearest latitude to that in the table will be used
ES_DENSITY	Average number of non-GSO earth stations active at the same time (/km^2)
ES_DISTANCE	Average distance between cell or beam footprint centre (km)
ES_LAT_MIN	Minimum limit of the latitude range of non-GSO ES (degrees)
ES_LAT_MAX	Maximum limit of the latitude range of non-GSO ES (degrees)
MIN_ANGLE_AT_ES	Minimum angle in degrees at the surface of the Earth between the lines to any two active non-GSO satellites. Assumed to be zero if not provided. Not applicable if the MIN_DURATION[Latitude] is non-zero
MIN_ANGLE_AT_SAT	The minimum angle in degrees at the non-GSO satellite between the lines to any two active non-GSO earth stations. Assumed to be zero if not provided
MAX_CO_FREQ_SAT	The maximum number of non-geostationary earth stations tracked co-frequency by a non-geostationary satellite within the EPFD(up) calculation. If a value is not provided, it is assumed that the maximum number of earth stations tracked co-frequency by a non-geostationary satellite is equal to the number of earth stations created for the epfd↑ run

These parameters would be supplied in XML format with header as follows:

<non_gso_operating_parameters es_lat_max="+90" es_lat_min="-90" es_distance="200" es_density="0.00001" c_name="orb_id" b_name="azimuth" a_name="latitude" high_freq_mhz="F2" low_freq_mhz="F1" param_id="1" angle_at_es = "5" min_angle_at_sat = 5>

where:

Field	Type or range	Units	Example
ntc_id	Integer	–	12345678
sat_name	String	–	My satellite network
param_id	Integer	–	1
low_freq_mhz	Double precision	MHz	10 000
high_freq_mhz	Double precision	MHz	12 000
a_name	{latitude} range −90 to +90 degrees	–	latitude
b_name	{azimuth} range 000 to 360 degrees	–	azimuth
c_name	{orb_id} range 01 to 9999 0 should be used to indicate that parameters will be applicable to all orbits	–	orb_id
es_density	Double precision	km^2	0.000 1
es_distance	Double precision	km	200
es_lat_min	Double precision	degree	−90
es_lat_max	Double precision	degree	+90
min_angle_at_sat	Double precision range 0 to +90 degrees	degree	15
min_angle_at_es	Double precision range 0 to +90 degrees	degree	5
max_co_freq	Integer range 0 to 9999	-	2
max_co_freq_sat	Integer, range 0 to 9999	-	2
min_duration	Integer, range 0 to 99999	second	400
elev_angle	Double precision, range 0 to +90 degrees	degree	5

After the header the XML contains arrays of MIN_EXCLUDE which can vary by orb_id and latitude while the MIN_DURATION, MAX_CO_FREQ values vary only by latitude. The MIN_ELEV array can vary by both latitude and azimuth.

Note that if the non-GSO ES type defined in the e.i.r.p. mask is specific rather than typical, then the fields *es_density* and *es_distance* are not used.

The non-GSO operating parameters would be stored in the same database as the pfd and e.i.r.p. masks.

An example non-GSO operating parameters XML file would therefore be:

<?xml version="1.0"?>

<satellite_system sat_name="MySatName" ntc_id="12345678">

 <non_gso_operating_parameters   es_lat_max="+90"   es_lat_min="-90"   es_distance="200" es_density="0.00001"   c_name="orb_id"   b_name="azimuth"   a_name="latitude" high_freq_mhz="F2" low_freq_mhz="F1" param_id="1" min_angle_at_sat = "0" min_angle_at es =0>

  <min_exclude c="1">

   <exclusion_zone_angle a="-75">0</exclusion_zone_angle>

   <exclusion_zone_angle a="-45">3</exclusion_zone_angle>

   <exclusion_zone_angle a="-15">5</exclusion_zone_angle>

   <exclusion_zone_angle a="15">5</exclusion_zone_angle>

   <exclusion_zone_angle a="45">3</exclusion_zone_angle>

```
      <exclusion_zone_angle a="75">0</exclusion_zone_angle>
    </min_exclude>
    <min_exclude oc="2">
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      <exclusion_zone_angle a="-15">6</exclusion_zone_angle>
      <exclusion_zone_angle a="15">6</exclusion_zone_angle>
      <exclusion_zone_angle a="45">6</exclusion_zone_angle>
      <exclusion_zone_angle a="75">0</exclusion_zone_angle>
    </min_exclude>
    <max_co_freq a="0">2</max_co_freq>
    <min_duration a="-50">400</min_duration>
    <min_duration a="0">1000</min_duration>
    <min_duration a="50">400</min_duration>
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      <elev_angle b="90">40</elev_angle>
      <elev_angle b="280">30</elev_angle>
      <elev_angle b="370">40</elev_angle>
    </min_elev>
  </non_gso_operating_parameters>
</satellite_system>
```

B4   pfd/e.i.r.p. masks

B4.1   Non-GSO downlink pfd mask

FreqMin	Minimum of frequency range in MHz for this pfd mask
FreqMax	Maximum of frequency range in MHz for this pfd mask
RefBW	The power level in the pfd mask should be given in kHz with respect to the same reference bandwidth as the epfd thresholds in the tables in Article **22** relevant for the frequency ranges covered. If the tables in Article **22** give two reference bandwidths (e.g. 40 kHz and 1 MHz) then the smaller bandwidth should be used.
MaskType	One of {α, or (az,el)}
Option 1 pfd_mask (satellite, latitude, α, ΔL)	The pfd mask is defined by: – the non-GSO satellite – the latitude of the non-GSO sub-satellite point – the separation angle α between this non-GSO space station and the GSO arc, as defined in § D6.4.4 – the difference ΔL in longitude between the non-GSO sub-satellite point and the point on the GSO arc where the α angle is minimised as defined in § D6.4.4
Option 2 pfd_mask (satellite, latitude, Az, El)	The pfd mask is defined by: – the non-GSO satellite – the latitude of the non-GSO sub-satellite point – the azimuth angle, defined in § D6.4.5 – the elevation angle, defined in § D6.4.5

B4.2   Non-GSO uplink e.i.r.p. mask

FreqMin	Minimum of frequency range in MHz for this pfd mask
FreqMax	Maximum of frequency range in MHz for this pfd mask
RefBW	The power level in the e.i.r.p. mask should be given in kHz with respect to the same reference bandwidth as the epfd thresholds in the tables in Article **22** relevant for the frequency ranges covered. If the tables in Article **22** give two reference bandwidths (e.g. 40 kHz and 1 MHz) then the smaller bandwidth should be used.
ES_ID	Reference of non-GSO ES or –1 if using generic ES
MaskFormat	Either LatitudeAndAngleGSOArc or LatitudeAzimuthElevationDeltaLong
ES_e.i.r.p. [Lat] [θ]	Non-GSO earth station e.i.r.p. as a function of latitude and the angle between the line from the non-GSO ES boresight line and the line from the non-GSO ES to a point on the GSO arc.
ES_e.i.r.p.[Lat][Az][El][DeltaLongES]	Non-GSO ES e.i.r.p. as a function of non-GSO ES latitude, current pointing (azimuth, elevation) and difference in longitude between non-GSO ES and point on the GSO arc

B4.3 Non-GSO inter-satellite e.i.r.p. mask

FreqMin	Minimum of frequency range in MHz for this e.i.r.p. mask
FreqMax	Maximum of frequency range in MHz for this e.i.r.p. mask
RefBW	The power level in the e.i.r.p. mask should be given in kHz with respect to the same reference bandwidth as the epfd thresholds in the Tables in Article **22** relevant for the frequency ranges covered. If the Tables in Article **22** give two reference bandwidths (e.g. 40 kHz and 1 MHz) then the smaller bandwidth should be used.
SAT_e.i.r.p.[Lat] [θ]	Non-GSO satellite e.i.r.p. as a function of latitude and the angle seen from the non-GSO satellite between the non-GSO sub-point and a point on the GSO arc.

B5 Validation of input parameters

This section describes the minimum met of validation of the input parameters: additional checks could also be undertaken.

B5.1 Non-GSO space station parameters

This methodology is applicable for the types of non-GSO systems with orbital characteristics as defined in Table 3. To ensure consistency with this assumption, the following tests are required to be undertaken for each non-GSO satellite:

Test for circular or near-circular orbit:

> If the $e > 0$ and $e <$ MAX_CIRCULAR_E then
>
> {
>
>> WarningMessage: setting orbit to be circular from eccentricity = e
>>
>> Set $e = 0$ and continue
>
> }

Test HEO system has $\omega = \pm\pi/2$:

> If the eccentricity >= MAX_CIRCULAR_E then
>
> {
>
>> Ensure w in range $\{-\pi, +\pi\}$
>>
>> If $(\text{abs}(\pi/2 - \text{abs}(w))) >$ MAX_HELO_DELTAW
>>
>> {
>>
>>> ErrorMessage: orbit apogree not at maximum latitude
>>>
>>> Exit
>>
>> }
>
> }

It is assumed that:

> MAX_CIRCULAR_E = 0.01
>
> MAX_HELO_DELTAW = 1e-5 degrees

With systems that use multiple sub-constellations, it must be checked that all are repeating or all are non-repeating.

B5.2 Non-GSO system operating parameters ranges

The following non-GSO system operating parameters are to be checked:

$\text{MIN\_EXCLUDE[Latitude]} \geq 0$

$\text{MIN\_ELEV[Latitude, Azimuth]} \geq 0$

$\text{MIN\_DURATION[Latitude]} \geq 1 \text{ second}$

$\text{MAX\_CO\_FREQ[Latitude]} \geq 0$

$\text{ES\_DENSITY} > 0$

$\text{ES\_DISTANCE} \geq 0$ ($\text{ES\_DISTANCE} = 0$ means that only one earth station can be distributed inside the victim GSO footprint)

$+90º > \text{ES\_LAT\_MIN} \geq -90º$

$+90º \geq \text{ES\_LAT\_MAX} > -90º$

$\text{ES\_LAT\_MAX} > \text{ES\_LAT\_MIN}$

$\text{MIN\_ANGLE\_AT\_ES} \geq 0$

$\text{MIN\_ANGLE\_AT\_SAT} \geq 0$

$\text{MAX\_CO\_FREQ\_SAT} \geq 0$

B5.3 Masks and system operating parameters XML files

The following non-GSO system operating parameters are to be checked:

– That there is only a single non-GSO system operating parameters set per frequency range.

– That there is a non-GSO system operating parameters set for each frequency range that is to be examined.

– That if the MIN_EXCLUDE varies by orbit plane, that a value is defined for each orbit plane.

It is also necessary to check that any ES e.i.r.p. masks using the LatitudeAndAngleGSOArc format are monotonically decreasing.

Attachment
to Part B

This Attachment to Part B details the parameters that the epfd software uses from the SRS database. If the extended set of system operating parameters are provided, then values should be taken from that XML file rather than the relevant SRS table.

Table 4 lists the current RR Appendix **4** information for non-GSO satellite systems included in the BR space networks system (SNS) database. The relationship between the database tables is shown in Fig. 2. Mask information and link tables are not shown in Fig. 2 but are described in Table 4.

Format description

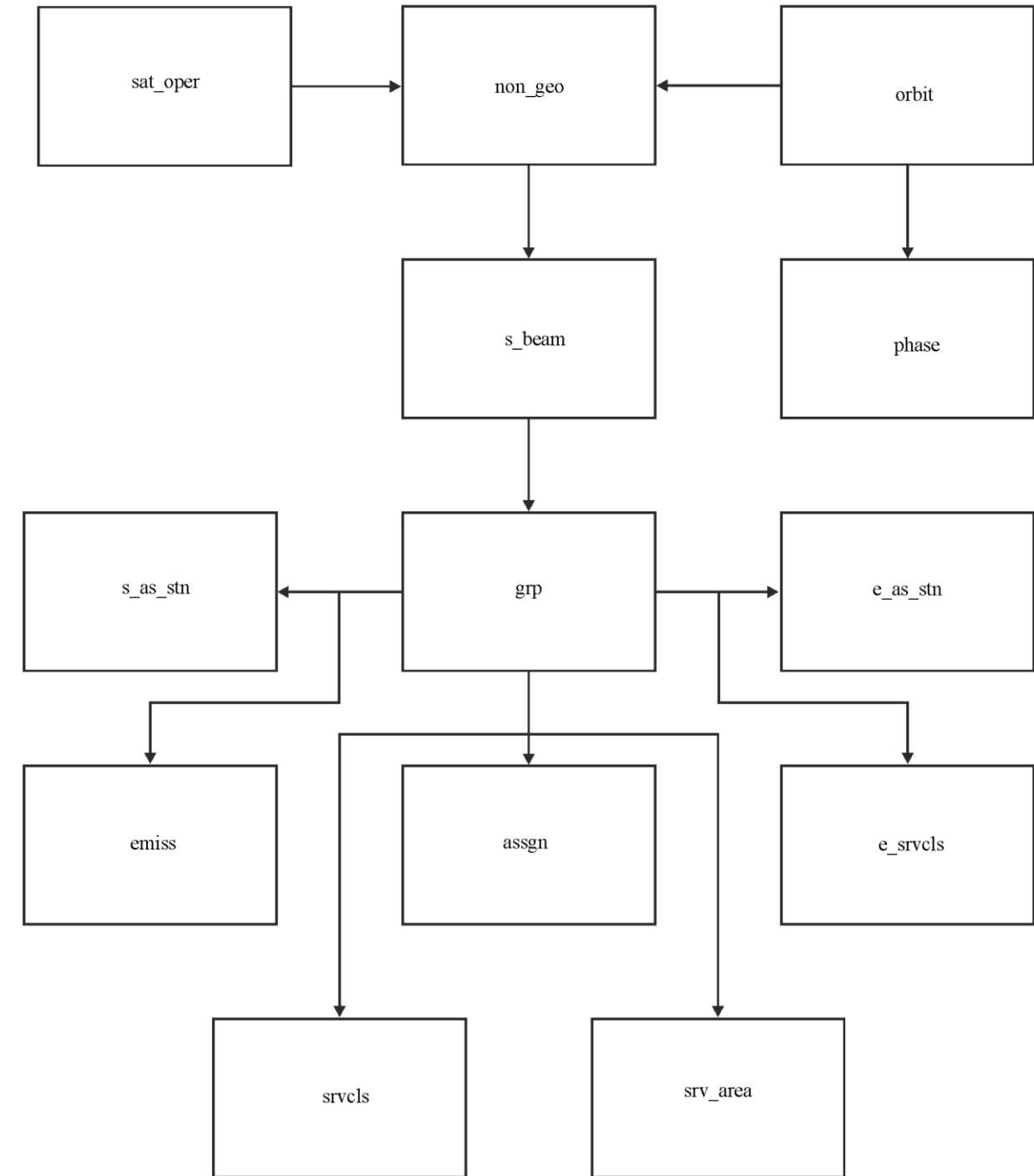| Value	Description
X	Used to describe alphanumeric data. e.g. X(9) specifies a 9-character field containing alphanumeric data XXX is equivalent to X(3).
9	Used to describe digits
'.'	Shows the position of a decimal point
S	Implies a sign (sign leading separate) e.g. S999.99 implies a numeric field with a range of values from –999.99 to +999.99 99 implies a numeric field with a range of values from 0 to 99

FIGURE 2

Extract from SRS entity relationship

S.1503-02

TABLE 4

SRS data for epfd analysis

Notice

Data Item	Data Type	Format	Description	Validation
ntc_id	Number	9(9)	Unique identifier of the notice	Primary Key
ntc_type	Text	X	Code indicating if the notice is of a geostationary satellite [G], Non-geostationary satellite [N], specific earth station [S] or typical earth station [T]	value != Null
d_rcv	Date/Time	9(8)	Date of receipt of the notice	
ntf_rsn	Text	X	Code indicating that the notice has been submitted under RR1488 [N], RR1060 [C], RR1107 [D], 9.1 [A], 9.6 [C], 9.7A [D], 9.17 [D], 11.2 [N], 11.12 [N], AP30/30A-Articles 2A, 4 and 5 [B], AP30B-Articles 6 and 7 [P], AP30B-Article 8 [N] or Res49 [U]	The software looks a value that is 'C' or 'N'
st_cur	Text	XX	Current processing status of the notice	The software looks for a value that is '50' in the Article **9.7A** check

Non-geo

Data Item	Data Type	Format	Description	Validation
ntc_id	Number	9(9)	Unique identifier of the notice	Primary Key
sat_name	Text	X(20)	Name of the satellite	
nbr_sat_td	Number	9	Nco for the uplink case	
density	Number	9(9)	Average density of non-GSO ES for the uplink case	
avg_dist	Number	9(9)	Average distance between co-frequency non-GSO ES for the uplink case	
f_x_zone	Text	X	Should be 'Y' for alpha based exclusion zone	
x_zone	Number	9(9)	Size of exclusion zone	

orbit

Data Item	Data Type	Format	Description	Validation
ntc_id	Number	9(9)	Unique identifier of the notice	Foreign Key
orb_id	Number	99	Sequence number of the orbital plane	Primary Key
nbr_sat_pl	Number	99	Number of satellites per non-geostationary orbital plane	value != Null && value > 0
right_asc	Number	999.99	Angular separation in degrees between the ascending node and the vernal equinox	value != Null
inclin_ang	Number	999.9	Inclination angle of the satellite orbit with respect to the plane of the Equator	value != Null

orbit (*continued*)

Data Item	Data Type	Format	Description	Validation
apog	Number	9(5).99	The farthest altitude of the non-geostationary satellite above the surface of the Earth or other reference body – expressed in kilometres Distances > 99 999 km are expressed as a product of the values of the fields "apog" and "apog_exp" (see below) e.g. $125\,000 = 1.25 \times 10^5$	value != Null && value > 0
apog_exp	Number	99	Exponent part of the apogee expressed in power of 10 To indicate the exponent; give 0 for 10^0, 1 for 10^1, 2 for 10^2, etc.	value != Null && value >= 0
perig	Number	9(5).99	The nearest altitude of the non-geostationary satellite above the surface of the Earth or other reference body – expressed in kilometres Distances > 99 999 km are expressed as a product of the values of the fields "perigee" and "perig_exp" (see below) e.g. $125\,000 = 1.25 \times 10^5$	value != Null && value > 0
perig_exp	Number	99	Exponent part of the perigee expressed in power of 10 To indicate the exponent; give 0 for 10^0, 1 for 10^1, 2 for 10^2, etc.	value != Null && value >= 0
perig_arg	Number	999.9	Angular separation (degrees) between the ascending node and the perigee of an elliptical orbit. If RR No. **9.11A** applies	
op_ht	Number	99.99	Minimum operating height of the non-geostationary satellite above the surface of the Earth or other reference body – expressed in kilometres Distances > 99 km are expressed as a product of the values of the fields "op_ht" and "op_ht_exp" (see below) e.g. $250 = 2.5 \times 10^2$	value != Null && value > 0
op_ht_exp	Number	99	Exponent part of the operating height expressed in power of 10 To indicate the exponent; give 0 for 10^0, 1 for 10^1, 2 for 10^2, etc.	value != Null && value >= 0
f_stn_keep	Text	X	Flag indicating if the space station uses [Y] or does not use [N] station-keeping to maintain a repeating ground track	value != Null && (value == 'Y' || 'N')
rpt_prd_dd	Number	999	Day part of constellation repeat period (s)	
rpt_prd_hh	Number	99	Hour part of constellation repeat period (s)	
rpt_prd_mm	Number	99	Minute part of constellation repeat period (s)	
rpt_prd_ss	Number	99	Second part of constellation repeat period (s)	
f_precess	Text	X	Flag indicating if the space station should [Y] or should not [N] be modelled with specific precession rate of the ascending node of the orbit instead of the J2 term	value != Null && (value == 'Y' || 'N')

orbit (*end*)

Data Item	Data Type	Format	Description	Validation
precession	Number	999.99	For a space station that is to be modelled with specific precession rate of the ascending node of the orbit instead of the J2 term, the precession rate in degrees/day measured counter-clockwise in the equatorial plane	If f_precess == 'Y' then value != Null && value > = 0
long_asc	Number	999.99	Longitude of the ascending node for the jth orbital plane measured counter-clockwise in the equatorial plane from the Greenwich meridian to the point where the satellite orbit makes its south-north crossing of the equatorial plane (0° = j < 360°)	value != Null && value > = 0
keep_rnge	Number	99.9	Longitudinal tolerance of the longitude of the ascending node	If f_stn_keep == 'Y' then value != Null && value > = 0

Phase

Data Item	Data Type	Format	Description	Validation
ntc_id	Number	9(9)	Unique identifier of the notice	Foreign Key
orb_id	Number	99	Sequence number of the orbital plane	Foreign Key
orb_sat_id	Number	99	Satellite sequence number in the orbital plane	value != Null && value > = 0
phase_ang	Number	999.9	Initial phase angle of the satellite in the orbital plane If RR No. **9.11A** applies	value != Null && value > = 0

Grp

Data Item	Data Type	Format	Description	Validation
ntc_id	Number	9(9)	Unique identifier of the notice	Foreign Key
grp_id	Number	9(9)	Unique identifier of the group	Primary Key
emi_rcp	Text	X	Code identifying a beam as either transmitting [E] or receiving [R]	value != Null && (value == 'E' ‖ 'R')
beam_name	Text	X(8)	Designation of the satellite antenna beam	
elev_min	Number	S9(3).99	Minimum elevation angle at which any associated earth station can transmit to a non-geostationary satellite or minimum elevation angle at which the radio astronomy station conducts single-dish or VLBI observations	value != Null && value > = 0
freq_min	Number	9(6).9(6)	Minimum frequency in MHz (assigned frequency – half bandwidth) (of all frequencies for this group)	value != Null && value > 0
freq_max	Number	9(6).9(6)	Maximum frequency in MHz (assigned frequency + half bandwidth) (of all frequencies for this group)	value != Null && value > 0
d_rcv	Date/Time	9(8)	Date of receipt of the list of frequency assignments pertaining to the group	
noise_t	Number	9(6)	Receiving system noise temperature	Only validated for **9.7A/B** checks

srv_cls

Data Item	Data Type	Format	Description	Validation
grp_id	Number	9(9)	Unique identifier of the group	Foreign Key
seq_no	Number	9(4)	Sequence number	value != Null && value > = 0
stn_cls	Text	XX	Class of station	

sat_oper

Data Item	Data Type	Format	Description	Validation
ntc_id	Number	9(9)	Unique identifier of the group	Foreign Key
lat_fr	Number	9(9)	Start of latitude range	−90 <= lat_fr < lat_to
lat_to	Number	9(9)	End of latitude range	lat_fr < lat_to <= 90
nbr_op_sat	Number	9	Nco for the down direction to use for latitudes in the range lat_fr to lat_to	> 0

mask_info

Data Item	Data Type	Format	Description	Validation
ntc_id	Number	9(9)	Unique identifier of the group	Foreign Key
mask_id	Number	9(4)	Sequence number	Foreign Key
f_mask	Text	X	Code identifying a mask as either earth station e.i.r.p. 'E' for space station e.i.r.p. or 'S' for space station or 'P" for pfd	value != Null && (value == 'E' ‖ 'S'‖ 'P')
f_mask_type	Text	X	Code describing format of mask, where 'A' = Alpha, 'Z' = Azimuth/elevation , 'O' = off-axis and 'D' = azimuth, elevation and deltaLong	value != Null && (value == 'A' ‖ 'Z'‖ 'O'‖'D')

e_as_stn

Data Item	Data Type	Format	Description	Validation
grp_id	Number	9(9)	Unique identifier of the group	Foreign Key
seq_no	Number	9(4)	Sequence number	value != Null && value >= 0
stn_name	Text	X(20)	Name of the transmitting or receiving station	
stn_type	Text	X	Code indicating if the earth station is specific 'S' or typical 'T'	value != Null && (value == 'S' ‖ 'T')
bmwdth	Number	999.99	Angular width of radiation main lobe expressed in degrees with two decimal positions	value != Null && value > 0

mask_lnk1

Data Item	Data Type	Format	Description	Validation
grp_id	Number	9(9)	Unique identifier of the group	Foreign Key
mask_id	Number	9(4)	Unique identifier of the mask	Foreign Key
orb_id	Number	99	Sequence number of the orbital plane	Foreign Key
sat_orb_id	Number	99	Satellite sequence number in the orbital plane	value != Null && value > = 0

mask_lnk2

Data Item	Data Type	Format	Description	Validation
grp_id	Number	9(9)	Unique identifier of the group	Foreign Key
seq_e_as	Number	9(4)	Sequence number of the associated earth station	Foreign Key
mask_id	Number	9(4)	Unique identifier of the mask	Foreign Key

mask_lnk3

Data Item	Data Type	Format	Description	Validation
ntc_id	Number	9(9)	Unique identifier of the notice	Foreign Key
param_id	Number	9(4)	Unique identifier of the system operating parameters	Foreign Key

Tables used in the Article 9.7A/9.7B calculations

e_stn

Data Item	Data Type	Format	Description	Validation
ntc_id	Number	9(9)	Unique identifier of the notice	Foreign Key
stn_name	Text	X(20)	Name of the earth station	value != Null
sat_name	Text	X(20)	Name of the associated space station	value != Null
lat_dec	Number	S9(2).9(4)	Latitude in degrees with four decimals	value != Null
long_dec	Number	S9(2).9(4)	Longitude in degrees with four decimals	value != Null
long_nom	Number	S999.99	Nominal longitude of the associated space station, give '–' for West, '+' for East	value != Null

e_ant

Data Item	Data Type	Format	Description	Validation
ntc_id	Number	9(9)	Unique identifier of the notice	Foreign key
emi_rcp	Text	X	Code identifying a beam as either transmitting [E] or receiving [R]	value != Null
bmwdth	Number	999.99	Beamwidth of the earth station antenna	
gain	Number	S99.9	Maximum isotropic gain of the earth station antenna	

PART C

Generation of pfd/e.i.r.p. masks

C1   Definition

The purpose of generating pfd/e.i.r.p. masks is to define an envelope of the power radiated by the non-GSO space stations and the non-GSO earth stations so that the results of calculations encompass what would be radiated regardless of what resource allocation and switching strategy are used at different periods of a non-GSO system life.

These masks are regulatory constraints in that the non-GSO FSS system should not exceed those values at any time and could be derived using the methodology below. They represent an envelope of the power produced by a system which will constrain how rapidly the pfd or e.i.r.p. can change between data points and how low values for the extreme points in arrays can get. Note that it is feasible for a system not to transmit at certain latitudes: in this case a null value of -1000 dBW should be used.

C2   Generation of satellite pfd masks

C2.1   General presentation

The satellite pfd mask is defined by the maximum pfd generated by any space station in the interfering non-GSO system as seen from any point at the surface of the Earth. A four dimensional pfd mask is recommended for use by the BR verification software and is defined following one of the two options:

Option 1: As a function of:

–   the non-GSO satellite;

–   the latitude of the non-GSO sub-satellite point;

–   the separation angle α between this non-GSO space station and the GSO arc, as seen from any point on the surface of the Earth, as defined in § D6.4.4;

–   the difference ΔL in longitude between the non-GSO sub-satellite point and the point on the GSO arc where the α angle is minimised, as defined in § D6.4.4.

Option 2: As a function of:

–   the non-GSO satellite;

–   the latitude of the non-GSO sub-satellite point;

–   the non-GSO satellite azimuth angle, defined in § D6.4.5;

–   the non-GSO satellite elevation angle, defined in § D6.4.5.

Whatever parameters are used to generate the pfd mask, the resulting pfd mask should be converted to one of the format options above.

Because the non-GSO space station can generate simultaneously a given maximum number of beams, it should be taken into account in order to better fit the system design and not be too constraining for non-GSO systems.

The mitigation techniques used by the non-GSO system, such as the GSO arc avoidance, are implemented in the calculation of the pfd mask. The GSO arc avoidance defines a non-operating zone on the ground in the field of view of a non-GSO space station. The location of this non-operating zone on the ground will move as a function of the latitude of the non-GSO sub-satellite point. To get

a more accurate model of a non-GSO system, the latitude of the non-GSO sub-satellite point is taken as a parameter to the pfd mask calculation.

C2.2 Mitigation techniques description

The mitigation technique implemented within the non-GSO system should be accurately explained in this section in order to be fully modelled in the calculation of the epfd↓.

With regard to the use of a non-operating zone around the GSO arc, there are at least two different ways of modelling a non-GSO system based on a cell architecture:

– Cell-wide observance of a non-operating zone: a beam of a non-GSO space station is switched off if the separation angle between this non-GSO space station and the GSO arc, at any point of the non-GSO cell, is less than α_0 (GSO arc avoidance angle).

– Cell-centre observance of a non-operating zone: a beam of a non-GSO space station is switched off when the centre of the cell sees this non-GSO space station at less than α_0 from the GSO arc.

Other mitigation techniques may be used by a non-GSO system which are not listed here. Information on these techniques will be provided by the non-GSO administration for the description and verification of the pfd mask.

C2.3 pfd calculation

C2.3.1 pfd calculation

The pfd radiated by a non-GSO space station at any point on the Earth's surface is the sum of the pfd produced by all illuminating beams in the co-frequency band.

Some non-GSO systems have tracking antennas which point to cells fixed on the Earth's surface and do not move with the spacecraft. However, since the pfd mask is generated with respect to the non-GSO location, assumptions must be made in the development of the pfd mask. Making the simplifying assumption that the cells move with the spacecraft can lead to inaccurate geographic distributions of epfd levels.

As non-GSO systems use mitigation techniques, there will be no main beam-to-main beam alignment. Therefore, de-polarization effects mean that both co-polarization and cross-polarization contributions must be included as sources of interference.

The implementation of the pfd mask explicitly accounts for both co-polarization and cross-polarization from non-GSO satellites into GSO earth stations for like types of polarization (circular-to-circular or linear-to-linear). Isolation between systems of different types of polarization (circular-to-linear) is not directly covered. A study has shown that the average total interference power over all axial ratios and polarization ellipse orientations is a very small net increase in the received interference power in the BSS antenna of 0.048 dB. The bounds of any cross-polarization contributions, that are very unlikely to be reached, are from –30 dB to +3 dB.

Then:

$$pfd = 10 \log\left(\sum_i^{N_{co}} 10^{pfd\_co_i/10} + \sum_j^{N_{cross}} 10^{pfd\_cross_j/10}\right)$$

where:

pfd : pfd radiated by a non-GSO space station (dB(W/m^2)) in the reference bandwidth

i : index of the beams illuminated in the polarization considered

N_{co} : maximum number of beams which can be illuminated simultaneously in the polarization considered

pfd_co_i : pfd produced at the point considered at the Earth's surface by one beam in the polarization considered (dB(W/m²)) in the reference bandwidth

j : index of the beams illuminated in the opposite polarization to the polarization considered

N_{cross} : maximum number of beams which can be illuminated simultaneously in the opposite polarization to the polarization considered

pfd_cross_j : pfd produced at the point considered at the Earth's surface by one beam in the opposite polarization to the polarization considered (dB(W/m²)) in the reference bandwidth

and

$$pfd\_co_i = P_i + G_i - 10\log_{10}(4\,\pi\,d^2)$$

where:

P_i : maximum power emitted by the beam i in the reference bandwidth (dB(W/BW$_{ref}$))

BW$_{ref}$: reference bandwidth (kHz)

G_i : gain generated by the beam i in the polarization considered at the point considered at the Earth's surface (dBi)

d : distance between the non-GSO space station and the point considered at the Earth's surface (if the non-GSO satellite antenna gain is in isoflux, d is the altitude of the non-GSO space station) (m)

and

$$pfd\_cross_j = P_j + G\_cross_j - 10\log_{10}(4\,\pi\,d^2)$$

where:

G_cross_j : cross-polarization gain generated by the beam j illuminated in the opposite polarization to the polarization considered, at the point considered at the Earth's surface (dBi).

It is expected that the parameters used to generate the pfd/e.i.r.p. mask correspond to the performance of the non-GSO satellite over its anticipated lifetime. The pfd levels should be an envelope over all possible traffic and beam combinations and represent the peak pfd in the given direction feasible over the lifetime of the system. Non-GSO satellite systems that employ adaptive antennas in which the beam size and sidelobe can be adjusted should take the combination that would result in the highest pfd expected during the anticipated lifetime in each direction when generating the pfd mask. The pfd for all angles for which the satellite operates will therefore be the highest pfd that would be generated, for example, when there is a traffic hot spot in that direction. This approach is consistent with the algorithm in Part D to calculate the epfd which takes account of frequency re-use constraints within the non-GSO system.

C2.3.2 Satellite antenna gain at the point considered at the Earth's surface

The objective of this section is to determine the gain in the direction of a point M at the Earth's surface when the satellite antenna points towards a cell i. The antenna coordinate can be defined by four ways of the coordinate system:

φ : spherical coordinate

v : u = sin θ cos φ, v = sin θ sin φ

B : A = θ cos φ, B = θ sin φ

(Az, El): $\sin(El) = \sin\theta \sin\varphi$, $\tan(Az) = \tan\theta \cos\varphi$

The antenna gain data can be provided in a number of formats and coordinate systems. As the key input into the epfd calculation is the pfd mask, not the antenna gain pattern used to derive the pfd mask, the format and coordinate system of this antenna gain pattern could be different from those used elsewhere in this document. In particular, it is important to note that the above equations related to the conversion between (θ, φ) and (Az, El) are different from those included in § D3.1.3.1 and which are used in the Worst-Case Geometry Algorithm.

As an example, the following calculations are performed in the antenna reference (A, B).

The sampling of the non-GSO antenna pattern should be adapted so that interpolation does not lead to gain level significantly different from real values.

Figure 3 presents the geometry in the antenna plane (A, B), while Fig. 4 presents the geometry between the (θ, φ) and (Az, El) angles using the definitions above.

FIGURE 3

Antenna plane (A, B)
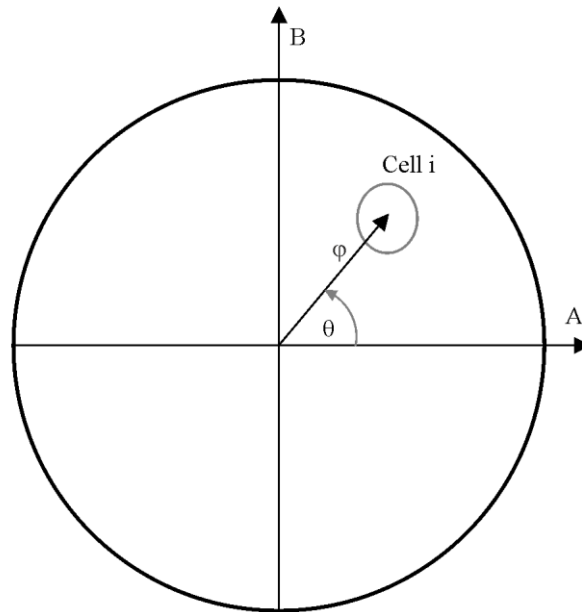
S.1503-03

FIGURE 4

(θ, φ) and (Az, El) geometry, illustrated using a reference frame centred at the satellite
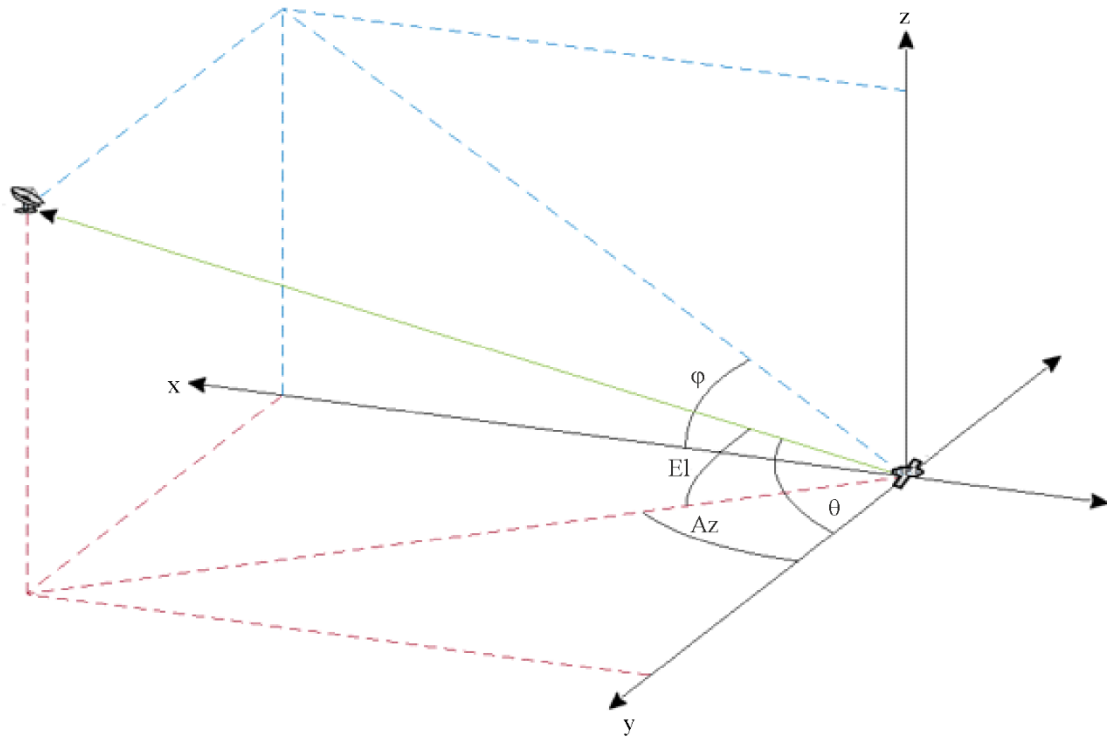
S.1503-04

The coordinates of the point M at the Earth's surface are (a, b) in the antenna plane (A, B), corresponding to (θ_M, φ_M) in the polar reference.

The coordinates of the point C centre of the cell i, are (A_c, B_c) in the antenna plane (A, B), and (θ_c, φ_c) in the spherical reference.

For satellite antenna gain patterns with functional descriptions (i.e. equations), the gain into the point M may be computed directly from the coordinates $C(A_c, B_c)$ and $M(a, b)$. For other patterns, the satellite antenna gains are provided in a grid of (A, B) points, and the point $M(a, b)$ may be located between four points of the grid (A, B).

In general, it is therefore necessary to undertake interpolation between data points. Consider a grid of values P for a range of x values $= \{x_1, x_2, \ldots\}$ and y values $= \{y_1, y_2, \ldots\}$ as in Fig. 5.

FIGURE 5

Interpolation between data points

S.1503-05
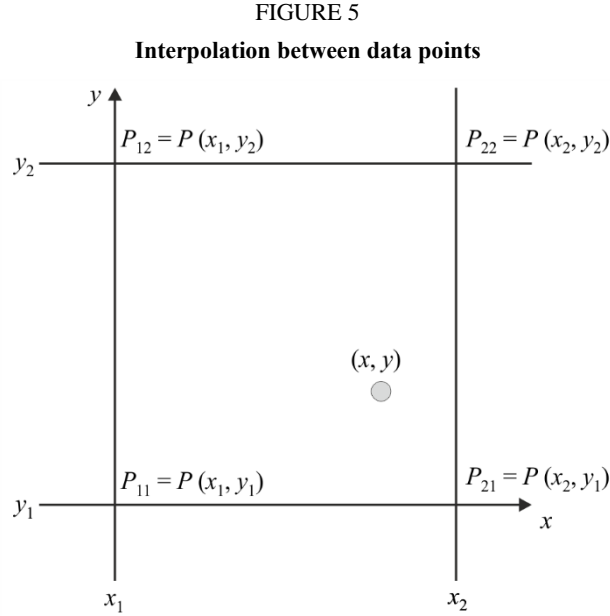
The value of parameter P at point (x, y) can be derived by identifying the bounding values and hence:

$$\lambda_x = \frac{x - x_1}{x_2 - x_1}$$

$$\lambda_y = \frac{y - y_1}{y_2 - y_1}$$

Then P can be interpolated using:

$$P = (1 - \lambda_x)(1 - \lambda_y)P_{11} + \lambda_x(1 - \lambda_y)P_{21} + (1 - \lambda_x)\lambda_y P_{12} + \lambda_x\lambda_y P_{22}$$

The sampling of the non-GSO satellite antenna pattern should be adapted so that interpolation does not lead to significant approximation.

The same criteria should be used when sampling the pfd mask.

C2.4 Methodology

The pfd mask is defined by the maximum pfd generated by any space station in the interfering non-GSO system and as a function of the parameters defined either in option 1 or option 2. For the generation of the pfd mask, the cells in the non-GSO satellite footprint are located according to the beam pointing utilized by the non-GSO system. For satellites with steerable antennas, the satellite can point to the same area of the Earth throughout its track through the sky.

These cells are fixed relative to the Earth's surface. For satellites that have antenna-pointing angles fixed relative to the satellite, the cell pattern is the same relative to the satellite but is moving relative to the Earth.

C2.4.1 Option 1

Option 1 has been described for a pfd mask defined as a function of the separation angle α, as an example.

The pfd mask is defined as a function of the separation angle α between this non-GSO space station and the GSO arc, as seen from any point on the surface of the Earth, and the difference ΔL in longitude between the non-GSO sub-satellite point and the GSO satellite.

The angle α is therefore the minimum topocentric angle measured from this particular earth station between the interfering non-GSO space station and any point in the visible GSO arc.

The objective of the mask is to define the maximum possible level of the pfd radiated by the non-GSO space station as a function of the separation angle between the non-GSO space station and the GSO arc at any point on the ground, per interval of ΔL.

At each point of the non-GSO satellite footprint, the pfd value depends on:

–   the configuration of the spot beams which are illuminated by the satellite;

–   the maximum number of co-frequency beams which can be illuminated simultaneously;

–   the maximum number of co-frequency, co-polarization beams which can be illuminated simultaneously;

–   the maximum power available at the satellite repeater.

The proposed methodology for the generation of the pfd mask is explained in the following steps:

Step 1: At any given time, in the field of view of a non-GSO space station, N_{total} is the maximum number of cells that can be seen with the minimum service elevation angle.

Step 2: In the field of view of the non-GSO space station, it is possible to draw iso-α lines, i.e. the points on the surface of the Earth which share the same value of α (see Figs 6 and 7).

FIGURE 6

Field of view of a non-GSO space station (Option 1)

S.1503-06
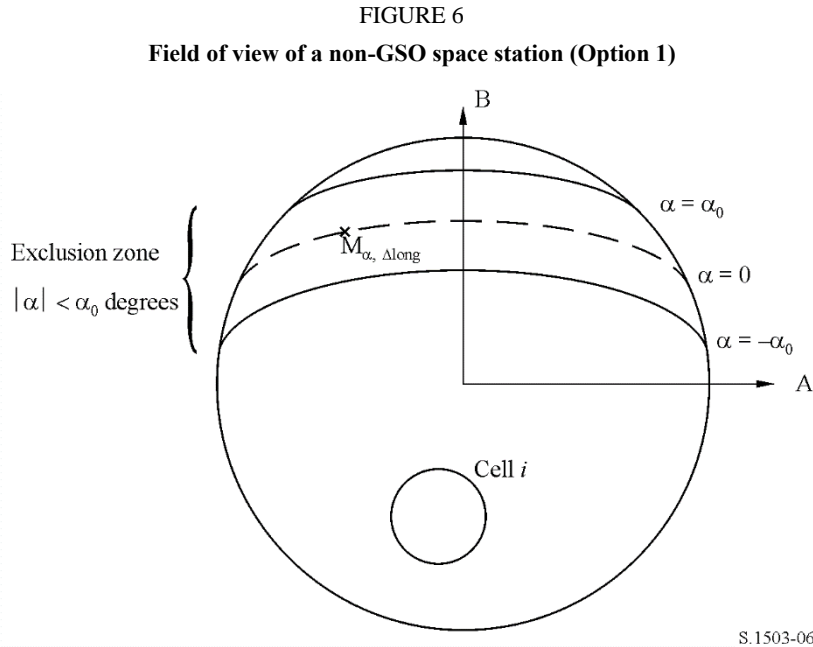
Step 3: Along the iso-α line, define intervals of ΔL: difference in longitude between the non-GSO sub-satellite point and the point on the GSO arc where the α angle is minimised.

Step 4: Per each interval of ΔL, the iso-α line can be defined by a set of n points $M_{\alpha,k}$ for $k = 1, 2,...n$. To determine the maximum pfd corresponding to a given value of α, it is necessary to calculate the maximum pfd at each of the points $M_{\alpha,k}$ for $k = 1, 2,...n$. The maximum pfd at a given $M_{\alpha,k}$ is determined by first finding the pfd contributed by each cell$_i$ toward $M_{\alpha,k}$ taking into account the dependency of the sidelobe patterns on the beam tilt angle. The maximum pfd contributions toward $M_{\alpha,k}$ are then summed, with the number of contributions constrained by the physical limitations of the space station:

–   Out of the N_{total} cells that can be seen within the coverage area of the space station under a minimum elevation angle for communication, only N_{co} can be illuminated at the same frequency bandwidth, in one sense of polarization, and N_{cross} in the other sense of polarization. This characterizes the limitation of the antenna system on the non-GSO space station. To calculate the mask in one polarization, the cells which can be illuminated in the polarization concerned are identified, and the cross-polarization level is considered for other cells.

–   Out of these N_{co} and N_{cross} cells, only a given number can be powered simultaneously. This characterizes the limitation of the repeater system of the non-GSO space station.

–   If applicable, the limitations in terms of frequency reuse pattern and polarization reuse pattern also need to be clarified.

–   If applicable, the power allocated to one cell may vary taking into account the elevation angle relative to this cell, for example:

FIGURE 7

View in 3D of the iso-α line
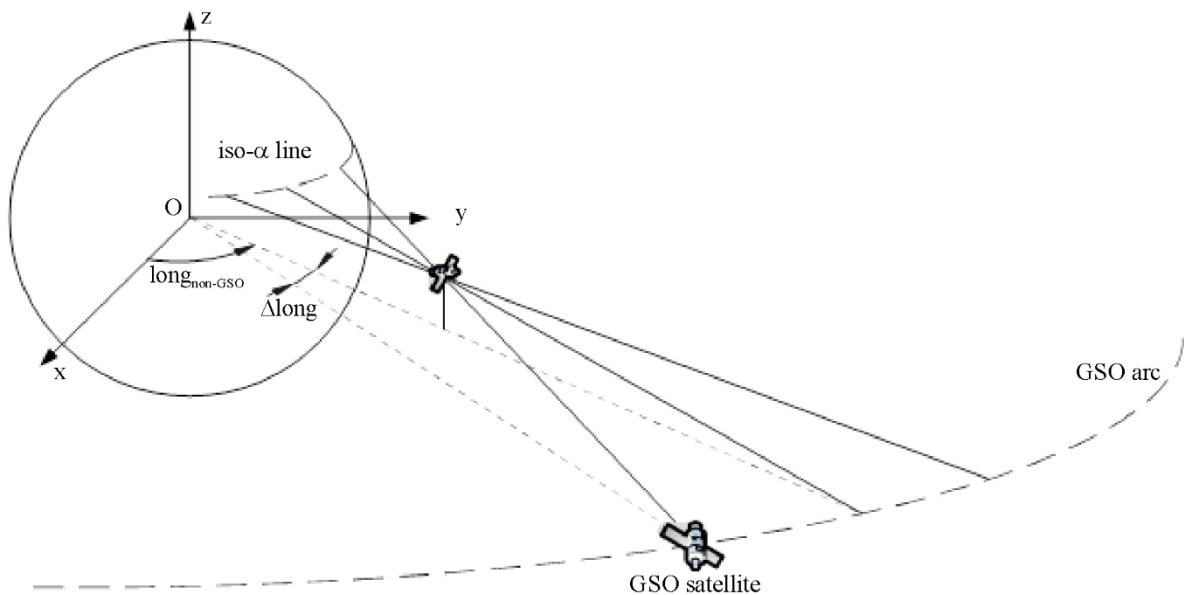
S.1503-07

Step 5: The generation of the pfd mask also needs to take into account accurately the mitigation technique implemented within the non-GSO system.

With regard to the use of a non-operating zone around the GSO arc, there are three different ways of modelling a non-GSO system based on a cell architecture:

–   cell-wide observance of a non-operating zone: a beam is switched off when one point on the Earth sees a non-GSO satellite within α_0 of the GSO arc. In this particular case, any beam illuminating a cell which is crossed by an iso-α line corresponding to a value $|\alpha| \leq \alpha_0$ is switched off;

–   cell-centre observance of a non-operating zone: a beam is switched off when the centre of the cell sees a non-GSO satellite within α_0 of the GSO arc. In this case, any beam illuminating a cell with its centre inside the non-operating zone bounded by the two iso-α_0 lines is switched off;

Step 6: The maximum pfd value corresponding to a given value α within an interval of ΔL is:

$$pfd(\alpha, \Delta L) = \max_{1,2,...n} \left(pfd\left(M_{\alpha,k}\right) \right)$$

Step 7: The location of an iso-α line, hence the value of the maximum pfd along this line depends on the latitude of the non-GSO sub-satellite point. Therefore, a set of pfd masks will need to be provided, each corresponding to a given latitude of the sub-satellite point.

Step 8: A set of pfd masks may be needed (one per non-GSO satellite).

C2.4.2 Option 2

The pfd mask is defined in a grid in azimuth and elevation, per latitude of the non-GSO sub-satellite as shown in Fig. 8.

The objective of the mask is to define the maximum possible level of the pfd radiated by the non-GSO space station in this azimuth elevation grid.

At each point of the non-GSO satellite footprint, the pfd value depends on:

–   the configuration of the spot beams which are illuminated by the satellite;

–   the maximum number of co-frequency beams which can be illuminated simultaneously;

–   the maximum number of co-frequency, co-polarization beams which can be illuminated simultaneously;

–   the maximum power available at the satellite repeater.

FIGURE 8

Field of view of a non-GSO space station (Option 2)
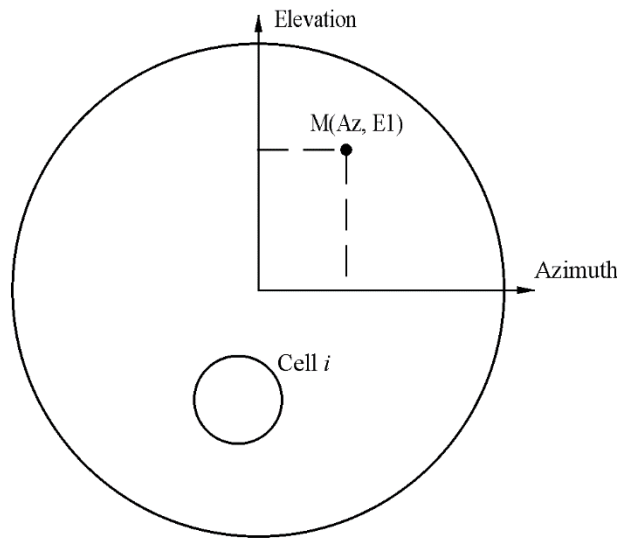
S.1503-08

The proposed methodology for the generation of the pfd mask is explained in the following steps:

Step 1: At any given time, in the field of view of a non-GSO space station, N_{total} is the maximum number of cells that can be seen with the minimum service elevation angle.

Step 2: For each point M(Az, El), determine the maximum pfd. The maximum pfd at a given $M_{\alpha,k}$ is determined by first finding the pfd contributed by each cell$_i$ toward M(Az, El) taking into account the dependency of the sidelobe patterns on the beam tilt angle. The maximum pfd contributions toward $M_{\alpha,k}$ are then summed, with the number of contributions constrained by the physical limitations of the space station:

–   Out of the N_{total} cells that can be seen within the coverage area of the space station under a minimum elevation angle for communication, only N_{co} cells can be illuminated at the same frequency bandwidth, in one sense of polarization, and N_{cross} cells in the other sense of polarization. This characterizes the limitation of the antenna system on the non-GSO space station. To calculate the mask in one polarization, the cells which can be illuminated in the polarization concerned are identified, and the cross-polarization level is considered for other cells.

–   Out of these N_{co} and N_{cross} cells, only a given number can be powered simultaneously. This characterizes the limitation of the repeater system of the non-GSO space station.

–   If applicable, the limitations in terms of frequency reuse pattern and polarization reuse pattern also need to be clarified.

–   If applicable the power allocated to one cell may vary taking into account the elevation angle relative to this cell, for example.

Step 3: The generation of the pfd mask also needs to take into account accurately the mitigation technique implemented within the non-GSO system.

With regard to the use of a non-operating zone around the GSO arc, there are three different ways of modelling a non-GSO system based on a cell architecture:

–   cell-wide observance of a non-operating zone: a beam is switched off when one point on the Earth sees a non-GSO satellite within α_0 of the GSO arc. In this particular case, any beam illuminating a cell which is crossed by an iso-α line corresponding to a value $|\alpha| \leq \alpha_0$ is switched off;

–   cell-centre observance of a non-operating zone: a beam is switched off when the centre of the cell sees a non-GSO satellite within α_0 of the GSO arc. In this case, any beam illuminating a cell with its centre inside the non-operating zone bounded by the two iso-α_0 lines is switched off.

Step 4: A set of pfd masks may need to be provided as a function of the latitude of the sub-satellite point.

Step 5: A set of pfd masks may be needed (one per non-GSO satellite).

C3   Generation of e.i.r.p. masks

C3.1   Generation of earth station e.i.r.p. masks

C3.1.1 General presentation

The earth station e.i.r.p. mask is defined by a set of tables of the maximum e.i.r.p. as a function of latitude and one of:

1)   The off-axis angle in the direction of the GSO arc as generated by an earth station. There can be different such e.i.r.p. tables applicable at different latitudes.

2)   The azimuth and elevation of the non-GSO satellite that the earth station is currently pointing at and difference in longitude between the earth station and reference point on the GSO arc. There can be different such e.i.r.p. tables applicable at different latitudes.

The non-GSO earth station is located in a non-GSO cell which is served by a maximum number of non-GSO space stations. The density of non-GSO earth stations which can operate co-frequency simultaneously is also used as an input to the calculation.

C3.1.2 Mitigation techniques description

The mitigation technique implemented within the non-GSO system should be accurately explained in this section in order to be fully modelled in the calculation of the epfd↑ (see § C2.2).

C3.1.3 Earth station antenna pattern

The earth station antenna pattern used needs to be identified to calculate the earth station e.i.r.p. mask.

C3.1.4 Methodology

Step 1:

The earth station gain pattern could be defined as a function of the off-axis angle at the non-GSO earth station between the boresight direction towards the non-GSO space station and a point on the GSO arc, and its e.i.r.p mask could be calculated as follows:

The earth station e.i.r.p. mask at a given latitude is defined by the maximum e.i.r.p. radiated in the reference bandwidth by the earth station as a function of the off-axis angle, and is given by:

$$ES\_e.i.r.p.(Lat, \theta) = G(Lat, \theta) + P(Lat)$$

where:

ES_e.i.r.p.(Lat, θ): equivalent isotropic radiated power in the reference bandwidth (dB(W/BW$_{ref}$))

        Lat: latitude of ES for that e.i.r.p. mask

        θ: off-axis angle at the non-GSO earth station between the boresight line towards non-GSO space station and a point on the GSO (e.g. the GSO space station) (degrees)

    G(Lat, θ): earth station directional antenna gain (dBi) at given latitude

     P(Lat): maximum power delivered to the antenna, in the reference bandwidth (dB(W/BW$_{raf}$)) at given latitude

    BW$_{raf}$: reference bandwidth (kHz).

Alternatively, the gain pattern could be provided in the format ES_e.i.r.p.(Lat, az, el, DeltaLongES) and the corresponding e.i.r.p mask could be calculated as follows:

The earth station e.i.r.p. mask at a given latitude is defined by the maximum e.i.r.p. radiated in the reference bandwidth by the earth station as a function of the azimuth, elevation and delta longitude angles, and is given by:

$$ES\_e.i.r.p.(Lat, az, el, \Delta LongES) = G(Lat, az, el, \Delta Long) + P(Lat)$$

where:

ES_e.i.r.p.(Lat, az, el, ΔlongES) : equivalent isotropic radiated power in the reference bandwidth (dB(W/BW$_{ref}$))

     Lat : latitude of ES for that e.i.r.p. mask

     az : azimuth component of the antenna pointing direction (degree)

     el : elevation component of the antenna pointing direction (degree)

  ΔLongES : difference in longitude between non-GSO earth station and point on the GSO arc (degree)

G(Lat, az, el, ΔLong) : earth station directional antenna gain (dBi) at given latitude

    P(Lat) : maximum power delivered to the antenna, in the reference bandwidth (dB(W/BW$_{raf}$)) at given latitude

    BW$_{raf}$: reference bandwidth (kHz).

Step 2: Assuming that the non-GSO cells are uniformly distributed on the Earth's surface, the simultaneous co-frequency transmit non-GSO earth stations are evenly distributed over the cell. Therefore the interferer can be located at the centre of the cell to perform the simulation.

This exercise would be repeated for all latitudes for which the ES_e.i.r.p. could be different.

C3.2   Generation of space station e.i.r.p. masks

The space station e.i.r.p. mask is defined by the maximum e.i.r.p. generated by a non-GSO space station as a function of the angle seen from the non-GSO space station between the line to the sub-point of the non-GSO space station considered and a point on the GSO arc.

The space station e.i.r.p. mask is defined by the maximum e.i.r.p. radiated in the reference bandwidth by the space station as a function of this angle, and is given by:

$$NON - GSO\_SS\_e.i.r.p.(\theta) = G(\theta) + P$$

where:

NON-GSO_SS_e.i.r.p.:   equivalent isotropic radiated power in the reference bandwidth $(dB(W/BW_{ref}))$

   θ: angle seen from the non-GSO space station between the line to the sub-point of the non-GSO space station considered and a point on the GSO arc (degrees)

   $G(\theta)$:   space station antenna gain pattern (dBi) corresponding to the aggregation of all beams

   P: maximum power, in the reference bandwidth $(dB(W/BW_{rif}))$

   BW_{rif}:   reference bandwidth (kHz).

C4   pfd and e.i.r.p. mask format

C4.1   General structure of masks

The pfd and e.i.r.p. masks are key inputs to Recommendation ITU-R S.1503 with format:

–   For epfd(down) runs, the pfd mask(s), containing tables of pfd(α, Δlong) or of pfd(azimuth, elevation) together with the latitude for which each table is valid.

–   For epfd(up) runs, the non-GSO earth station e.i.r.p. mask(s), each one contains tables of e.i.r.p. (θ) or e.i.r.p. (.az, el, Δlong) together with the latitude for which each table is valid.

–   For epfd(IS) runs, the non-GSO satellite e.i.r.p. masks, each one contains tables of e.i.r.p. (θ) together with the latitude for which each table is valid.

During the simulation, the software will calculate the relevant parameters, such as latitude and off-axis angle or α angle, and then use the mask to calculate a pfd or e.i.r.p. using the following approach:

1)   The array of {Latitude, Table} is searched and the table which has the nearest latitude to the value calculated in the simulation is selected.

2)   Using the selected table, the pfd or e.i.r.p. is then calculated by interpolation using:

   a)   pfd: calculated using bi-linear interpolation in either pfd(α, Δlong) or pfd(azimuth, elevation);

   b)   e.i.r.p.(θ): calculated using linear interpolation in e.i.r.p. (θ);

   c)   e.i.r.p.(az, el, Δlong): using the methodology in § D5.2.7.

Each table is independent i.e. at different latitudes it can use a different grid resolution and range. The mask does not need to cover the whole range: outside the supplied values the last valid value is assumed to be used.

However, it should be noted that for latitude and {azimuth, elevation, α, Δlong} regions where no actual pfd is produced, in order to avoid using nearest latitude table containing operational pfd values it is advisable to provide extremely low pfd values for these ranges to simulate no transmission scenario.

The pfd mask table is not assumed to be symmetric in {azimuth, elevation, α, Δlong} and should be given for the full range from positive to negative extremes. In the case that the {azimuth, elevation, α, Δlong, off-axis angle} calculated in the simulation is outside the ranges given in the pfd or e.i.r.p. masks, then the last valid value should be used.

For the ES e.i.r.p. masks, there is the option to specify the position by (latitude, longitude) rather than density via a reference to a specific ES in the SRS. Note that it is not permitted to mix types: either all non-GSO ES are to be defined via specific ES or all via the density field.

Each mask has header information giving:
– Notice ID
– Satellite name
– Mask ID
– Lowest frequency mask is valid in MHz
– Highest frequency mask is valid in MHz
– Reference bandwidth of mask in kHz
– Mask type
– Parameters of mask.

The reference bandwidth of the mask is required as there are more than one bandwidth in the epfd thresholds in Article **22** of the Radio Regulations. The mask is scaled assuming the pfd or e.i.r.p. has a constant spectral power density, so that the pfd or e.i.r.p. to use in the calculations is:

$$pfd\_Calc = pfd\_Mask + 10\log10[\,Threshold\_Bandwidth\,/\,refbw\_khz]$$

If no refbw_khz is present in the mask than ref_bw_khz=40 is assumed.

$$e.i.r.p.\_Calc = e.i.r.p.\_Mask + 10\log10[\,Threshold\_Bandwidth\,/\,refbw\_khz]$$

The pfd and e.i.r.p. levels can vary by latitude: at least one latitude value (by default, 0 degree) should be given.

Each XML file should contain one mask (pfd or e.i.r.p.).

The masks relationships are shown in Figs 9 to 12.

FIGURE 9

Structure of pfd mask data for epfd(down)

S.1503-09
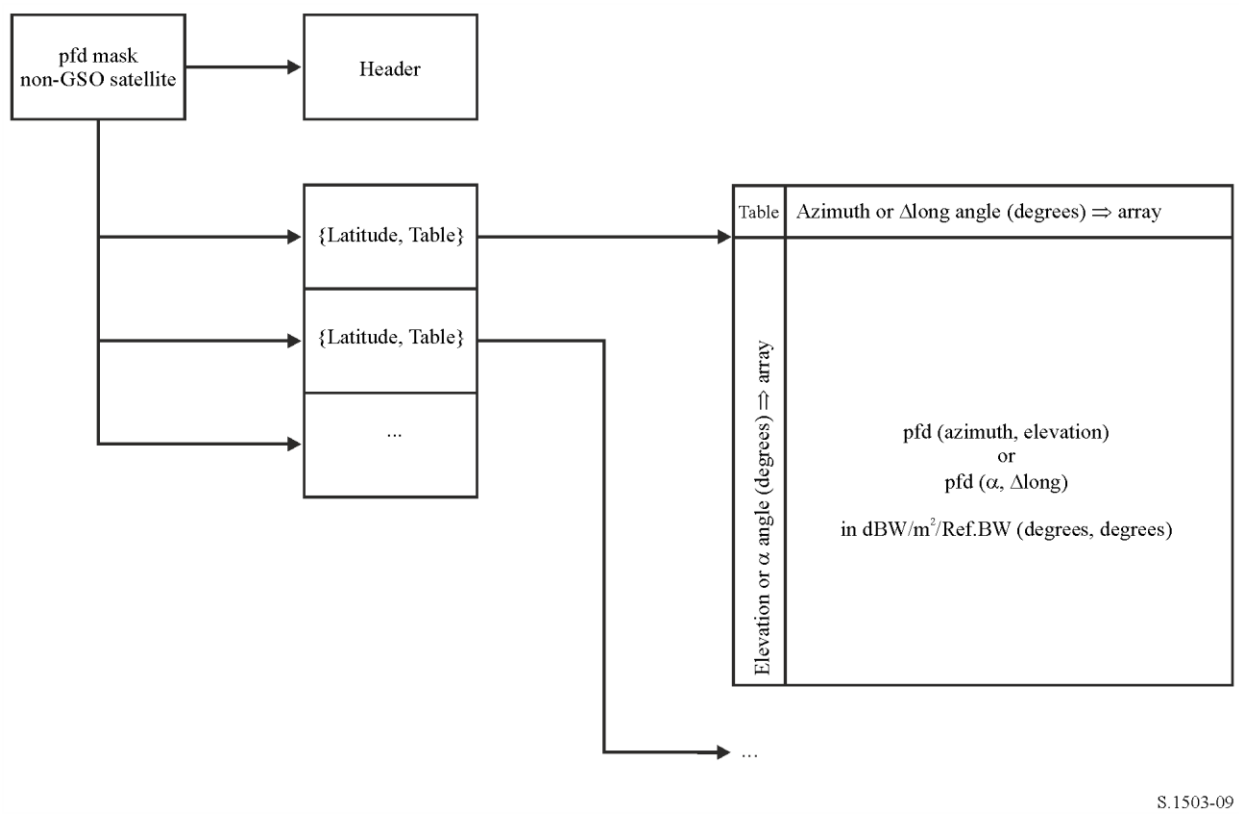
FIGURE 10

Structure of off-axis based e.i.r.p. mask data for epfd(up)
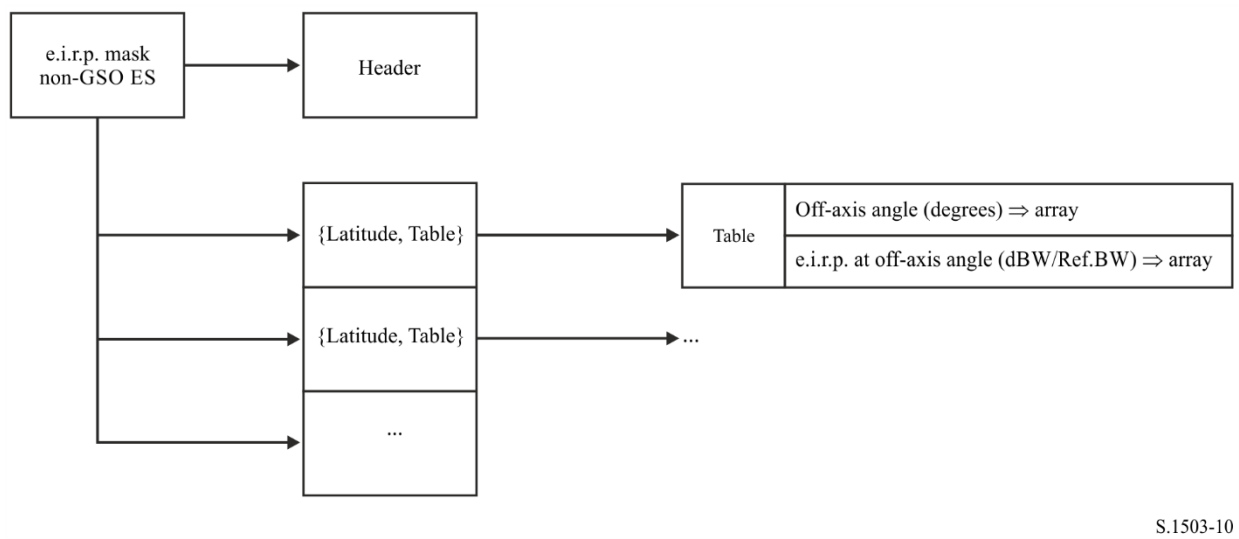
S.1503-10

FIGURE 11

Structure of azimuth elevation based e.i.r.p. mask data for epfd(up)
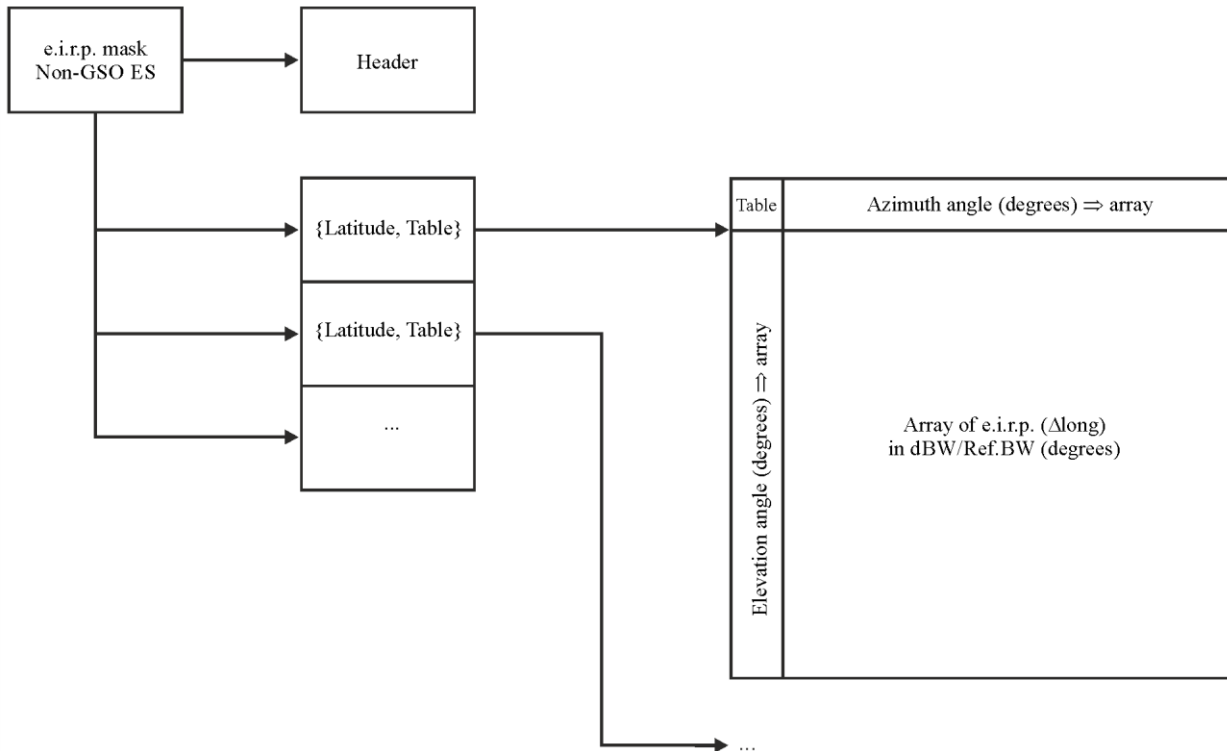
S.1503-11

FIGURE 12

Structure of e.i.r.p. mask data for epfd(IS)
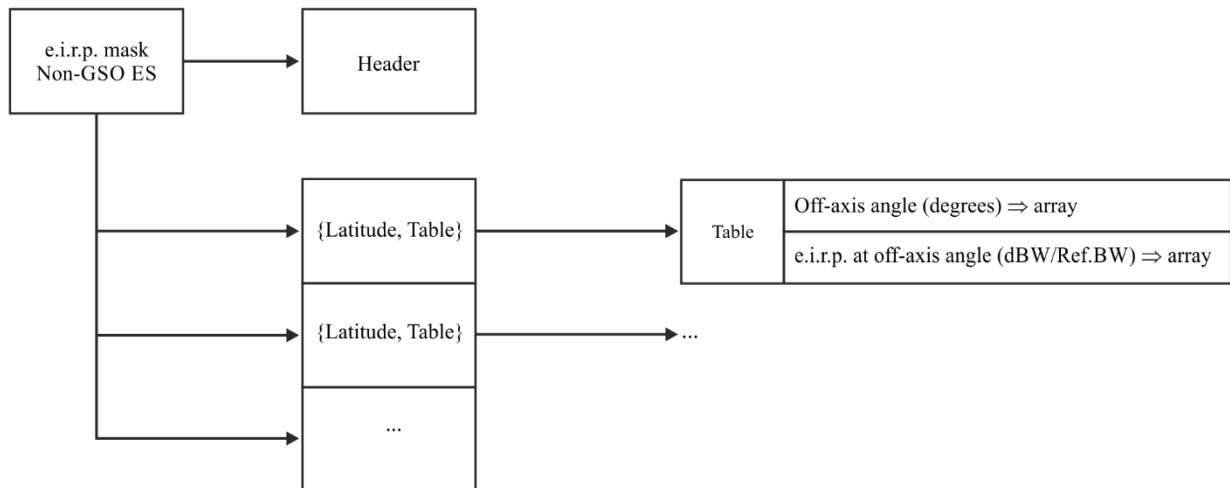
S.1503-12

The pfd masks are to be provided to the ITU BR in XML format as:

– It is both machine readable and human readable

– Allows both format and type checking

– Is an international standard for exchange of data.

The XML format is plain text with opening and closing blocks, as in:

<satellite_system>

</satellite_system>

Within each section there are then fields relevant to that block. All angles should be given in degrees.

At the top level the satellite system is identified via its notice ID and name using:

<satellite_system ntc_id="NNNNNNN" sat_name="NAME">

[Header]

[Tables]

</satellite_system>

Within this structure there is the header followed by each of the tables.

The format for each mask is described in more detail in the sections below.

C4.2 pfd mask for epfd(down)

The header format of the pfd mask is as follows:

<pfd_mask mask_id="N" low_freq_mhz="F1" high_freq_mhz="F2" refbw_khz = "BW" type="Type" a_name="latitude" b_name="B" c_name="C">

where (see Table 5):

TABLE 5

pfd mask header format

Field	Type or range	Units	Example
mask_id	Integer	–	3
low_freq_mhz	Double precision	MHz	10 000
high_freq_mhz	Double precision	MHz	12 000
refbw_khz	Double precision	kHz	40
type	{alpha_deltaLongitude, azimuth_elevation}	–	alpha_deltaLongitude
a_name	{latitude}	–	latitude
b_name	{alpha, azimuth}	–	alpha
c_name	{deltaLongitude, elevation}	–	deltaLongitude

For each of a, b, c there are then arrays of values, such as:

<by_a a="N">

</by_a>

The values within that open/close structure then all relate to a = N: a similar structure is used for b values.

The innermost group gives the actual pfd value, such as:

<pfd c="0">–140</pfd>

An example pfd mask would therefore be:

<satellite_system ntc_id="12345678" sat_name="MySatName">

```
<pfd_mask mask_id="3" low_freq_mhz="10000" high_freq_mhz="40000" refbw_khz =
"40"      type="alpha_deltaLongitude"      a_name="latitude"      b_name="alpha"
c_name="deltaLongitude">

<by_a a="0">

    <by_b b="–180">

        <pfd c="–20">–150</pfd>

        <pfd c="0">–140</pfd>

        <pfd c="20">–150</pfd>

    </by_b>

    <by_b b="–8">

        <pfd c="–20">–165</pfd>

        <pfd c="0">–155</pfd>

        <pfd c="20">–165</pfd>

    </by_b>

    <by_b b="–4">

        <pfd c="–20">–170</pfd>

        <pfd c="0">–160</pfd>

        <pfd c="20">–170</pfd>

    </by_b>

    <by_b b="0">

        <pfd c="–20">–180</pfd>

        <pfd c="0">–170</pfd>

        <pfd c="20">–180</pfd>

    </by_b>

    <by_b b="4">

        <pfd c="–20">–170</pfd>

        <pfd c="0">–160</pfd>

        <pfd c="20">–170</pfd>

    </by_b>

    <by_b b="8">

        <pfd c="–20">–165</pfd>

        <pfd c="0">–155</pfd>

        <pfd c="20">–165</pfd>

    </by_b>

    <by_b b="180">

        <pfd c="–20">–150</pfd>
```

> *<pfd c="0">–140</pfd>*
>
> *<pfd c="20">–150</pfd>*
>
> *</by_b>*
>
> *</by_a>*
>
> *</pfd_mask>*
>
> *</satellite_system>*

The XML format can be used to submit a shorthand form to avoid duplicated data but the table will be completed by interpolation or repeated use of the previous value in an array. The form of the pfd mask used by the epfd calculation algorithm in Part D is a grid at each latitude of pfd(x, y) where (x, y) are the two variables of the mask.

At each latitude there will be an array of x and y values:

$$x_i = \{x_1, x_2, .. x_n\}$$

$$y_i = \{y_1, y_2, .. y_n\}$$

These arrays can vary between latitudes.

Then for each (x_i, y_i) there is an associated pfd value and hence there are $n \times m$ pfd values in the table, as in the simplified 4×4 table below:

(x, y) array	x_1	x_2	x_3	x_4
y_1	pfd(1,1)	pfd(2,1)	pfd(3,1)	pfd(4,1)
y_2	pfd(1,2)	pfd(2,2)	pfd(3,2)	pfd(4,2)
y_3	pfd(1,3)	pfd(2,3)	pfd(3,3)	pfd(4,3)
y_4	pfd(1,4)	pfd(2,4)	pfd(3,4)	pfd(4,4)

The data submitted can be a subset of this, for example:

(x, y) array	x_1	x_2	x_3	x_4
y_1	–	pfd(2,1)	pfd(3,1)	–
y_2	pfd(1,2)	–	–	pfd(4,2)
y_3	pfd(1,3)	–	–	pfd(4,3)
y_4	–	pfd(2,4)	pfd(3,4)	–

In this case, the pfd table would be completed by a combination of assumptions. Firstly, if there are edge of table values not specified, to extend the mask by using the nearest defined value and assuming it continues:

$$pfd(1,1) = pfd(2,1)$$

$$pfd(4,1) = pfd(3,1)$$

$$pfd(1,4) = pfd(2,4)$$

$$pfd(4,4) = pfd(3,4)$$

Then if there are central table values not specified, to complete using linear interpolation from the surrounding values as follows:

$$pfd(2,2) = Interpolate\{x_2, pfd(1,2), pfd(4,2), x_1, x_4\}$$

$$\text{pfd}(2,3) = \text{Interpolate}\{x_3, \text{pfd}(1,2), \text{pfd}(4,2), x_1, x_4\}$$

$$\text{pfd}(3,2) = \text{Interpolate}\{x_2, \text{pfd}(1,3), \text{pfd}(4,3), x_1, x_4\}$$

$$\text{pfd}(3,3) = \text{Interpolate}\{x_3, \text{pfd}(1,3), \text{pfd}(4,3), x_1, x_4\}$$

This completion of the pfd mask could be undertaken when it is read in or on-the-fly during the calculation of the pfd for a specific geometry.

C4.3 e.i.r.p. mask for epfd(up)

The header format of the e.i.r.p.(up) mask is as follows:

<eirp_mask_es mask_id="N" low_freq_mhz="F1" high_freq_mhz="F2" refbw_khz = "BW" a_name="latitude" b_name = "offaxis angle" ES_ID = "−1">

where (see Table 6):

TABLE 6

Non-GSO ES e.i.r.p. mask header format

Field	Type or range	Units	Example
mask_id	Integer	–	1
low_freq_mhz	Double precision	MHz	10 000
high_freq_mhz	Double precision	MHz	12 000
refbw_khz	Double precision	kHz	40
format	Character	–	"T" or "A"
a_name	{latitude}	degrees	latitude
b_name	{offaxis angle}	degrees	angle
ES_ID	Integer	–	12345678 −1 if not specific ES
c_name	{azimuth angle}	degrees	45
d_name	{elevation angle}	degrees	15
e_name	{deltalongES angle}	degrees	5

If the format ="T" then there are then for each relevant latitude arrays of e.i.r.p. values for given off-axis angles, such as:

<eirp b="0">30.0206</eirp>

The e.i.r.p. mask should be monotonically decreasing.

An example e.i.r.p.(up) mask would therefore be:

<satellite_system ntc_id="12345678" sat_name="MySatName">

<eirp_mask_es mask_id="1" low_freq_mhz="10000" high_freq_mhz="40000" refbw_khz = "40" format = "T" a_name = "latitude" b_name="offaxis angle", ES_ID=−1>

<by_a a="0">

<eirp b="0">30.0206</eirp>

<eirp b="1">20.0206</eirp>

<eirp b="2">12.49485</eirp>

<eirp b="3">8.092568</eirp>

<eirp b="4">4.9691</eirp>

<eirp b="5">2.54634976</eirp>

<eirp b="10">–4.9794</eirp>

<eirp b="15">–9.381681</eirp>

<eirp b="20">–12.50515</eirp>

<eirp b="30">–16.90743</eirp>

<eirp b="50">–18.9471149</eirp>

<eirp b="180">–18.9471149</eirp>

</by_a>

</eirp_mask_es>

</satellite_system>

If the format = *"A"* then at each latitude there would be a set of tables for every (azimuth, elevation) pointing angle covered, with each table of e.i.r.p. against the difference in longitude between the ES and the point on the GSO arc.

An example e.i.r.p.(up) mask would therefore be:

<satellite_system ntc_id="12345678" sat_name="MySatName">

<eirp_mask_es mask_id="1" low_freq_mhz="10000" high_freq_mhz="40000" refbw_khz = "40" format = "A" a_name = "latitude" c_name="azimuth angle" d_name = "elevation angle" e_name = "DeltaLongES", ES_ID=–1>

<by_a a="0">

<by_c c = "0">

<by_d d= "0">

<eirp e="0">30.0206</eirp>

<eirp e="1">20.0206</eirp>

<eirp e="2">12.49485</eirp>

<eirp e="3">8.092568</eirp>

<eirp e="4">4.9691</eirp>

<eirp e="5">2.54634976</eirp>

<eirp e="10">–4.9794</eirp>

<eirp e="15">–9.381681</eirp>

<eirp e="20">–12.50515</eirp>

<eirp e="30">–16.90743</eirp>

<eirp e="50">–18.9471149</eirp>

<eirp e="180">–18.9471149</eirp>

</by_d>

C4.4   e.i.r.p. mask for epfd(IS)

The header format of the e.i.r.p.(IS) mask is as follows:

<eirp_mask_ss mask_id="N" low_freq_mhz="F1" high_freq_mhz="F2" refbw_khz = "BW"
a_name= "latitude" b_name="offaxis angle">

where (see Table 7):

TABLE 7

Non-GSO satellite e.i.r.p. mask header format

Field	Type or range	Units	Example
mask_id	Integer	–	1
low_freq_mhz	Double precision	MHz	10 000
high_freq_mhz	Double precision	MHz	12 000
refbw_khz	Double precision	kHz	40
a_name	{latitude}	–	latitude
b_name	{angle}	–	angle

There are then for each relevant latitude arrays of e.i.r.p. values for given off-axis angles, such as:

<eirp b="0">30.0206</eirp>

The e.i.r.p. mask should be monotonically decreasing.

An example e.i.r.p.(IS) mask would therefore be:

<satellite_system ntc_id="12345678" sat_name="MySatName">

<eirp_mask_ss mask_id="2" low_freq_mhz="10000" high_freq_mhz="40000" refbw_khz =
"40" a_name = "latitude" b_name="offaxis angle">

<by_a a="0">

<eirp b="0">30.0206</eirp>

<eirp b="1">20.0206</eirp>

<eirp b="2">12.49485</eirp>

<eirp b="3">8.092568</eirp>

<eirp b="4">4.9691</eirp>

<eirp b="5">2.54634976</eirp>

<eirp b="10">–4.9794</eirp>

<eirp b="15">–9.381681</eirp>

<eirp b="20">–12.50515</eirp>

<eirp b="30">–16.90743</eirp>

<eirp b="50">–18.9471149</eirp>

<eirp b="180">–18.9471149</eirp>

</by_a>

</eirp_mask_ss>

</satellite_system>

PART D

Software for the examination of non-GSO filings

D1   Introduction

D1.1   Scope

The scope of this section is to specify part of a software requirements document (SRD) for a computer program that can be used by the BR to calculate whether a specific non-GSO system proposed by an administration meets epfd limits.

There are three key tasks that the software must complete as identified in Fig. 1:

1)   determination of the runs to execute;

2)   for each run, determination of worst case geometry;

3)   for each run, calculation of epfd statistics and checking compliance with the limits.

D1.2   Background

This section assumes that the following approaches are used:

epfd↓ calculation: Each non-GSO satellite has a pfd mask and the pfd for each satellite is used to calculate the aggregate epfd↓ at an earth station of a GSO system. This is repeated for a series of time steps until a distribution of epfd↓ is produced. This distribution can then be compared with the limits to give a go/no go decision.

epfd calculation: The Earth is populated with a distribution of non-GSO earth stations. Each earth station points towards a non-GSO satellite using pointing rules for that constellation, and transmits with a defined e.i.r.p.. From the e.i.r.p. mask for each earth station, the epfd↑ at the GSO can be calculated. This is repeated for a series of time steps until a distribution of epfd↑ is produced. This distribution can then be compared with the limits to give a go/no go decision.

epfd$_{is}$ calculation: From the e.i.r.p. mask for each space station, the epfd$_{is}$ at the GSO space station can be calculated. This is repeated for a series of time steps a distribution of epfd$_{is}$ is produced. This distribution can then be compared with the limits to give a go/no go decision.

The SRD provides detailed algorithms that would allow it to be implemented in software by any interested parties without reference to any specific development methodology.

D1.3   Overview

This Part D is structured into the following sections:

Section D2:   Determination of runs to execute

Section D3:   Determination of worst case geometry for each run

Section D4:   Calculation of time step size and number of time steps

Section D5:   Calculation of epfd statistics and limit compliance checking

Section D5.1:   Defines the epfd↓ algorithm

Section D5.2:   Defines the epfd↑ algorithm

Section D5.3:   Defines the epfd$_{is}$ algorithm

Section D6:   Defines the core geometry and algorithms used by both epfd calculations including gain patterns

Section D7:   Specifies the output formats and process to obtain a go/no-go decision.

Note that where square brackets are included as part of a parameter name, this indicates an index into an array, not tentative text.

D1.4   General assumptions and limitations

A general limitation on the generation of epfd statistics is:

Bin size: $S_B = 0.1$ dB

To be consistent with the evaluation algorithm in § D7.1.3 epfd values calculation for each time step should be rounded to the lower values with a maximum precision of 0.1 dB.

The calculation of angle to GSO arc, α, as described in § D6.4.4 should, where feasible, be calculated using the analytic method. If this method is unable to provide a solution, then the iterative approach may be used based upon a number of test points, with specified separation between them:

Separation between GSO test points: 1e-6 radians.

The test points should be a located at integer multiples of 1e-6 radians.

D1.5   Database and interface

Automatic verification analysis should take input data from the SRS or other databases, combined with BR resources such as DLLs to define epfd limits and calculate antenna gains. Custom analysis can request some parameters, such as GSO satellite and ES locations, from the user.

D2   Determination of runs to execute

D2.1   Article 22 runs

For an Article **22** run a key task is to determine which runs to execute given a non-GSO filing and the epfd limits specified in the RR.

In any direction, if there are no masks, whether pfd or e.i.r.p., then it is not necessary to undertake any runs.

It is necessary to look in the SRS grp, freq tables to:

–   Identify the date involved

–   Identify the list of frequencies.

It is also necessary to check the frequencies of the system operating table: if there are different sets of parameters at different frequencies then a run will have to be executed for each unique set of pfd/e.i.r.p. mask, orbit elements and system operating characteristics.

For each {freq_min, freq_max, date} combination is used to call the LimitsAPI. If there are duplicate limits returned, then only the minimum frequency case need be run.

```
For all unique Satellite {freq_min, freq_max, date} in non-GSO notice
{
    From LimitsAPI request all FSS epfd(down) limits for {freq_min, freq_max,
date}
    For all unique epfd(down) limits returned


    {
      Set FrequencyRun = max(fmin(mask), fmin(limits)) + RefBW/2
      CreateRun:
```

```
            Direction = Down
            Service = FSS
            Frequency = FrequencyRun
            ES_DishSize = From Limits API
            ES_GainPattern = From Limits API
            epfd_Threshold = From Limits API
            Ref_BW = From Limits API
        }
    From LimitsAPI request all BSS epfd(down) limits for {freq_min, freq_max,
date}
    For all unique epfd(down) limits returned
    {

      Set FrequencyRun = max(fmin(mask), fmin(limits)) + RefBW/2
      CreateRun:
          Direction = Down
          Service = BSS
          Frequency = FrequencyRun
          ES_DishSize = From Limits API
          ES_GainPattern = From Limits API
          epfd_Threshold = From Limits API
          Ref_BW = From Limits API


    }
}
For all unique ES {freq_min, freq_max} in non-GSO notice
{
    From LimitsAPI request all epfd(up) limits for {freq_min, freq_max, date}
    For all unique epfd(up) limits returned
    {
      Set FrequencyRun = max(fmin(mask), fmin(limits)) + RefBW/2
      CreateRun:
          Direction = Up
          Frequency = FrequencyRun
          Sat_Beamwidth = From Limits API
          Sat_GainPattern = From Limits API
          epfd_Threshold = From Limits API
          Ref_BW = From Limits API
    }
}
For all unique Satellite {freq_min, freq_max, date} in non-GSO notice
{
    From LimitsAPI request all epfd(is) limits for {freq_min, freq_max, date}
    For all unique epfd(is) limits returned
    {
      Set FrequencyRun = max(fmin(mask), fmin(limits)) + RefBW/2
      CreateRun:
          Direction = Intersatellite
          Frequency = FrequencyRun
          Sat_Beamwidth = From Limits API
          Sat_GainPattern = From Limits API
          epfd_Threshold = From Limits API
          Ref_BW = From Limits API
```

```
    }
}
```

D2.2   Number 9.7A of the Radio Regulations

For RR No. **9.7A** runs the criteria and threshold is defined in RR Appendix **5** and runs are generated
as follows:

```
If the selected earth station meets the criteria in Appendix 5
{
    Get the frequency range of the selected ES(fmin, fmax)
    Get all non-GSO networks in the SRS that overlap that frequency range
    For each non-GSO network returned
    {
        Query Limits API with the selected ES(fmin, fmax)
        {
            Get RefBW from Appendix 5 Data
            Set FrequencyRun = max(ES_fmin, Mask_fmin) + RefBW/2
            CreateRun:
             Direction = Down
             Frequency = FrequencyRun
             ES_DishSize = From ES filing
             ES_GainPattern = From ES filing
             epfd_Threshold = From Appendix 5
             Ref_BW = From Appendix 5
        }
    }
}
```

D2.3   Number 9.7B of the Radio Regulations

For RR No. **9.7B** runs the criteria and threshold is defined in RR Appendix **5** and runs are generated
as follows:

```
Get (fmin, fmax) from non-GSO notice
{
    Get all ES in the SRS that overlap that frequency range
    For each ES returned
    {
      If the earth station meets the criteria in Appendix 5
      {
          Query Limits API with ES(fmin, fmax)
          Get RefBW from Appendix 5 Data
          Set FrequencyRun = max(ES_fmin, Mask_fmin) + RefBW/2
          CreateRun:
             Direction = Down
             Frequency = FrequencyRun
             ES_DishSize = From ES filing
             ES_GainPattern = From ES filing
             epfd_Threshold = From Appendix 5
             Ref_BW = From Appendix 5
      }
    }
```

```
        }
}
```

D3   Worst-case geometry

The epfd limits in RR Article **22** are applicable for all GSO ESs and all pointing angles towards that part of the GSO arc visible from that ES. It is, however, not feasible to model all such geometries within the verification software. The worst-case geometry (WCG) is a reference GSO satellite location and either an ES or boresight of the GSO satellite's beam which is used when examining a non-GSO system for compliance with the epfd limits in RR Article **22**. It remains necessary for the non-GSO operator to meet the epfd limits in RR Article **22** for all other geometries including the testing of specific GSO networks as noted in § A1.3.

The WCG is selected by an algorithm, the worst-case geometry algorithm (WCGA), which undertakes an examination of the pfd/e.i.r.p. masks together with the non-GSO satellite orbital parameters to identify the highest single entry epfd value. Where there are multiple geometries with the same highest single entry epfd value, then the geometry is selected that should have this highest single entry epfd for the greatest percentage of time, identified by considering the angular velocity or elevation angle. These assumptions are based on the critical epfd levels being the highest ones which are those that are most readily measurable.

The WCGA is based upon iterating over a set of positions, typically of the non-GSO satellite. The geometry is assumed to be symmetric in longitude and the satellite can be set at the required latitude exactly using a simple point-mass model. However the epfd calculation engine described in § D5 can use a range of orbit models with a specific time step and therefore the longitude at which a satellite reaches a specified latitude will be different from that in the WCGA. Hence an additional stage is required which for the non-GSO satellite that results in the highest single entry epfd the difference in longitude is calculated between:

–   The longitude of the non-GSO satellite when it reaches the specified latitude using a point mass model in the WCGA, converting to (latitude, longitude) using a static time $t =$ simulation start time (e.g. relative time $= 0$).

–   The longitude at which the non-GSO satellite is closest to the specified latitude using the full orbit model and the fine time step calculated for the given run, converting to (latitude, longitude) using the relevant simulation time.

This difference in longitude is shown in Fig. 13.

FIGURE 13

Adjusting longitude of WCG to take account of orbit model and simulation time

S.1503-13
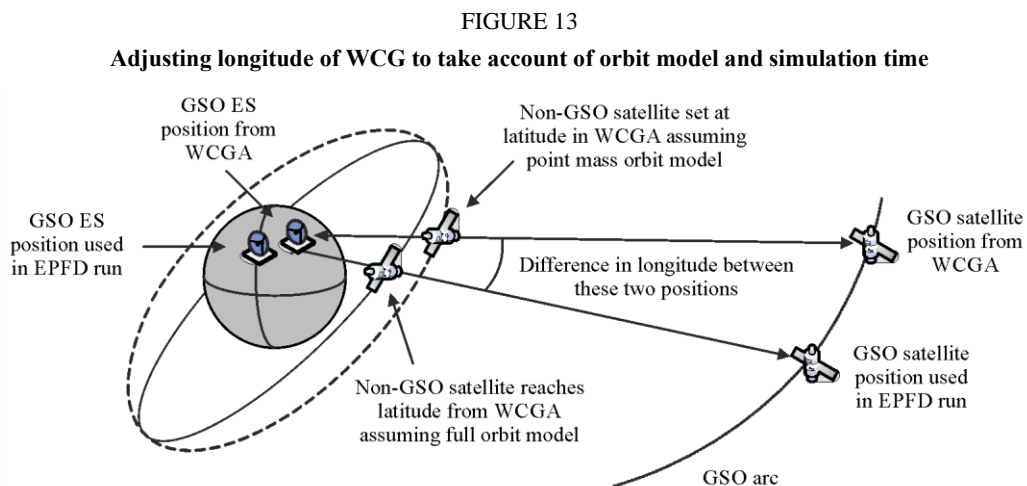
This difference in longitude is then used to adjust the position of the GSO satellite and ES calculated in the WCGA so that the non-GSO satellite with the pfd mask that causes the highest epfd goes through the geometry that causes this epfd value during its first orbit. When iterating for latitude using the time step, the time step that gives the nearest latitude is used in the longitude calculation.

Note that the algorithm in this Recommendation is not designed to take account of either ITU-R Regions or specific longitudes as the epfd limits in RR Article **22** are meant to be applicable for all GSO ES locations and visible parts of the GSO arc.

Care is required when comparing floating point numbers to check for rounding errors. In the WCGA it is acceptable to round to the nearest 0.1 dB rather than round up. The search grid is in steps of 0.1° and binary search routines terminate when the difference in angles is less than 1e-5 radians.

D3.1   WCG epfd↓

D3.1.1 Inputs

The inputs to the algorithm include:

pfd_mask: the pfd mask to check

α_0[lat] :   the GSO arc avoidance angle of the non-GSO satellite by latitude = MIN_EXCLUDE[Latitude]

h :   the minimum operating height of the non-GSO satellite

ε_0[lat, az] :   the minimum elevation angle of the non-GSO satellite by latitude and azimuth

$\{a, e, i\}$:   the orbit parameters of the non-GSO system

ES: the parameters of the ES including gain pattern.

D3.1.2 Algorithm

This section describes the algorithm to determine the WCG for the epfd(down) direction.

Note that there could be different ranges of frequency in the pfd masks: this process is assumed to be repeated for each valid frequency range. For each valid frequency ranges there could be different pfd masks, multiple sets of $\{a, e, i\}$ or system operating parameters (e.g. GSO avoidance angles that vary by non-GSO satellite): the process should be repeated over each such set.

The WCG is based upon search in (θ, φ) as seen by the non-GSO satellite, with particular care taken for the region $(-\alpha_0, +\alpha_0)$ including $\alpha = 0$. This search is repeated at a number of test non-GSO satellite latitudes. In addition, specific checks are made for the highest latitudes for which $\alpha = \{-\alpha_0, 0, +\alpha_0\}$ to ensure compatibility with the methodology in Recommendation ITU-R S.1714.

For each test point considered, the algorithm calculates the epfd using the pfd mask and receive antenna gain, and compares that to the threshold for the relevant latitude. The gain is calculated using the α angle for the off-axis angle φ: for the BSS ES antenna gain pattern, which might not be symmetric around the boresight, the θ should be the value calculated assuming the ES points at the location at the point correspond to the α angle. Note that the algorithm can be implemented in a way that calculates the WCG for multiple dish sizes using vectorisation.

It is likely that multiple test points will result in the same difference between epfd level and threshold. To assess which should be used as the WCG, the angular velocity of the non-GSO satellite as seen by the ES is calculated, and the geometry selected is that:

1.   Gives the highest difference between epfd level and threshold to the resolution of the resulting statistics (0.1 dB).

2.   If multiple geometries meet point 1, select the one that would result in geometry that gives the lowest angular velocity of the satellite as seen by the ES.

The search algorithm is shown in Figs 14 and 15, where:

$$\Delta\alpha = \alpha - \alpha_0[lat]$$

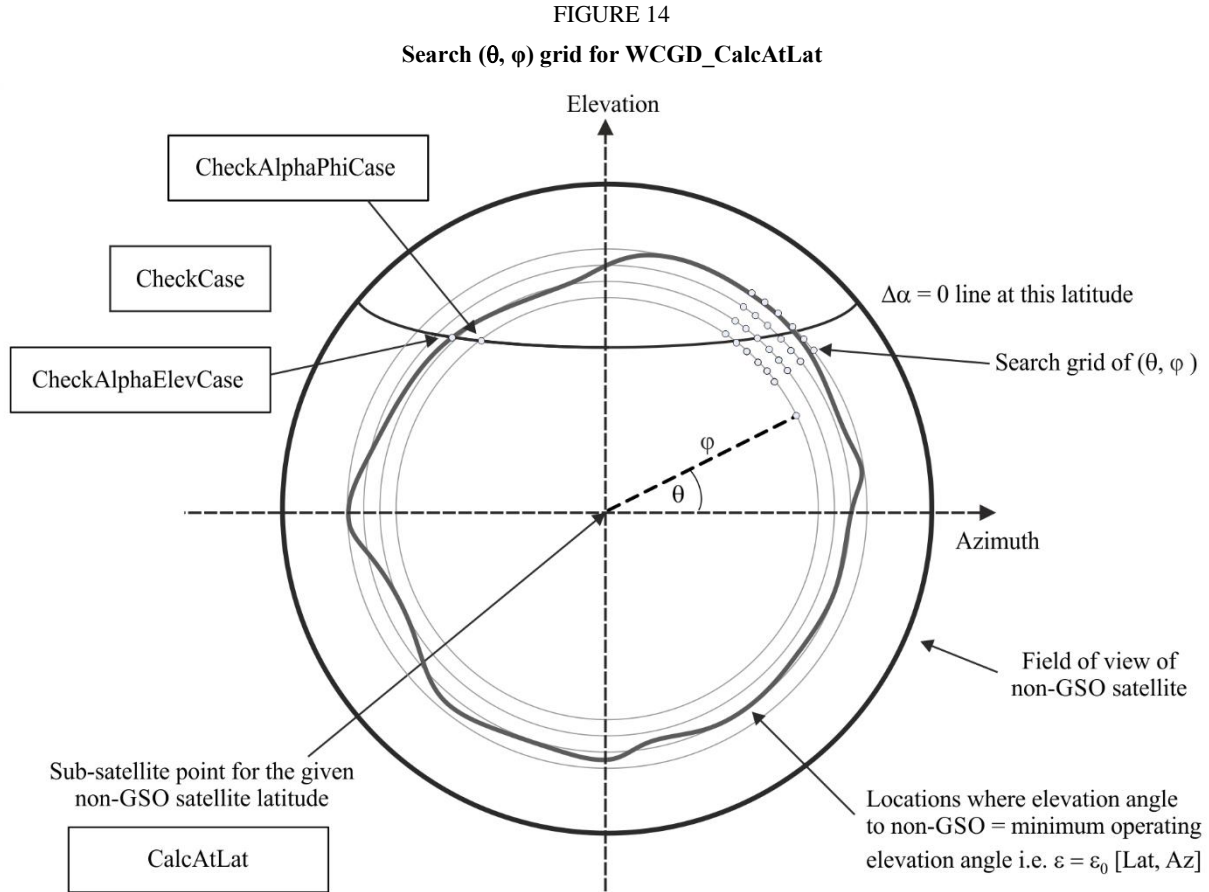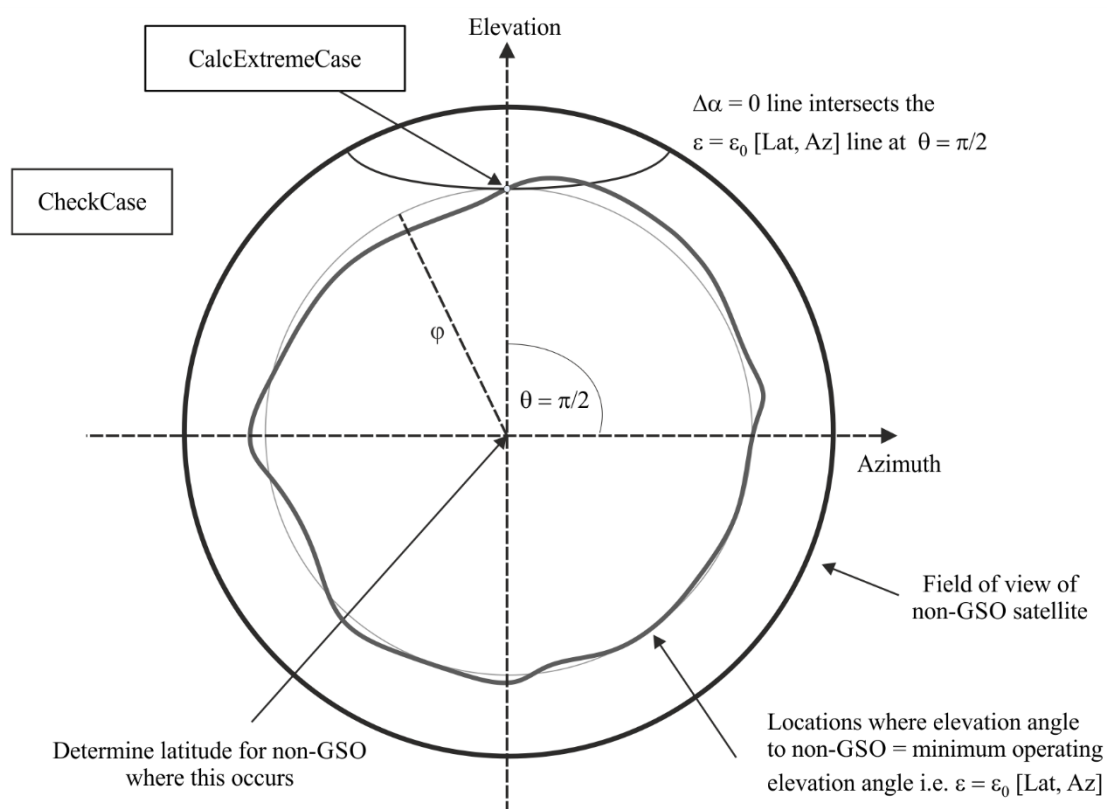$$\Delta\varepsilon = \varepsilon - \varepsilon_0[lat, az]$$

FIGURE 14

Search (θ, φ) grid for WCGD_CalcAtLat

S.1503-14

FIGURE 15

Geometry for WCGD_CheckExtremeCase

S.1503-15

The algorithm is described in the following pseudo code for specified GSO ES type:

```
WCGA_Down:
    Set WorstEPFDBin = −9999
    Set WorstAngularVelocity = +9999
    Identify ε₀,min = minimum value over all values in the ε₀[lat, az] table
    For all satellites in the order listed in ITU DB
    {
      Determine PFD mask to use for this satellite
      If this PFD mask and satellite orbit (a, e, i) combination has not been
checked so far then or this satellite uses a different α₀[lat] then
        Call GetWCGA_Down(SystemParams)
      End if
    }
    Next satellite

Note that SystemParams = (PFD_Mask, α₀[lat], ε₀[lat, az], ES, OrbitParams, ε₀,min)
as required

GetWCGA_Down (SystemParams):
    StepSize = 0.1°
    If (i = 0)
    {
      WCGD_CalcAtLat(SystemParams, latitude = 0)
    }
```

```
    Else
    {
      LatNumSteps = RoundUp(i / StepSize)
      For n = 0 to LatNumSteps inclusive
      {
          latitude = i * n / LatNumSteps
          WCGD_CalcAtLat(SystemParams, latitude)
          If (n > 0)
          {
              WCGD_CalcAtLat(SystemParams, -latitude)
          }
      }
      WCGD_CheckExtremeCase(SystemParams, 0, θ = +π/2}
      WCGD_CheckExtremeCase(SystemParams, 0, θ = −π/2}
      WCGD_CheckExtremeCase(SystemParams, +1, θ = +π/2}
      WCGD_CheckExtremeCase(SystemParams, −1, θ = −π/2}
      WCGD_CheckExtremeCase(SystemParams, +1, θ = +π/2}
      WCGD_CheckExtremeCase(SystemParams, −1, θ = −π/2}
    }
}


WCGD_CalcAtLat(SystemParams, latitude):
    Locate non-GSO satellite at latitude
    Calculate height of non-GSO satellite from its radius, r
    If height of non-GSO satellite < minimum operating height then return
    Calculate φ₀ for elevation angle ε₀, min and radius r
    WCGD_CheckCase(SystemParams, latitude, θ = 0, φ = 0)
    NumPhiSteps = RoundUp(φ₀ / StepSize)
    PhiStepSize = φ₀ / NumPhiSteps
    For φ = PhiStepSize to φ₀ inclusive in NumPhiSteps steps
    {
      ThetaMin = −π/2
      ThetaMax = +3π/2
      If the PFD mask is symmetric in DeltaLong or Azimuth and elevation table
is also symmetric between east and west
      {
          ThetaMax = π/2
      }
      NumThetaSteps = max(16, RoundUp(2πφ/PhiStepSize))
      ThetaStepSize = (ThetaMax-ThetaMin)/NumThetaSteps
      For ThetaStep = 0 to NumThetaSteps inclusive
      {
          θ = ThetaMin + ThetaStep*ThetaStepSize
          WCGD_CheckCase(SystemParams, latitude, θ, φ)
      }
      WCGD_CheckAlphaPhiCase(SystemParams, latitude, φ, 0, RHS)
      WCGD_CheckAlphaPhiCase(SystemParams, latitude, φ, +1, RHS)
      WCGD_CheckAlphaPhiCase(SystemParams, latitude, φ, −1, RHS)
      If the PFD masks is not symmetric then
      {
          WCGD_CheckAlphaPhiCase(SystemParams, latitude, φ, 0, LHS)
          WCGD_CheckAlphaPhiCase(SystemParams, latitude, φ, +1, LHS)
```

```
            WCGD_CheckAlphaPhiCase(SystemParams, latitude, φ, -1, LHS)
        }
    }
    WCGD_CheckAlphaElevCase(SystemParams, latitude, 0, RHS)
    WCGD_CheckAlphaElevCase(SystemParams, latitude, +1, RHS)
    WCGD_CheckAlphaElevCase(SystemParams, latitude, -1, RHS)
    If the PFD mask is not symmetric then
    {
      WCGD_CheckAlphaElevCase(SystemParams, latitude, 0, LHS)
      WCGD_CheckAlphaElevCase(SystemParams, latitude, +1, LHS)
      WCGD_CheckAlphaElevCase(SystemParams, latitude, -1, LHS)
    }
```

WCGD_CheckCase(SystemParams, latitude, θ, φ):

```
    Convert (θ,φ) to (az, el) in the satellite reference frame
    Create line from non-GSO satellite N in direction (az, el)
    Identify point P in which line intersects Earth
    Calculate the latitude of P, latP
    If Absolute(latP) > 81.2 degrees then exit this function
    If latP < ES_LAT_MIN then exit this function
    If latP > ES_LAT_MAX then exit this function
    If number of non-GSO satellites that operate at this latitude is zero then
exit this function
    Calculate the (aznGSO, elnGSO) of the non-GSO satellite as seen by the ES
    Find the nearest latitude to latP in the ε0[latP, AznGSO] table
    At point P calculate (α, Δlong) angles wrt point N
    At point P calculate AngularVelocity using methodology below
    Calculate PFD from mask, latitude & (az, el, α, Δlong)
    Calculate G(α) and G(α0[latP])
    Calculate the elGSO of the point on the GSO arc associated with the calculated
α
εGSO = the appropriate minimum elevation angle in Table 8
If ((α ≥ α0[latP] and elnGSO ≥ ε0[latP, AznGSO] and elGSO >= εGSO)
     or G(α) > min(Gmax -30 dB, G(α0[latP])) ) then
    {
      Calculate EPFDThreshold from latitude of point P on the Earth's surface
      Calculate EPFDMargin = PFD + Grel(α) - EPFDThreshold
      Calculate EPFDbin = EPFDMargin/BinSize
      If WorstEPFDBin < EPFDBin
      {
        WorstEPFDBin = EPFDBin
        Worst AngularVelocity = AngularVelocity
        Store this (N, P)
      }
      Else if (WorstEPFDBin = EPFDBin &&
            WorstAngularVelocity > AngularVelocity)
      {
        WorstAngularVelocity = AngularVelocity
        Store this (N, P)
      }
    }
```

```
WCGD_CheckAlphaPhiCase(SystemParams, Latitude, φ, Sign, Side):
     Set θ range according to side to check (left or right)
     If bracket δα = 0 then
     {
       Use binary search to iterate on θ until WCGD_GetDeltaAlpha(SystemParams,
Sign, θ, φ) = 0
       WCGD_CheckCase(SystemParams, latitude, θ, φ)
     }



WCGD_CheckAlphaElevCase(SystemParams, Latitude, Sign, Side):
     Set θ range according to side to check (left or right)
     If bracket δα = 0 then
     {
       Use binary search to iterate on θ until within 1e-5 radians
       {
          For each θi
          {
             Call WCGD_CalcPhiFromThetaElev(SystemParams, θi) to determine φi
             Call WCGD_GetDeltaAlpha(SystemParams, Sign, θi φi) to determine δαi
          }
       } selecting θ that brackets δα = 0
       WCGD_CheckCase(SystemParams, latitude, θ, φ)
     }

WCGD_CalcPhiFromThetaElev(SystemParams, ThetaTest, PhiMax):
     φ0 = 0
     φ1 = PhiMax
     Use binary search to iterate on φ until within 1e-5 radians
     {
       For each φi
       {
          Call WCGD_CalcDeltaElev(SystemParams, ThetaTest, φi)

       }
     } selecting φ that brackets δε = 0
     Return φ

WCGD_GetDeltaAlpha(SystemParams, Sign, θ, φ):
     Convert (θ,φ) to (az, el)
     Create line in direction (az, el) from non-GSO satellite
     Identify point P where line intersects Earth
     Calculate latitude of P, lat_P
     Determine exclusion zone size at this point, α_0[lat_P]
     At point P calculate α
     deltaA = Sign*α_0[lat_P]
     Return α - deltaA

WCGD_GetDeltaElev(SystemParams, θ,φ):
     Convert (θ,φ) to (az, el)
     Create line in direction (az, el) from non-GSO satellite
```

```
    Identify point P where line intersects Earth
    Calculate latitude of P, latP
    Calculate (aznGSO, elnGSO) of non-GSO satellite as seen by point P
    At point P calculate ε0[lat, az]
    Return elnGSO – ε0[lat, az]
```

WCGD_CheckExtremeCase(SystemParams, Signα, θ):
```
    Set latitude range according to sign (north or south hemisphere)
    If bracket δα = 0 then
    {
      Use binary search to iterate until latitude range less than 1e-5 radians
      {
        For each test latitude, Lat
        {
            Call WCGD_CalcDeltaAlphaFromLatElev(SystemParams, Lat, Sign, θi) to
determine δαi and corresponding φi
        }
      } Selecting latitudes that bracket δα = 0
      WCGD_CheckCase(SystemParams, latitude, θ, φ)
    }
```

WCGD_CalcDeltaAlphaFromLatElev(SystemParams, Latitude, Sign, θ):
```
    Set satellite at Latitude
    Get φ using WCGD_CalcPhiFromThetaElev SystemParams, θ, PhiMax)
    Calculate δα from WCGD_CalcDeltaAlpha(SystemParams, Sign, θ, φ)
    Return δα, φ
```

The algorithm uses the geometry given in the sections below.

D3.1.3 Geometry

D3.1.3.1 Conversion between (az, el) and (θ, φ)

The following equations can be used:

$$\cos(\varphi) = \cos(az)\cos(el)$$
$$\sin(el) = \sin(\theta)\sin(\varphi)$$

Note that it is necessary to check the sign of the *az* or φ to ensure that the arccos / arcsin is calculated correctly.

It should also be noted that the equations above should be used in the application of the worst-case geometry algorithm and that they are different from the equations converting (θ, φ) into (Az, El) included in § C2.3.2.

The (θ, φ) coordinate system and its relationship to the (az, el) coordinate system is shown in Figs 16 and 17 below.

FIGURE 16

Conversion between (Azimuth, Elevation) and (θ, φ) from satellite viewpoint
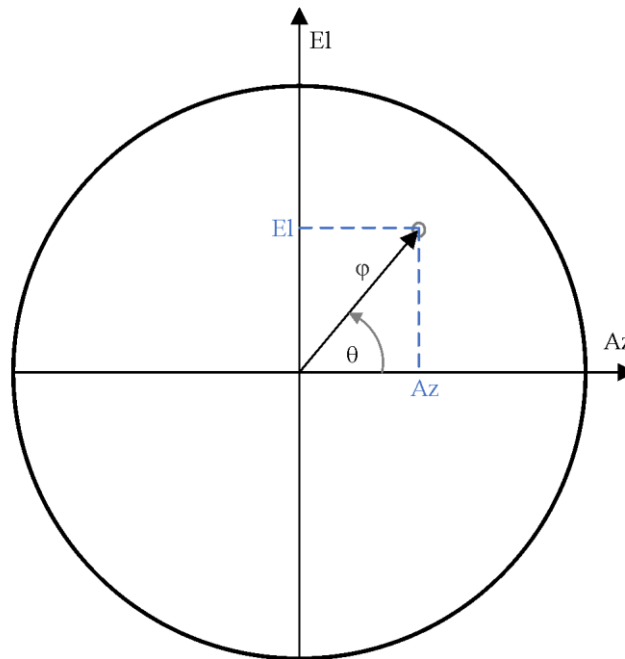
S.1503-16

FIGURE 17

Conversion between (Azimuth, Elevation) and (θ, φ) in 3D
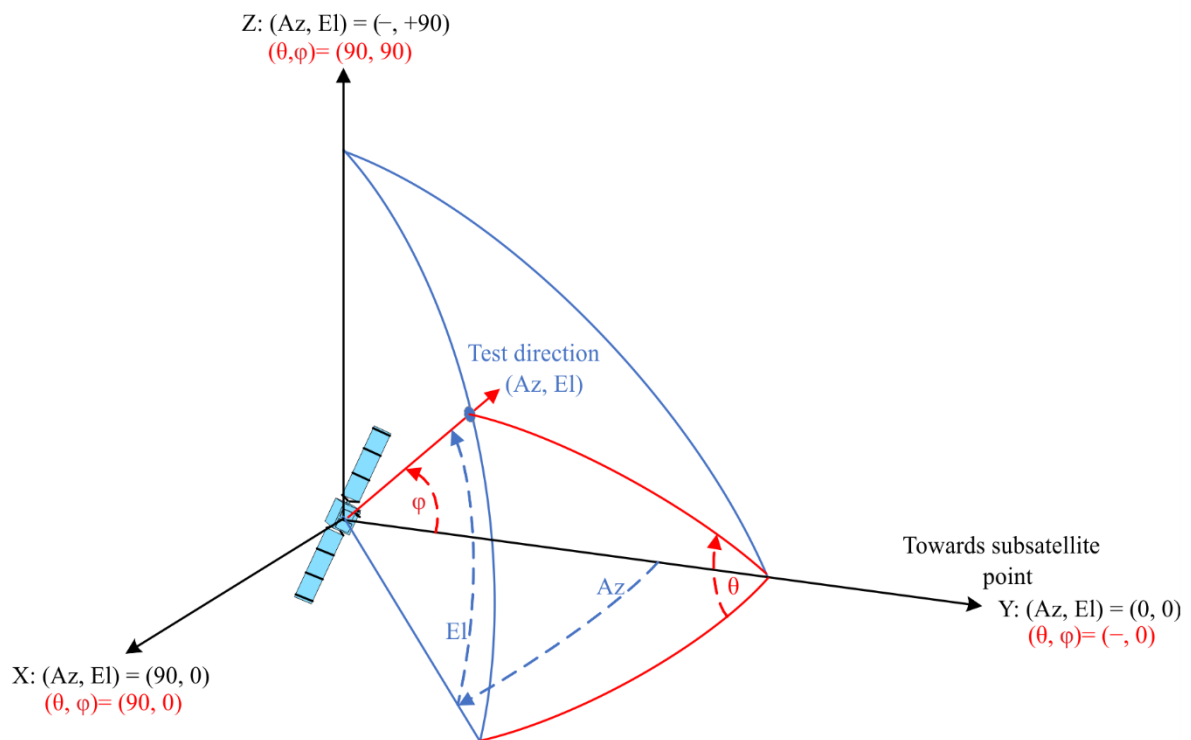
S.1503-17

The φ angle is between the two lines:

–   from the satellite to the sub-satellite point

     –   from the satellite to the test direction.

The θ angle is around the boresight in an anti-clockwise direction from the elevation = 0 plane.

D3.1.3.2 Setting satellite at latitude

Key steps in this algorithm are the calculation of the position and velocity vectors of the non-GSO satellite and ES. For circular orbit systems the latitude can be used to derive the true anomaly, ν, using:

$$\sin(\omega + \nu) = \frac{\sin lat}{\sin i}$$

For elliptical systems, it is necessary to use binary search. Assuming the system is designed to have with argument of perigee = ±π/2, then the satellite will go from minimum to maximum latitude when the mean anomaly varies from [0, π]. Therefore, the binary search can start with M = (0, π) and iterate from there.

To derive the position and velocity vectors, the following equations could be used:

In the satellite plane:

$$\underline{r}_{sat} = r_{sat}(\cos\nu\,\underline{P} + \sin\nu\,\underline{Q})$$

$$\underline{v}_{sat} = \sqrt{\frac{\mu}{p}}(-\sin\nu\,\underline{P} + (e + \cos\nu)\,\underline{Q})$$

where:

       P, Q: unit vectors in the orbit plane with origin the centre of the Earth and P aligned with the orbit's major axis as described in § D6.3.3

       a, e, ν: orbital elements.

Also:

$$r_{sat} = \frac{p}{1+e\cos\nu}$$

$$p = a(1 - e^2)$$

The non-GSO's position and velocity vectors can then be converted from the PQW orbit plane based frame to Earth centred vectors using the standard rotation matrix via the (Ω, ω, i) orbital elements. For the WCG calculation it can be assumed that second order effects including the J_2 factor need not be considered.

The position vector equation can also be used to calculate a latitude from a true anomaly, ν, and hence by iteration locate the satellite at the required latitude.

D3.1.3.3 Calculation of maximum φ in satellite viewpoint

For a given latitude and hence satellite radius, the maximum angle at the satellite from sub-satellite point φ_0 can be derived from the elevation angle ε using:

$$\sin(\varphi_0) = \frac{R_e}{r_{sat}}\sin\left(\frac{\pi}{2} + \varepsilon\right)$$

D3.1.3.4 Calculation of angular velocity

The inputs are as follows:

       ES position vector: $\underline{r}_{es}$

       ES velocity vector: $\underline{v}_{es}$

       Non-GSO satellite position vector: $\underline{r}_{sat}$

Non-GSO satellite velocity vector: $\underline{v}_{sat}$

From these, it is possible to calculate the apparent velocity and vector from the ES to the satellite:

$$\underline{r} = \underline{r}_{sat} - \underline{r}_{es}$$

$$\underline{v} = \underline{v}_{sat} - \underline{v}_{es}$$

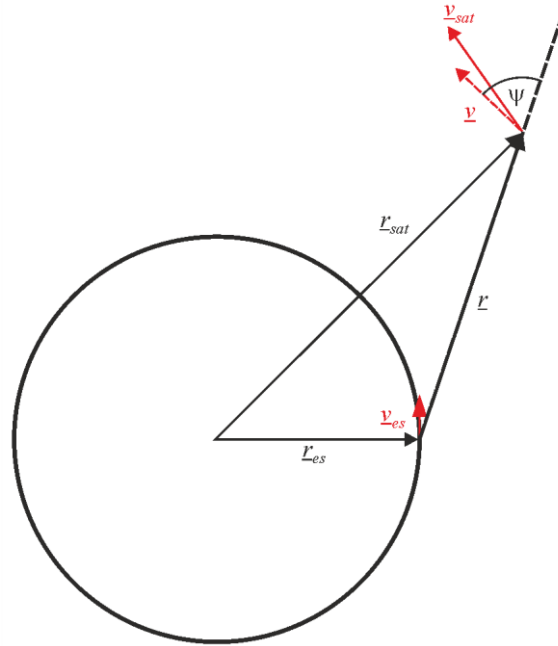The angle between these two vectors can then be calculated:

$$\cos \psi = \frac{r \cdot v}{rv}$$

The instantaneous angular velocity is then:

$$\theta = \frac{v}{r} \sin \psi$$

The various terms are shown in Fig. 18.

FIGURE 18

Vectors to calculate non-GSO satellite apparent angular velocity

S.1503-18

Note that a low angular velocity will result in higher likelihoods of interference and hence for a given epfd value the WCG that gives the least apparent angular velocity would be the one to use.

The ES's velocity vector can be derived from its position vector (x, y, z) as follows:

$$\underline{v}_{es} = w_e \begin{pmatrix} -y \\ x \\ 0 \end{pmatrix}$$

where w_e is the Earth's angular velocity in radians per second.

D3.2 WCG epfd↑

Note that as the epfd limits in Article **22** are for 100% of the time there is no need to consider the likelihood of particular geometries, only the maximum epfd(up) value.

If there are multiple sub-constellations with alternative orbital elements or some satellites use different exclusion zone angles, then the process should be repeated for each unique set.

D3.2.1 Inputs

The inputs to the algorithm are as follows:

ES_e.i.r.p.:   the non-GSO ES e.i.r.p. mask to check. This could vary by latitude, with each latitude range having an e.i.r.p. pattern, defined as a table of e.i.r.p. vs off-axis angle towards the GSO arc or by latitude, azimuth and elevation, with each latitude/azimuth/elevation having an e.i.r.p pattern defined as a table of e.i.r.p. against difference in longitude between the ES and GSO satellite

θ_{adB} :   the GSO satellite's beam half power beamwidth

$\varepsilon_{0,GSO}$:   the minimum elevation angle of the GSO system

$\varepsilon_0[lat, az]$:   the minimum elevation angle of the non-GSO system, which could vary by latitude and azimuth

$\alpha_0[lat]$:   the minimum exclusion angle of the non-GSO system, which could vary by latitude and non-GSO satellite

$N_{co}[lat]$:   the number of non-GSO satellites that can provide co-frequency service at a specific location on the Earth's surface, which could vary by latitude

ES_DISTANCE, ES_DENSITY :   the average distance on the Earth's surface between co-frequency beams from the non-GSO system (km) and density of co-frequency non-GSO ES or:

ES(lat, long) :   the latitude and longitude of the specific ES of the non-GSO system

$\{a,i,e, \Omega,\omega,\nu\}$:   the orbit parameters of the non-GSO system including whether the system's ground track repeats and if so the repeat time.

D3.2.2 GSO system parameters

It is assumed that the GSO system's minimum operating elevation angle and beamwidth are as in Table 8.

TABLE 8

WCG(up) GSO system parameters

Frequency band	$f < 10$ **GHz**	10 **GHz** $\leq f <$ 17 **GHz**	$f \geq 17$ **GHz**
Beamwidth (degrees)	1.5	4	1.55
Minimum elevation angle (degrees) ε_{EOC}	10	10	20

Table 9 shows the geocentric angle that corresponds to the minimum elevation angle and hence the maximum angle at the GSO satellite towards the beam boresight φ_{BS}:

TABLE 9

WCG(up) derived minimum and maximum values

Frequency band	$f < 10$ **GHz**	10 **GHz** $\leq f <$ 17 **GHz**	$f \geq 17$ **GHz**
φ_{EOC} at GSO satellite (degrees)	8.567	8.567	8.172

Frequency band	$f < 10$ GHz	10 GHz $\leq f <$ 17 GHz	$f \geq 17$ GHz
φ_{BS} at GSO satellite (degrees)	7.817	6.567	7.397
Geocentric angle χ for φ_{BS} (degrees)	56.230	42.552	50.934

These were generated using the geometry in Fig. 19 and the following equations.

FIGURE 19

GSO pointing angles for WCGA(UP) geometry
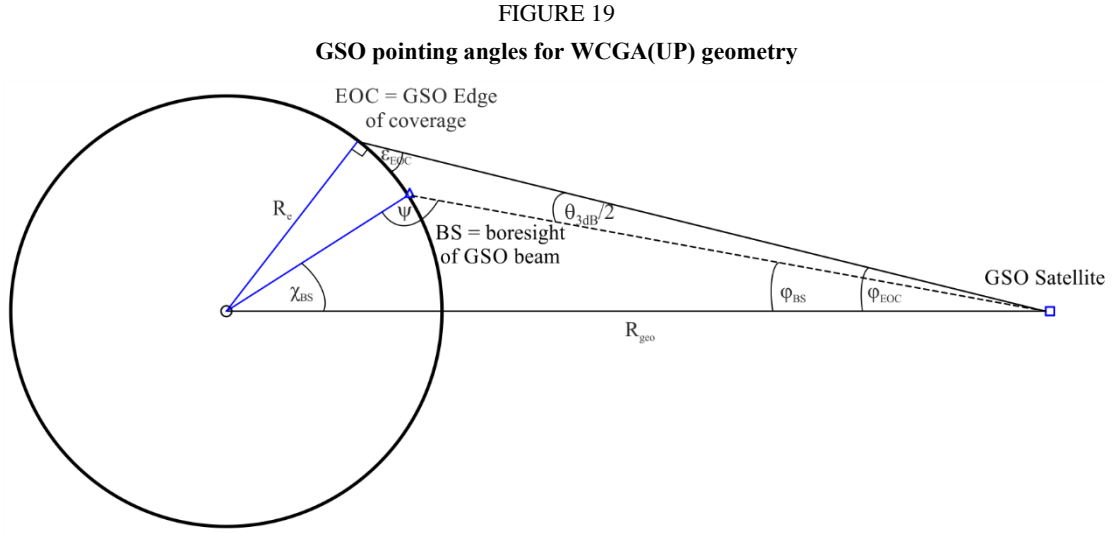
S.1503-19

Here the φ_{BS} can be derived as follows:

$$\sin\varphi_{EOC} = \frac{R_e}{R_{geo}} \sin\left(\frac{\pi}{2} + \varepsilon\right)$$

$$\varphi_{BS} = \varphi_{EOC} - \frac{\theta_{3dB}}{2}$$

Then, noting that as $\psi > \pi/2$:

$$\sin(\pi - \psi) = \frac{R_{geo}}{R_e} \sin(\varphi_{BS})$$

Hence:

$$\chi_{BS} = \pi - \varphi_{BS} - \psi$$

D3.2.3   Algorithm

The WCGA for the epfd(up) case is as follows:

```
WCGA_UP:
   Calculate φBS from εEOC
   From φBS calculate χBS
   If ES from density
      Call WCGA_UP_General
   Else
      If non-GSO satellite repeats
         Call WCGA_UP_SpecifcES_Repeating
      Else
         Call WCGA_UP_SpecifcES_NonRepeating
```

```
        Endif
    Endif
```

The various cases, their functions and geometries are described in the following sections.

D3.2.3.1 Aggregate epfd calculation

In the general case the aggregate epfd(up) can be calculated using:

$$epfd(up) = \sum_{i=1}^{i=N_{ES}} e.i.r.p.(lat) - L_S + G_{rel,rx} + 10\log_{10}(NUM_{ES}) + 10\log_{10}\left(N_{co,ES}(lat)\right)$$

Note the summation is in absolute though the equation is given in dB terms with addition and where:

e.i.r.p. *(lat)* : e.i.r.p. towards the GSO for the given non-GSO ES latitude either as a function of latitude and off-axis angle towards the GSO arc or function of latitude, boresight (azimuth, elevation) and difference in longitude between the non-GSO ES and GSO satellite

L_S : spreading factor

Grel,rx : relative gain at the GSO satellite using the Rec. ITU-R S.672 gain pattern

NUM_ES : is a factor for systems using density rather than specific ES (and which typically relates to the access method) derived from the non-GSO system's density and distance fields as given in § D5.2.5

NUM_ES = ES_DISTANCE * ES_DISTANCE * ES_DENSITY

$N_{co,ES}(lat)$: maximum number of co-frequency non-GSO ES that can transmit at a given location.

The summation is over the N_{ES} non-GSO deployed within the GSO satellites 15 dB beamwidth footprint using the algorithm in § D5.2.5. This depends upon the separation distance between co-frequency beams which is a parameter provided by the non-GSO system.

For the WCG(up) calculation, it is assumed that the aggregate epfd is dominated by the single entry epfd at the boresight plus an aggregation factor and so this can be estimated by extracting the non-GSO parameters from the summation as in:

$$epfd(up) \cong e.i.r.p.(lat) + 10\log_{10}(NUM_{ES}) + +10\log_{10}\left(N_{co,ES}(lat)\right) + \sum_{i=1}^{i=N_{ES}} G_{rel,rx} - L_S$$

This last term is only dependent upon the geometry (in particular the geocentric angle, χ) and the gain pattern in Recommendation ITU-R S.672 but not upon any of the non-GSO parameters and hence can be pre-computed.

$$\left(\frac{D_{ES}}{100}\right)^2 F_{672}(x) = \sum_{i=1}^{i=N_{ES}} G_{rel,rx} - L_S$$

A method to calculate based upon an assumed non-GSO ES separation distance ES_DISTANCE = D_{ES} = 100 km is via the following Pade approximation:

$$y = a + \frac{bx + cx^2 + dx^3 + ex^4 + fx^5}{1 + gx + hx^2}$$

where:

TABLE 10

F$_{672}$ Pade approximation parameters

Parameter	Beamwidth = 4°	Beamwidth = 1.55° $x < 35°$	Beamwidth = 1.55° $x > 35°$	Beamwidth = 1.5°
a	−133.536851	−133.323814	−133.323814	−142.1952459
b	0.001384021	0.017909858	0.02314611	−0.001235207
c	0.000637798	−0.011981864	−0.001336397	0.00121213
d	6.9531E-07	0.002350044	2.26511E-05	−4.77102E-05
e	−1.94494E-07	−4.61428E-05	−6.95017E-08	6.5926E-07
f	1.41944E-09	−3.30E-07	−7.75011E-10	−2.83069E-09
g	−0.033027982	−0.408584467	−0.036720978	−0.033787173
h	0.000434998	0.054553642	0.000370144	0.000306156

For the specific ES case the D_{ES} is not defined and so a value of 100 should be used while NUM_ES set to 1 so this term does not contribute.

Given the F$_{672}$ factor, the epfd(up) for a given geometry can be estimated using:

$$epdf(up) \cong e.i.r.p.(lat) + 10\log_{10}(NUM_{ES}) + +10\log_{10}\left(N_{co,ES}(lat)\right) + \left(\frac{D_{ES}}{100}\right)^2 F_{672}(\chi)$$

D3.2.3.2   Worst pointing

The epfd calculation above relies on the ability to calculate the maximum e.i.r.p. towards the GSO. As well as the e.i.r.p. mask, this will depend upon a number of additional factors including:

–   Latitude of the non-GSO ES

–   Minimum elevation angle(s) at that latitude ε$_0$[*az*, *lat*]

–   Exclusion zone size α$_0$[*lat*]

–   Constellation (or sub-constellation) orbit parameters.

The influence of some of the factors can be seen in the examples below assuming the non-GSO ES is in the northern hemisphere so that the centre of the Figure is pointing south.

Equatorial orbit, low latitude

FIGURE 20

Equatorial orbit low latitude
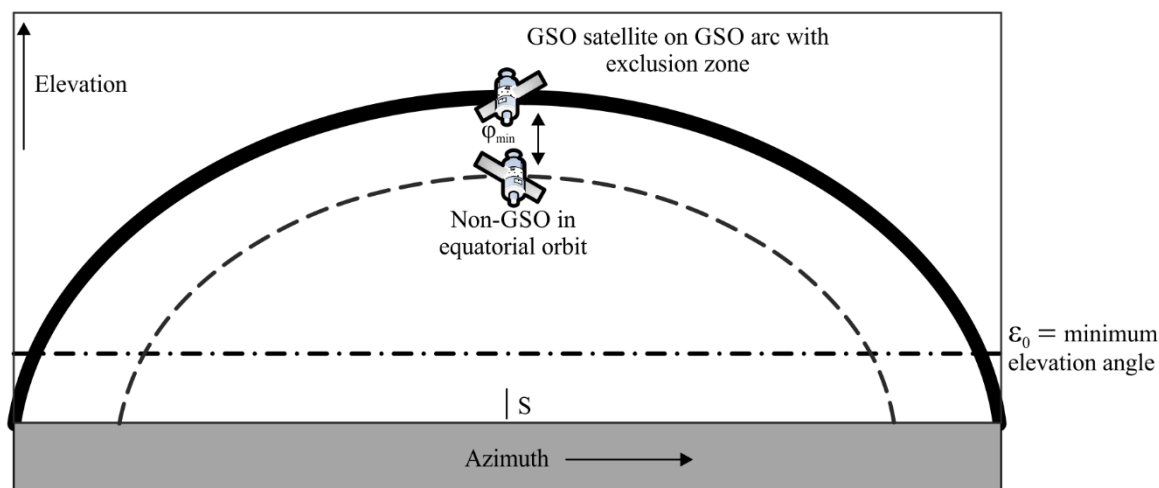
S.1503-20

Here the non-GSO satellite never intersects the GSO orbit or the exclusion zone and so the φ_{min} is the angle at the non-GSO ES between the equatorial orbit and GSO arc in the azimuth of consideration.

Note that a purely equatorial orbit would be repeating so would be handled by a separate case within the WCG. However it is included to show the edge case and gain an understanding of the geometry involved.

Equatorial orbit, high latitude

FIGURE 21

Equatorial orbit high latitude
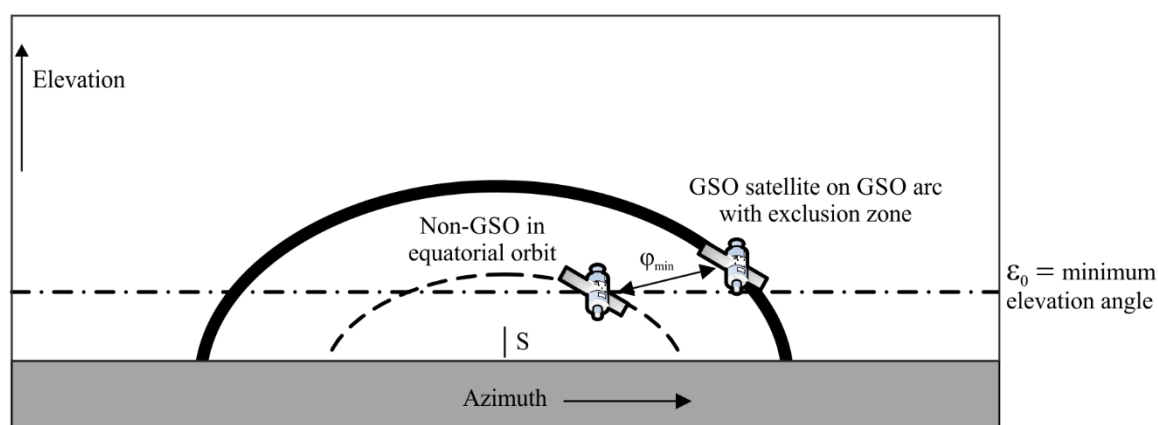
S.1503-21

Here again the non-GSO satellite orbit never intersects the GSO orbit or exclusion zone but for the azimuth of the GSO satellite the non-GSO satellite would not be active as it is below the minimum elevation angle. Hence the φ_{min} is between the nearest azimuth for which the non-GSO satellite would be above the horizon. However this point would be considered as the applicable point for another position on the GSO satellite where the minimum off-axis angle would be smaller and hence e.i.r.p.

larger. It is therefore suggested that if the non-GSO satellite is below the minimum elevation angle for that azimuth it need not be considered.

Polar orbit, low latitude

FIGURE 22

Polar orbit low latitude
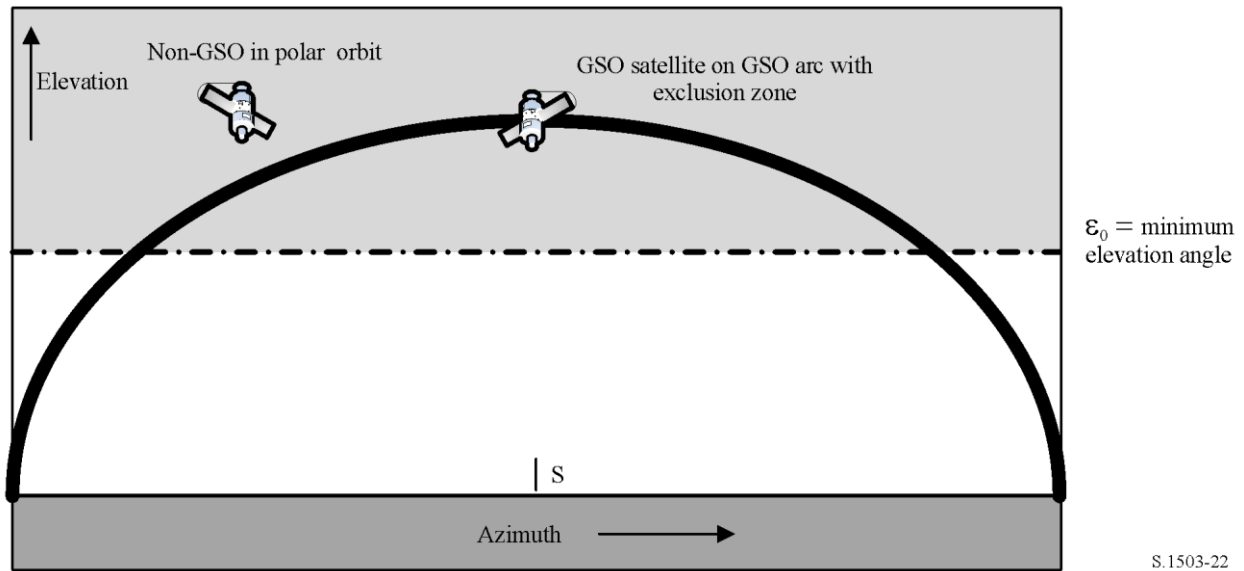
S.1503-22

In this case the polar orbiting satellite could be located at any pointing angle (*az*, *el*) as seen by the non-GSO ES. The limiting case is then the edge of the exclusion zone, so that $\varphi_{min} = \alpha_0[lat]$.

Polar orbit, high latitude

FIGURE 23

Polar orbit high latitude
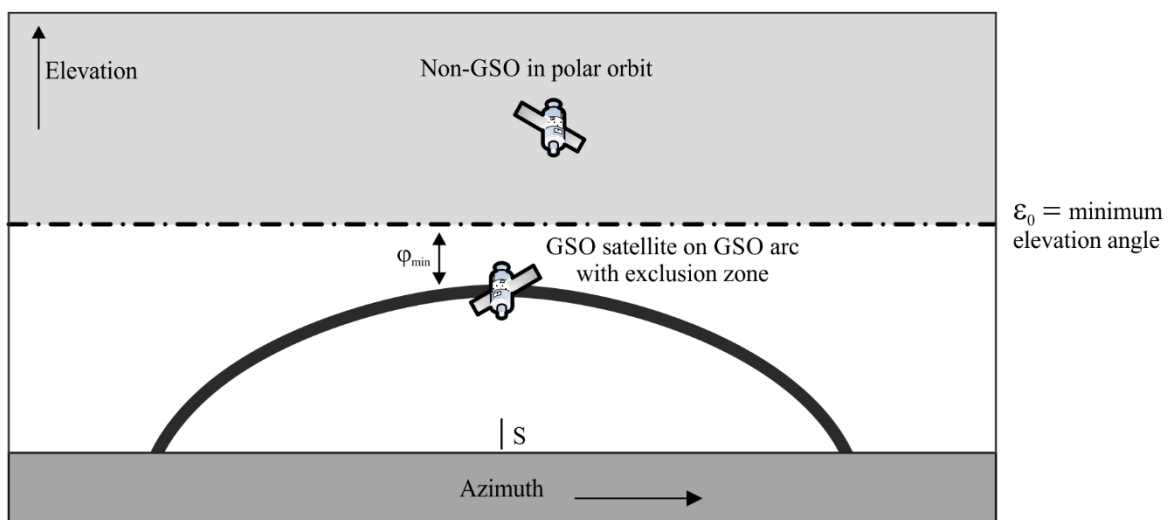
S.1503-23

In this case the GSO arc is always below the minimum elevation angle and hence the minimum off-axis angle φ_{min} is the difference between the minimum elevation angle and elevation angle of the GSO arc in the azimuth / latitude of interest.

Note this also the case for the previous scenario (polar orbit, low latitude) for the extreme edge case where the GSO arc has a low elevation angle as seen by the non-GSO ES.

Low inclination, no in-line geometry

FIGURE 24

Low inclination, no in-line geometry
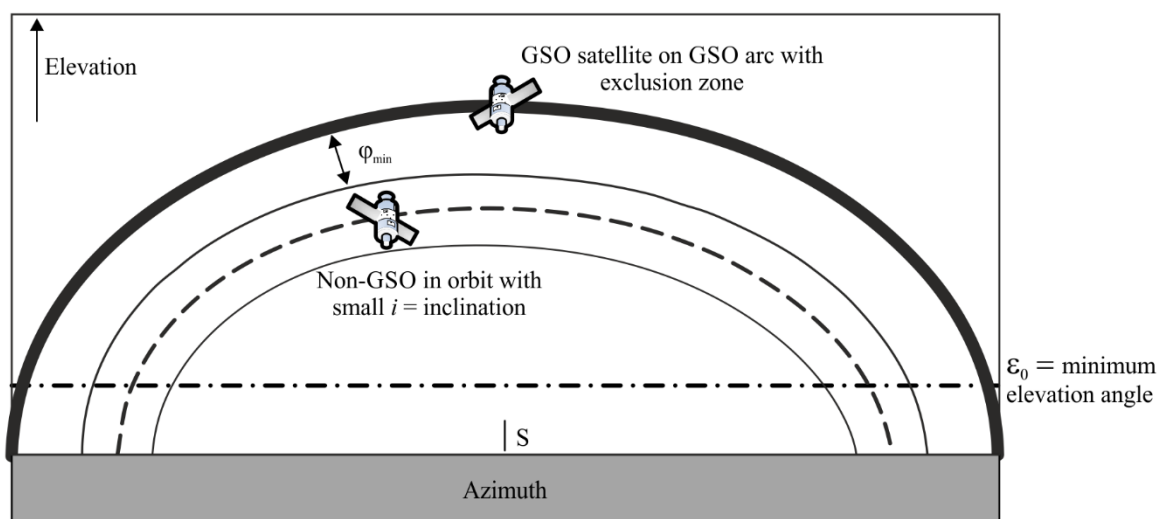
S.1503-24

This example is similar to the equatorial case in that there is no in-line geometry, and hence the φ_{min} angle to use is the angular separation between the edge of the visible zone and GSO arc or the exclusion zone angle $\alpha_0[lat]$, whichever is larger.

Low inclination with in-line geometry

FIGURE 25

Low inclination with in-line geometry
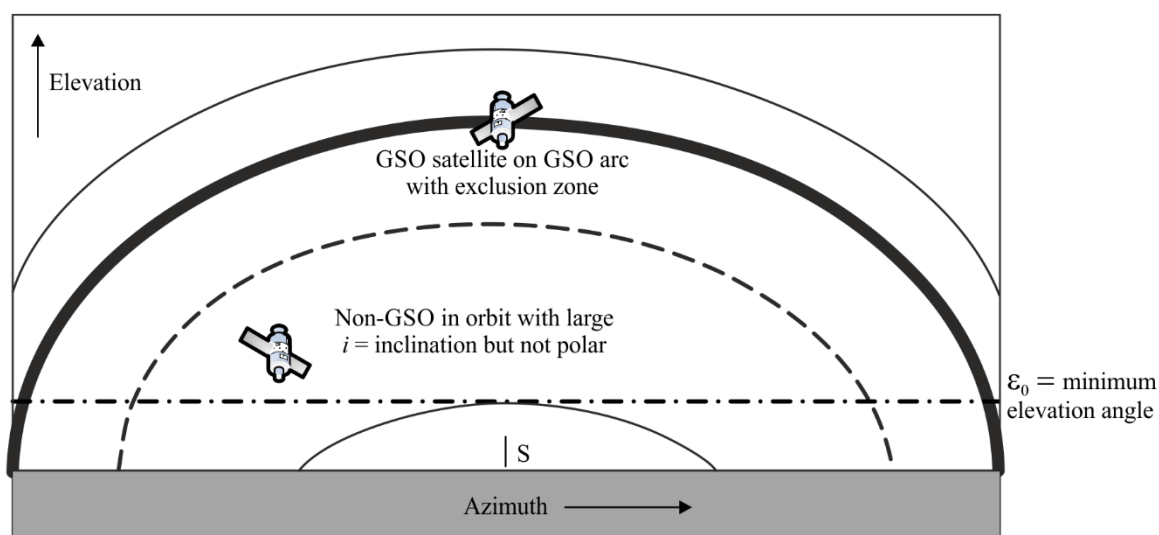
S.1503-25

This is an extension of the previous case with the inclination increased until the visible zone spreads either side of the GSO arc. The minimum off-axis angle is then the exclusion zone size so that $\varphi_{min} = \alpha_0[lat]$.

General case

The geometry of the general case is shown in Fig. 26.

FIGURE 26

General case with orbit shell
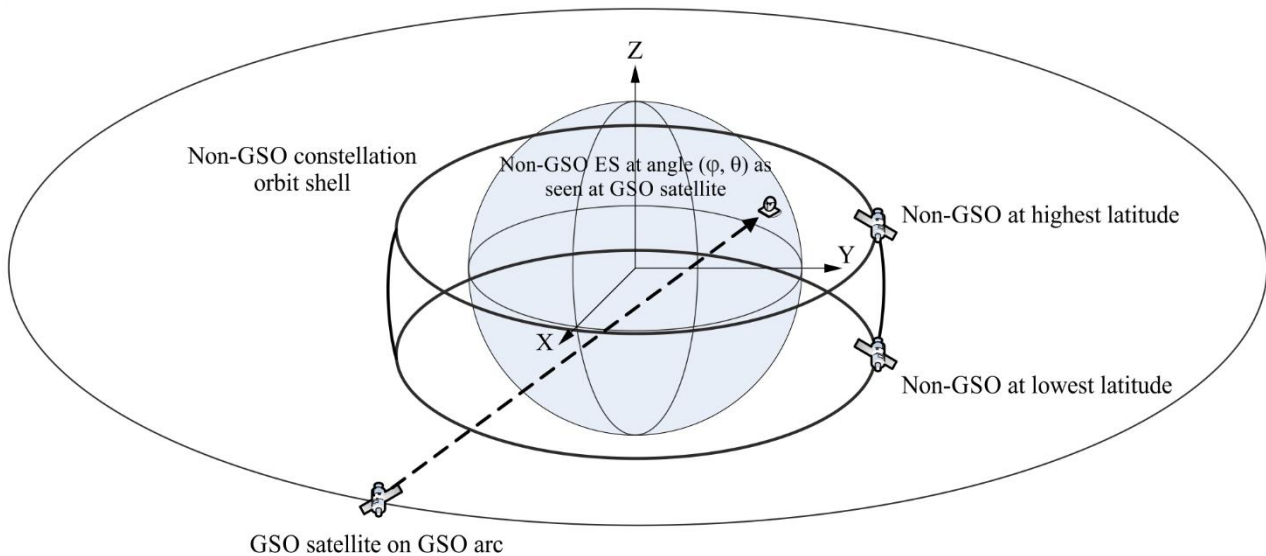
S.1503-26

The general method iterates over the field of view of the GSO satellite and determines the associated ES location.

For non-GSO systems with non-repeating orbits, the result will be the same for all longitudes of the GSO system, and hence a GSO longitude = 0° can be used.

For non-GSO systems with repeating orbit, an initial run should be undertaken and the average longitude of each of the non-GSO satellites calculated over the repeat period together with the likelihood of the non-GSO satellite being within 1 degree of that average longitude. The GSO satellite should be located at the average longitude of the non-GSO satellite with the highest likelihood of being within 1 degree of that satellite's average longitude.

Then given:

–   GSO satellite longitude

–   Non-GSO ES φ (latitude, longitude)

–   Maximum or minimum latitude of the non-GSO satellite

–   Radius of the non-GSO satellite when at the maximum/minimum latitude.

It is then possible to iterate on the longitude of the non-GSO satellite which minimises the angle to the GSO satellite as seen at the ES. This is the converse of the α angle and hence is called the β angle. This can be derived using iteration or the analytic method as described in § D6.4.4.4. There will be two positions, the β_+ associated with the maximum latitude and the β_- associated with the minimum latitude of the non-GSO system.

It is also possible to determine points that are in the direction of the β_+ and β_- points with angle α_0 from the GSO satellite as in Figs 27, 28 and 29. This results in points $\{a, b, c, d\}$ that can then be checked to see if they are valid, in particular that:

–   They are at least α_0 away from the GSO satellite (arc)

–   They are within the $[\beta_+, \beta_-]$ range of the non-GSO satellite as seen by the ES

–   They are above the minimum non-GSO elevation angle for the non-GSO ES latitude and azimuth of the test point.

If they are valid then they can be considered as possible options for the minimum off-axis angle towards the GSO satellite at the non-GSO ES when pointing at a non-GSO satellite.

FIGURE 27

WCG(up) general case when [β_+, β_-] bracket the GSO arc
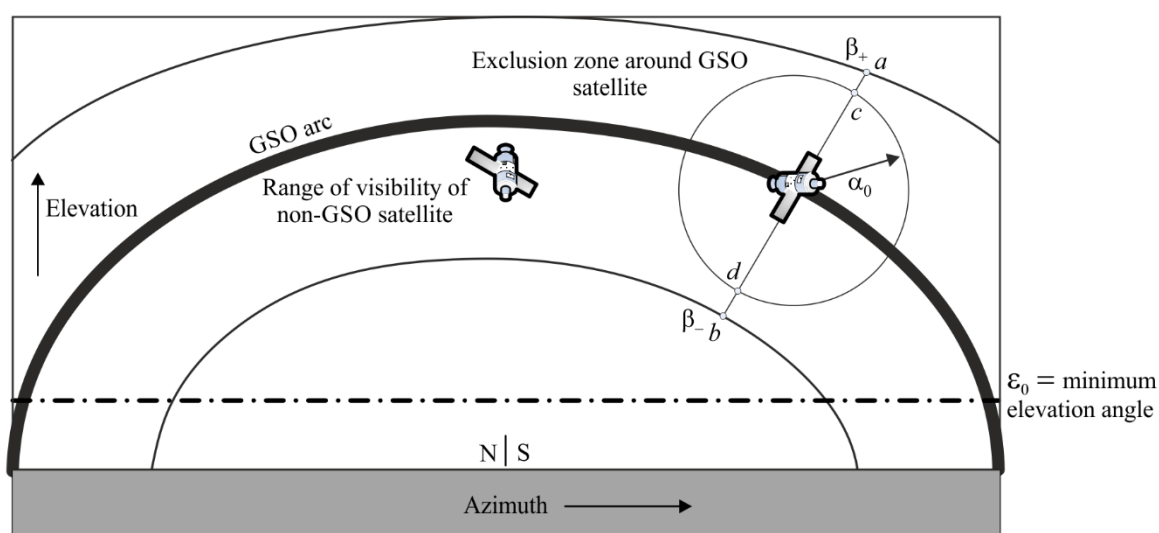
S.1503-27

FIGURE 28

WCG(up) general case when [β_+, β_-] do not bracket the GSO arc or intersect minimum α
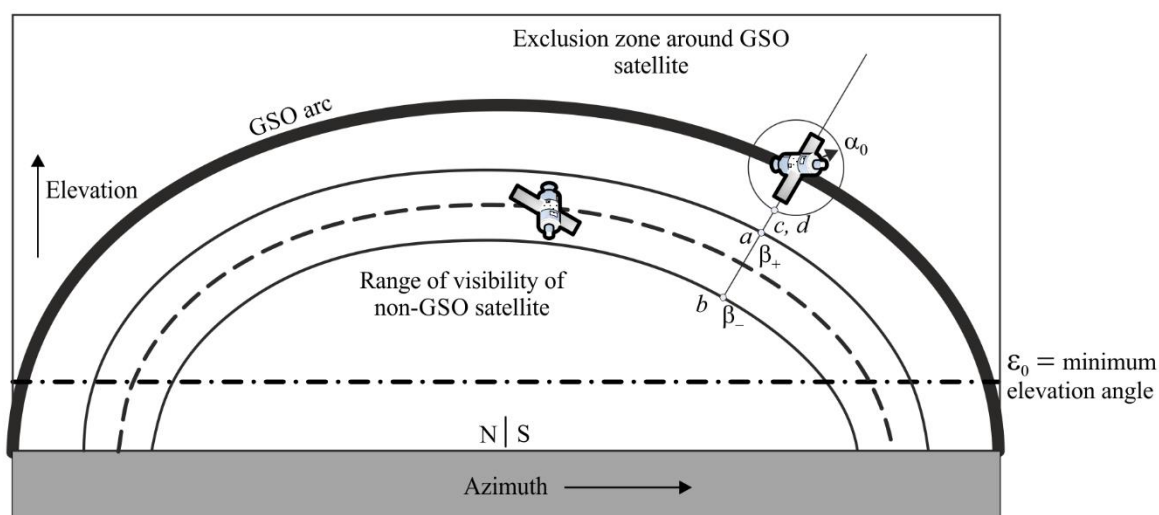
S.1503-28

FIGURE 29

WCG(up) general case when [β+, β-] do not bracket the GSO arc but does intersect minimum α
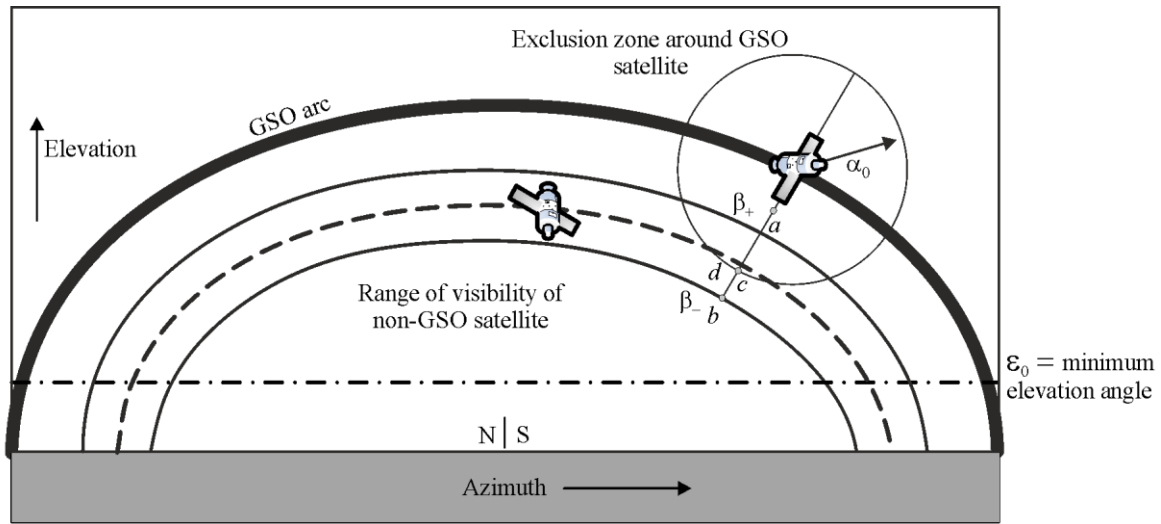
S.1503-29

There is also a fifth test point {e} to handle the case when the GSO arc is below the minimum elevation angle as shown in Fig. 30.

FIGURE 30

WCG(up) general case when [β+, β-] bracket the GSO arc but it is below the minimum elevation angle
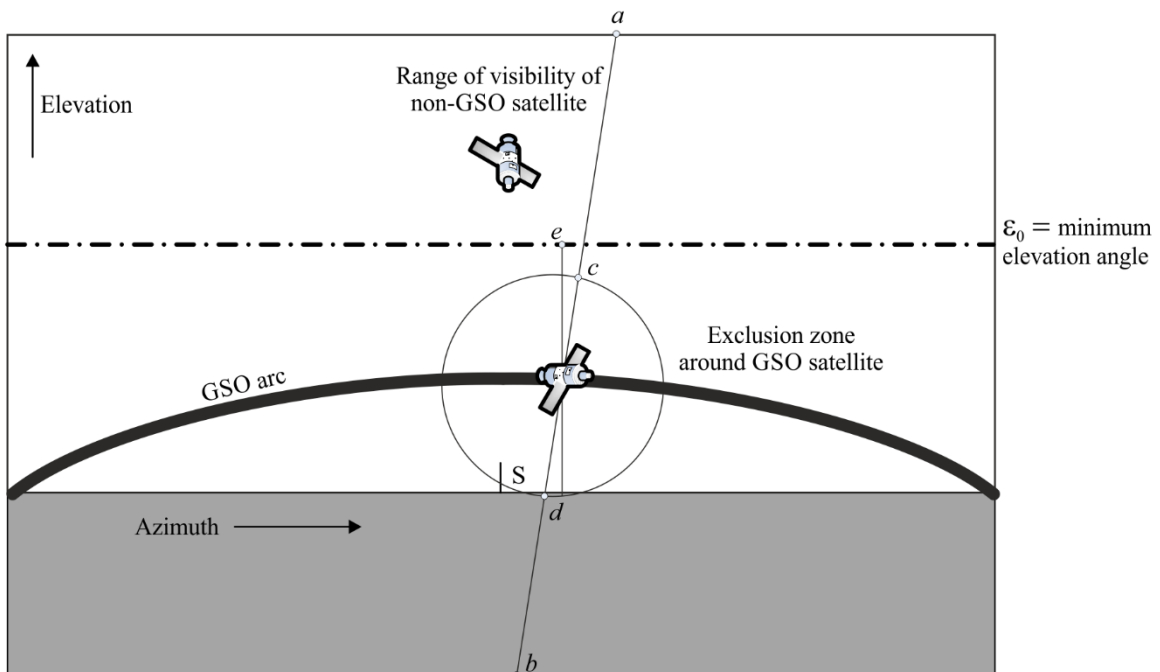
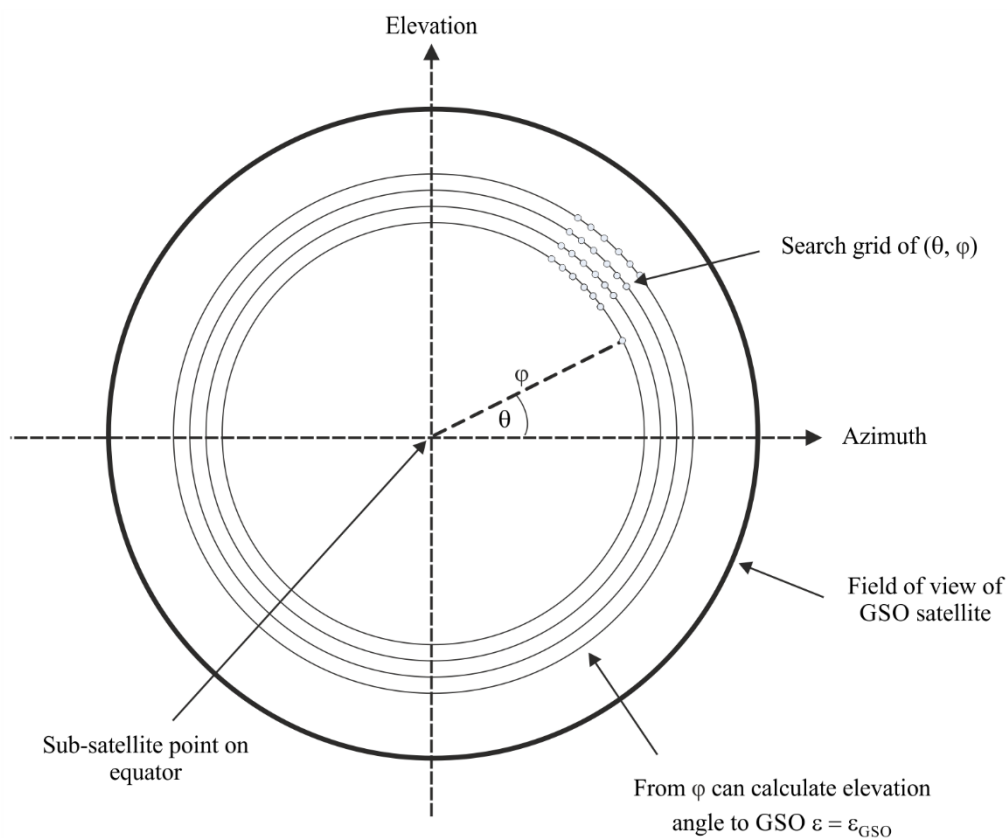S.1503-30

D3.2.3.3 WCG_Up_General

The general case iterates over the field of view of the victim GSO satellite as shown in Fig. 31.

FIGURE 31
Search of GSO satellite field of view

S.1503-31

The search is undertaken in (θ, φ) as described below:

WCGA_UP_General:
```
     CheckCaseUpGeneral(0, 0)
     NumberOfPhiSteps = Integer(Degrees(φ₀)/ 0.1)
     For PhiStep = 1 to NumberOfPhiSteps inclusive
        φ = φ₀ * PhiStep / NumberOfPhiSteps
        ThetaStepSizeDegrees = 0.1 * φ₀ / φ
        NumberOfThetaSteps = max(16, Integer(360 /  ThetaStepSizeDegrees))
        For ThetaStep = 0 to NumberOfThetaSteps-1 inclusive
           θ = radians(ThetaStepSizeDegrees * ThetaStep)
           CheckCaseUpGeneral(θ, φ)
        Next ThetaStep
     Next PhiStep
```

CheckCaseUpGeneral(θ, φ):
```
     Convert (θ, φ) to (az, el) at a GSO satellite set at longitude = 0
     Use (az, el) to create line from the GSO satellite
     Calculate the intersection point of that line and the spherical Earth
```

```
Calculate the (lat, long) of the non-GSO ES at the intersection point
Check that the latitude is in the range of the non-GSO system i.e between
ES_LAT_MIN and ES_LAT_MAX
Check that the N_co(lat) > 0
If the latitude is ok then
    If the non-GSO system uses a repeating orbit then
    {
        Call WCGA_UP_SpecifcES_Repeating
        Return
    }
    For this (lat, long) calculate the geocentric angle χ
    For the GSO system's beamwidth, calculate the F₆₇₂(χ)
    If the e.i.r.p. mask is defined by offaxis angle then
    {
        Call CalcMinOffaxisAngle to calculate φ for this location
        If find a minimum offaxis angle then calculate the epfd(up) using:
```

$$epfd(up) = e.i.r.p.(lat, \varphi) + 10\log_{10}(NUM\_ES) + 10\log_{10}\big(N_{co}(lat)\big) + \left(\frac{D_{ES}}{100}\right)^2 F_{672}(\chi)$$

```
        If this is the highest epfd(up) then store this value and (θ, φ)
    }
    Else the ES e.i.r.p. mask is defined by (az, el, DeltaLongES) then
    {

        Call  CalcES_e.i.r.p.(Non-GSO  ES  lat,  long)  to  calculate
e.i.r.p.(lat) for this location
        Calculate the epfd(up) using:
```

$$epfd(up) = e.i.r.p.(lat) + 10log_{10}(NUM\_ES) + 10log_{10}\big(N_{co}(lat)\big) + \left(\frac{D_{ES}}{100}\right)^2 F_{672}(\chi)$$

```
        If this is the highest epfd(up) then store this value and (θ, φ)

Endif
Endif
```

Note that the method to calculate the maximum latitude of the non-GSO system is given in § D3.2.3.6.

```
CalcES_e.i.r.p.(non-GSO ES lat, long)
    Calculate the DeltaLongES
    Create a vector r_ES of the non-GSO ES
    Set Maxe.i.r.p. = -9999
    Identify the ES_e.i.r.p. table for this non-GSO latitude
    Set StepSizeDeg = 0.5
    Set NumAz = 1 + integer(360 degrees / StepSizeDeg)
    Set NumEl = 1 + integer(90 degrees / StepSizeDeg)
    For all az_i = 0 to NumAz not inclusive
        Az = -180 + az_i * 360 / NumAz
```

```
        For all el_i = 0 to NumEl inclusive

            El = 0 + el_i * 90 / NumEl

            Create a vector razel in direction (az, el)

            Select the appropriate es e.i.r.p. (az, el) array

            If the (az, el) direction is outside the exclusion zone and above
the minimum elevation for this azimuth and there could be a satellite in this
direction then

            {

                Calculate the ES_e.i.r.p.az,el towards the GSO for this (az, el,
DeltaLong)

                If ES_e.i.r.p.az,el is greater than ES_e.i.r.p. then use this value
instead

            }

        Next el_i

    Next az_i
```

To determine if there could be a non-GSO satellite in a given (az, el) direction from a non-GSO ES at position r_{ES}, the following algorithm can be used, assuming that the vectors r_{ES} and r_{azel} are in Earth centred coordinates (x, y, z):

Inputs:

Non-GSO ES position vector $= r_{ES}$

Vector in direction (az, el) $= r_{azel}$

non-GSO satellite orbit inclination angle $= i$

non-GSO satellite semi-major axis $= a$

non-GSO satellite eccentricity $= e$

If the non-GSO satellite eccentricity $= 0$ (i.e. circular orbit):

There could be a satellite in direction (az, el) if

$-i \le \text{Latitude}(a) \le +i$

Otherwise, if the non-GSO satellite eccentricity > 0 (i.e. elliptical orbit):

There could be a satellite in direction (az, el) if the following are both true:

$-i \le \text{Latitude}(a(1+e)) \le +i$

$-i \le \text{Latitude}(a(1-e)) \le +i$

Where the function CalcLatitude(d) is:

Create a line from the non-GSO ES in direction (az, el) using parameter λ:

$$r = r_{ES} + \lambda r_{azel}$$

The value of λ for which the line is at distance d from the centre of the Earth can be calculated by solving the quadratic equation:

$$r_{azel}^2 \lambda^2 + 2(r_{ES} \cdot r_{azel})\lambda + r_{ES}^2 - d^2 = 0$$

The root for which $\lambda > 0$ should be used to calculate the position vector r.

From this the latitude can be calculated using:

$$\text{Latitude}(d) = \text{asin}(r.z \, / \, r)$$

```
CalcMinOffaxisAngle(non-GSO ES lat, long)
```

> Calculate the (az_{GSO}, ε_{GSO}) of the GSO satellite as seen by the non-GSO ES
>
> Determine the radius $R_{n,+}$ of the non-GSO satellite when its *lat = +i*
>
> Determine the radius $R_{n,-}$ of the non-GSO satellite when its *lat = -i*
>
> If $R_{n,+}$ or $R_{n,-}$ are below the minimum operating height then determine the latitude of the non-GSO satellite when at this height and use this instead
>
> For each of {$R_{n,+}$, $R_{n,+}$} and {lat_+, lat_-}, calculated the {β_+, β_-} angles and associated non-GSO satellite positions identified as (a, b) in Figs. 27-29
>
> For each of the {β_+, β_-} positions, use spherical geometry to derive points (c, d) which have angle at the ES of α_0 along the lines to point (a, b) respectively
>
> For each of (a, b, c, d) points, calculate the (azimuth, elevation) as seen by the ES
>
> Set the MinimumAngle to be +9999
>
> For each of points (a, b, c, d):
>
>> If point is within {β_+, β_-} range and at least α_0 away from GSO satellite and above the ε_0(lat, azimuth) then
>>
>> {
>>
>>> MinimumAngle = min(MinimumAngle, angle for this point)
>>
>> }
>
> Next point
>
> If {β_+, β_-} bracket the GSO arc and the elevation of the GSO satellite is less than the minimum elevation angle for the GSO satellite azimuth then
>
> {
>
>> MinimumAngle = min(MinimumAngle, max(α_0, ε_0[Lat, Az_{GSO}] − ε_{GSO}))
>
> }
>
> Return MinimumAngle or if not found, an error code

D3.2.3.4 WCGA_UP_SpecifcES_Repeating

If there are specific ES locations and the non-GSO satellite network using a repeating track orbit then there will be a highly limited number of geometries that are feasible. It is therefore possible to fly the satellite for the repeat period and then, for each ES, for each non-GSO satellite, calculate the α. If $\alpha \le \alpha_0$, or the elevation angle is below the minimum, then the ES would not transmit, otherwise the epfd towards that location can be derived.

Not all geometries will be feasible. For example:

– Non-GSO ES above 81.29° N or S will not see the GSO arc and so can be excluded.

– There will be a maximum difference in longitude between that of the non-GSO ES determined by the edge of coverage (EOC) elevation angle of the GSO system.

– The non-GSO ES will not transmit to the non-GSO satellite when it is within the exclusion zone defined by $\alpha < \alpha_0$.

– The non-GSO ES will not transmit to the non-GSO satellite when its elevation angle is below the minimum $\varepsilon < \varepsilon_0$[lat, az].

– The non-GSO satellite is below the minimum operating height h_{min}.

– The number of non-GSO satellites that can ES at this latitude is zero.

– These are therefore checked in the following algorithm:

```
WCGA_UP_SpecifcES_Repeating
```

```
Calculate time step according to algorithm in § D4.3
For t = 0 to repeat time of constellation
    Update positions of non-GSO satellites for this time step
    For each non-GSO ES
        If the non-GSO ES lat is <+81.29° && >-81.29° && Nco[Lat] > 0 then
            For each non-GSO satellite
                If satellite is visible and above minimum operating height
                    Calculate the elevation angle ε and azimuth
                    Calculate the exclusion zone angle α
                    If (ε ≥ ε₀[lat, az] and α ≥ α₀[lat) then
```

$$EPFD(up) = EIRP(\alpha, lat) + 10\log_{10}\big(N_{co}(lat)\big)$$

```
                        If this is the worst epfd so far then store this
geometry
                    Endif
                Endif
            Next satellite
        Endif
    Next ES
Next time step
```

D3.2.3.5   WCGA_UP_SpecifcES_NonRepeating

For the non-repeating case the non-GSO satellites will populate an orbit shell but only some of the geometries considered in the general case will be feasible as the non-GSO ES will only be at specific latitudes. Therefore this approach searches across the GSO arc as seen by each of the non-GSO ES then takes a similar approach to the general case.

```
WCGA_UP_SpecifcES_NonRepeating:
    For each non-GSO ES
        If the non-GSO ES latitude is <+81.29° or >-81.29° then
            Calculate MaxDeltaLong = acos((Re/Rgeo)/cos(ES_lat))
            NumLongSteps = (integer)(degrees(MaxDeltaLong)/0.1°)
            For DeltaLongStep = -NumLongSteps to +NumLongSteps
                DeltaLong = MaxDeltaLong * DeltaLongStep / NumLongSteps
                GSO_Long = ES_Long + DeltaLong
                Calculate (az, el) of ES as seen by GSO satellite
                Convert (az, el) to (θ, φ)
                Call CheckCaseUpGeneral(θ, φ)
            Next DeltaLongStep
        Endif
    Next ES
```

D3.2.3.6 Range in latitude

When calculating the WCG(up) and also the epfd(up), it is necessary to identify where the ES could be located. While most systems in types A and B have global coverage, non-GSO networks of type C will be limited in the latitude range. For systems with multiple sub-constellations, this range could vary between sub-constellations.

The latitude range can be derived from the satellite's height, its inclination angle and the minimum operating elevation angle for the ES, as in Fig. 32 below.

FIGURE 32

Calculation of maximum latitude for ESs
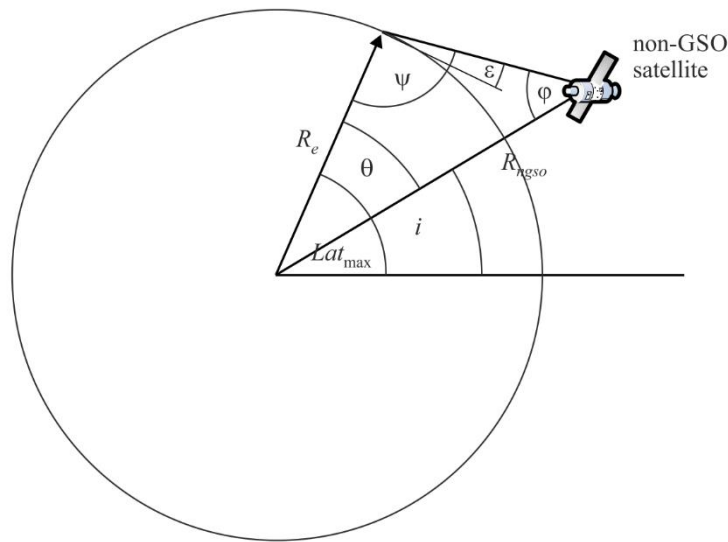
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For elliptical systems, there will be two values, one for the apogee and another for the perigee, and so the inputs would be:

Semi-major axis of orbit (km):	a
Eccentricity of orbit:	e
Minimum elevation angle (radians):	ε
Inclination angle (radians):	i

From these parameters, the following calculations can be undertaken:

$$r_a = a(1 + e)$$

$$\psi = \frac{\pi}{2} + \varepsilon$$

$$\varphi_a = \sin^{-1}\left(\frac{R_e}{r_a}\sin\psi\right)$$

$$\theta_a = \pi - (\psi + \varphi_a)$$

Then:

$$Lat_{\max} = i + \theta_a$$

Similarly, using:

$$r_p = a(1 - e)$$

Using the same equations but replacing suffix (*a*) with (*p*), the following can be derived:

$$Lat_{\min} = -i - \theta_p$$

This assumes that for elliptical systems, the apogee is in the northern hemisphere, i.e. that one of the following is true:

$e = 0$

$\omega = 270°$

where:

ω: argument of perigee.

In the case that:

$e > 0$

$\omega = 90°$

Then the following adjustments should be made:

$Lat_{\max}' = -Lat_{\min}$

$Lat_{\min}' = -Lat_{\max}$

In the case that the orbit inclination is zero and eccentricity zero (i.e. for an equatorial circular orbit) then these equations reduce to:

$$Lat_{\max} = \theta$$

$$Lat_{\min} = -\theta$$

D3.3   WCG epfd$_{IS}$

D3.3.1 Inputs

The inputs to the algorithm are as follows:

SS_e.i.r.p.:   the satellite e.i.r.p. mask to check

θ_{adB} :   the GSO satellite's beam half power beamwidth

ε :   the minimum elevation angle of the GSO system

$a, i, e, \Omega, \omega, \nu$:   the orbit parameters of the non-GSO system.

The GSO satellite's beam half power beamwidth and minimum elevation angle can be selected using the same method as in § D3.2.2 for the WCG epfd(up).

If there are multiple sub-constellations with alternative orbital elements then the process should be repeated for each unique set of {*a, e, i*}.

D3.3.2 Algorithm

```
WCGA_IS:
    From the epfd limits get the gain pattern to use
    From the epfd limits get the GSO beamwidth θₐdB
    From  θₐdB calculate φ₁, φ₂
    Using the gain pattern calculate Grel(φᵢ) for i = 1,2
    From φ₁ calculate LatBS
    If for all satellites i = 0 then
    {
      Worst Case Geometry:
```

```
            BS.Latitude = 0
            BS.Longitude = Lat_BS
            GSO.Longitude = 0
    }
    Else
    {
      Set WorstEPFDBin = -9999
      Set WorstAngularVelocity = +9999
      For all satellites in the order listed in ITU DB
      {
          Determine e.i.r.p. mask to use for this satellite
          If this e.i.r.p. mask has not been checked so far then
          Call GetWCGA_IS(e.i.r.p._mask, i)
        End if
      Next satellite
    }
    If no solution has been found then
    {
      Convert (θ=i, φ=φ1) to (az, el)
      Using (az, el), create line from the GSO satellite
      Put the ES at the first intersection point with the Earth
    }
    Rotate GSO, BS in longitude to ensure inline event

GetWCGA_IS(e.i.r.p._Mask, i):
    LatStep = i / RoundUp(i) in degrees
    For lat=-i to +i in LatStep steps
    {
      Set satellite at latitude to calculate r, v
      If satellite is above minimum operating height
      {
          From r, φ_i calculate ψ_i
          From φ_i, ψ_i calculate D_i, θ_i
          Try to calculate Δlong_i
          In the cases that the geometries are feasible
          {
              From the GSO gain pattern calculate G_rel(φ_i)
              From the e.i.r.p. mask calculate e.i.r.p.(ψ_i)
              Calculate epfd_i
              Calculate r_gso, v_gso
              Calculate θ of non-GSO satellite as seen by GSO
              If epfd_i is higher than Worstepfd
              {
               Store this geometry
               WorstAngularVelocity = θ
               Worstepfd = epfd_i
              }
              Else if epfd_i is the same bin as Worstepfd
              {
               If θ is lower than WorstAngularVelocity
               {
                  Store this geometry
                  WorstAngularVelocity = θ
```

```
                }
              }
            }
          }
        }
```
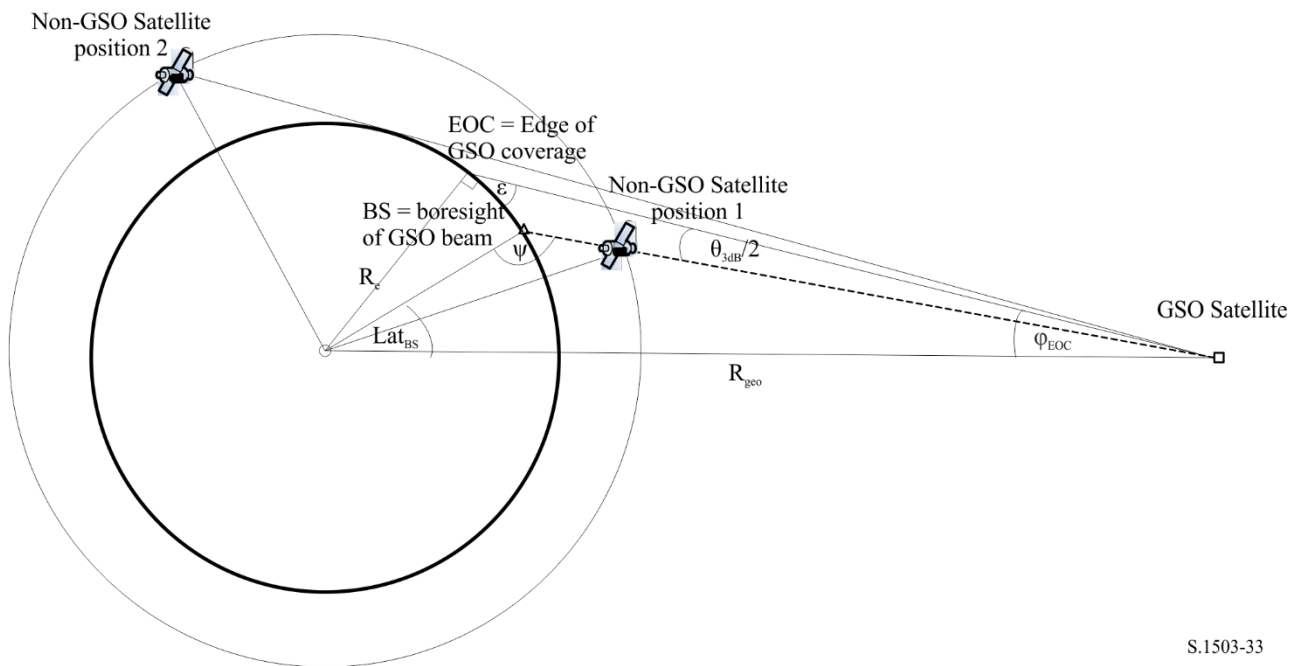
D3.3.3 Geometry

There are two potentially significant geometries, which is when the non-GSO satellite just becomes visible as seen by the GSO satellite and when it traverses the GSO satellite beam, as in Fig. 33.

FIGURE 33

**Two WCG(IS) non-GSO satellite locations**

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In some cases, the same WCG location will handle both geometries – e.g. for an equatorial satellite system a beam at the extreme in azimuth will be aligned for both geometries.

From the radius of the non-GSO satellite at each of the positions, it is possible to calculate the off-axis angle at the satellite and hence e.i.r.p.(θ) together with the distance as in Fig. 34.

FIGURE 34

Two WCG(IS) calculation of satellite off-axis angle
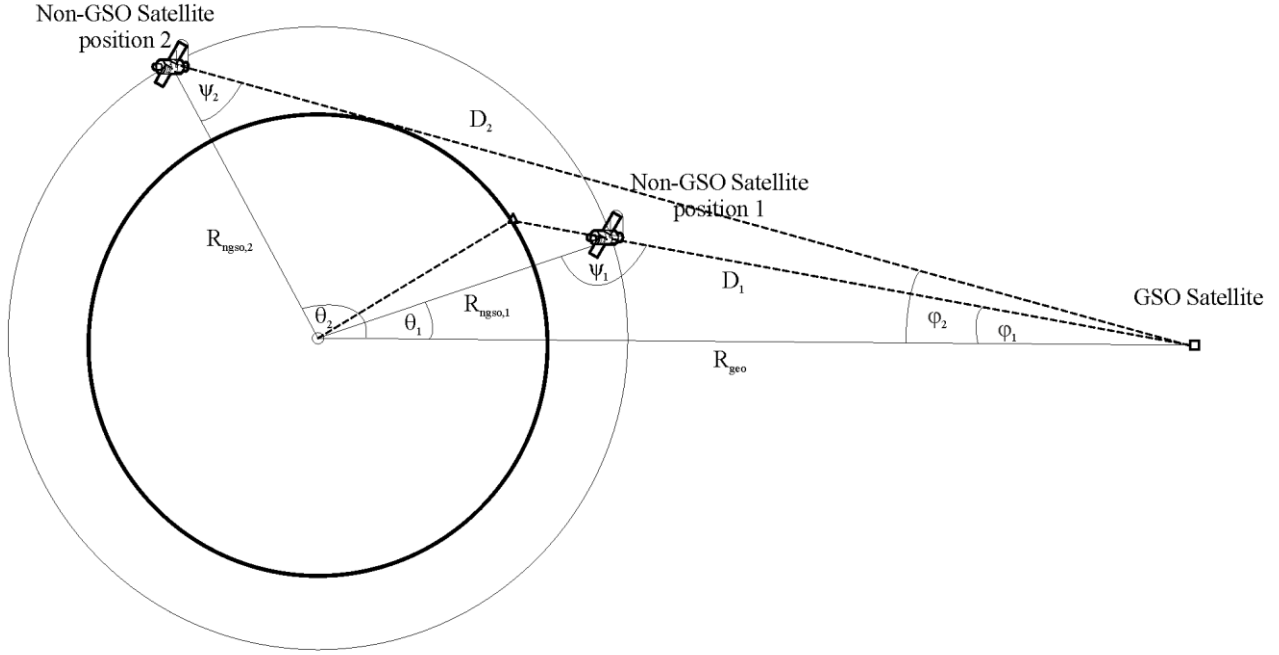
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where:

$$\varphi_1 = \varphi_{BS} \text{ (from above)}$$

$$\sin \varphi_2 = \frac{R_e}{R_{gso}}$$

Hence:

$$\sin \psi_i = \frac{R_{geo}}{R_{ngso,i}} \sin \varphi_i$$

where $i = \{1, 2\}$ noting that $\psi_1 > \frac{\pi}{2}$ and that $\psi_2 < \frac{\pi}{2}$ so that:

$$\psi_1 = \pi - \sin^{-1}\left[\frac{R_{geo}}{R_{ngso,1}} \sin \varphi_1\right]$$

$$\psi_2 = \sin^{-1}\left[\frac{R_{geo}}{R_{ngso,2}} \sin \varphi_2\right]$$

Then:

$$\theta_i = \pi - \varphi_i - \psi_i$$

$$D_i = R_{ngso,i} \frac{\sin \theta_i}{\sin \varphi_i}$$

Hence given a non-GSO satellite with radius distance $R_{ngso,i}$ at the two specified geometries, the two single entry epfd levels can be calculated as:

$$epfd_i = e.i.r.p.(\psi_i) + G_{rel,i} - 10 \log_{10}(4\pi D_i^2)$$

Note that $G_{rel,1} = 0$ and $G_{rel,2} = G_{rel}(\varphi_2 - \varphi_1)$ and D is in metres.

By setting the non-GSO satellite at a specified latitude, *lat*, (where it has longitude *long*), it is therefore possible to derive the single entry epfd from the radius vector and the two geometries identified above.

In some cases, there will be no in-line geometry – for example for elliptical systems at apogee the line from the non-GSO satellite to the GSO arc will at no point intersect the Earth. This can be checked by calculating the difference in longitude between the non-GSO satellite and the point on the GSO arc from the geometry above and the non-GSO satellite's latitude using:

$$\cos \Delta long_i = \frac{\cos \theta_i}{\cos lat_i}$$

If there is no solution to this equation, then there is no position that meets the required geometry. Other positions could be excluded if the non-GSO satellite was below the minimum operating height.

If there is a solution, then the position of the non-GSO and GSO satellite can be calculated from:

$$\underline{r}_{ngso} = R_{ngso} \begin{pmatrix} \cos(lat)\cos(long) \\ \cos(lat)\sin(long) \\ \sin(lat) \end{pmatrix}$$

$$\underline{r}_{gso} = R_{gso} \begin{pmatrix} \cos(long - \Delta long) \\ \sin(long - \Delta long) \\ 0 \end{pmatrix}$$

For the $i = 1$ case the boresight is where the line $\underline{L}$ from the GSO to non-GSO satellite intersects the Earth's surface.

$$\underline{L}_1(\lambda) = \underline{r}_{gso} + \lambda\left(\underline{r}_{ngso} - \underline{r}_{gso}\right)$$

For the $i=2$ case the boresight is on a line created using an adjusted non-GSO satellite position, calculated using:

$$R'_{ngso,2} = R_{geo} \frac{\sin \varphi}{\sin \psi'_2}$$

where:

$$\psi'_2 = \pi - \varphi_1 - \theta_2$$

Given multiple locations with the same single entry epfd, then the one to use would be the one with the lowest angular velocity, using the same method as for WCGA(down), noting that the velocity vector of the GSO satellite can be derived in the same way as for earth stations, i.e.:

$$\underline{v}_{gso} = w_e \begin{pmatrix} -y \\ x \\ 0 \end{pmatrix}$$

The position of the GSO satellite would be chosen such that one of the non-GSO satellites with the e.i.r.p. mask identified traverses the critical geometry during its first orbit, using the same methodology as for the WCGA(up).

Additional geometry for the WCG for epfd(IS) is described in §§ D3.1.3 and D3.2.3 above.

D4   Calculation of time step size and number of time steps

D4.1   Simulation time increment and accuracy

The simulation time increment is one of the most important parameters for the determination of a distribution function of interference from non-GSO networks on the basis of the simulation model. Its specified value should guarantee absence of cases when high-level short-term interference exceeding an acceptable level is missed and is not considered. Otherwise results of simulation analysis will be inaccurate and sometimes erroneous. The decrease of a simulation time increment

allows to increase accuracy of obtained results but at the same time results in increase of total number of simulation time increments and amount of required calculations.

The description of calculation algorithms for simulation time increment in uplink, downlink and intersatellite cases are shown below.

The algorithms are based upon a set of orbital characteristics, such as the inclination angle. If there are multiple sets, e.g. for multiple sub-constellations, then the longest run time and smallest time step over all sub-constellations should be used.

When an artificial precession is used, the same value should be used for all satellites of the non-GSO system. The value used should be the one calculated for the satellite used to derive the time step size and run duration.

In order to reduce run times, the following procedure should be used to adjust the time step size for non-repeating orbits cases where the number of time steps exceeds 1e8:

```
Calculate time step and run time using N_hit = 16
If orbit is non-repeating
    If number of time steps exceeds 1e8 then:
```
$$N'_{hit} = \frac{N_{hit}}{min(N_{course}, \sqrt{N_{satellites}})}$$
```
        Re-calculate time step and run time
```
$$N'_{course} = floor\left(\frac{N'_{hit}}{N_{hit}} N_{course}\right)$$
$$TS'_{course} = TS'.N'_{course}$$
```
    Endif
Endif
```

D4.2 Description of the procedure for the determination of minimum downlink simulation time increment

The value of simulation time increment should guarantee acquisition and description of the most short-term interference scenarios with the required accuracy. The high-level short-term interference is caused by emission of a non-GSO space station which is in-line situation (a non-GSO satellite passes through the main beam of a GSO earth station antenna). Therefore, the method for determining a simulation time increment Δt_{ref} is based on ensuring the required number N_{hit} of epfd↓ estimations during the time interval Δt when a non-GSO satellite passes through the main beam of a GSO earth station antenna:

$$\Delta t_{ref} = \frac{\Delta t}{N_{hit}} \tag{1}$$

Δt_{ref} should be rounded to the nearest non-zero millisecond.

The time required for a non-GSO satellite passing through the main beam of a GSO earth station antenna depends on mutual location of the earth and space stations of the GSO network as well as on orbital parameters of the non-GSO network. The value of Δt should be computed at the location where the time for a non-GSO satellite to pass through the GSO main beam is smallest. Since this occurs when a GSO earth station is located directly under a GSO space station, pass time Δt is determined by equations (2) and (3) (see Fig. 35).

$$\Delta t = \frac{2\varphi}{\omega} \tag{2}$$

where:

$$\varphi = \frac{1}{2}\theta_{3dB} - \arcsin\left[\frac{R_e}{R_e+h}\sin\left(\frac{1}{2}\theta_{3dB}\right)\right]$$

$$\omega = \sqrt{\left(\omega_s\cos(i) - \omega_e\right)^2 + \left(\omega_s\sin(i)\right)^2} \tag{3}$$

$$\omega_s = \frac{0.071}{\left[(R_e+h)/R_e\right]^{1.5}}$$

ω_s: non-GSO satellite angular velocity of rotation around the Earth at the minimum operational altitude (degrees/s); for multiple orbits, the greatest such ω_s should be selected

ω_e: Earth rotation angular velocity at the equator (degrees/s)

i: orbit inclination (degrees)

θ_{3dB}: GSO earth station antenna 3 dB beamwidth (degrees)

R_e: Earth radius (km)

h: orbit altitude (km) (see Note 1).

NOTE 1 – In the case that the constellation has multiple values of h for different sub-constellations or planes, the lowest value should be used. In the case of elliptical orbits the minimum operating height should be used.

FIGURE 35

Calculation of epfd(down) time step size

SS: Space Station
ES: Earth Station

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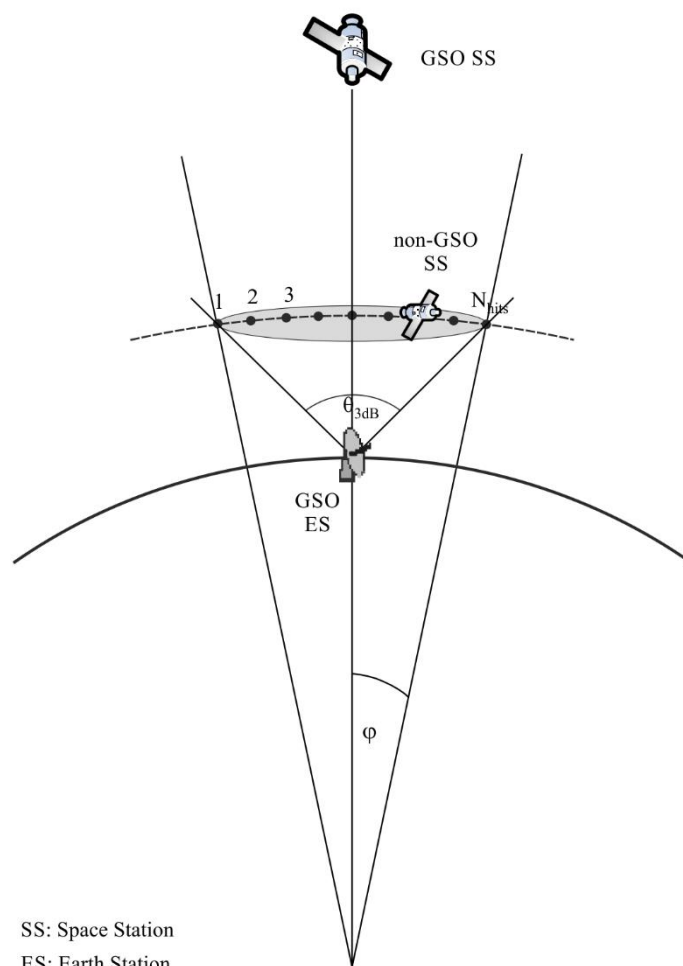
The N_{hit} value defines simulation accuracy. The higher the N_{hit} value the higher the accuracy of the final results.

N_{hit} should be set to 16 as derived in § D4.5. In a case when a non-GSO network satellite constellation consists of satellites with different orbital parameters it is necessary to determine a simulation time increment for each type of the orbits concerned and to define a minimum one.
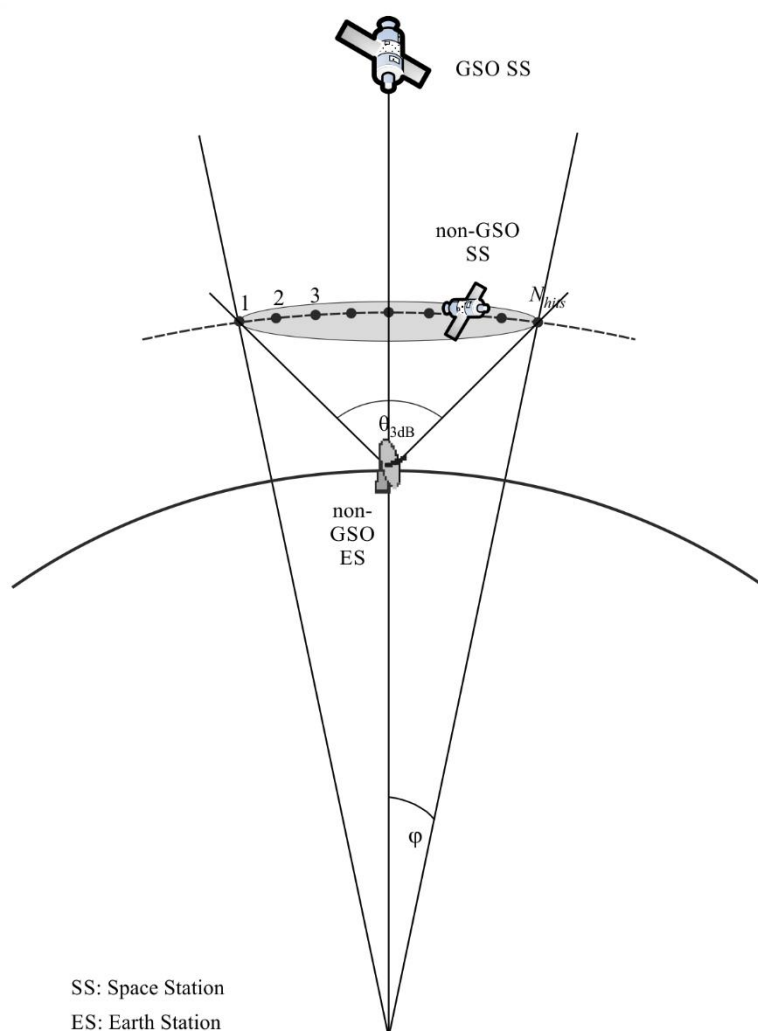
TABLE 11

Input data

Parameter	Designation	Units
Orbit inclination	i	degree
Orbit altitude or for elliptical orbits the minimum operating height	h	km
GSO earth station antenna 3 dB beamwidth	θ_{3dB}	degree
Number of epfd↓ calculations required during the time a non-GSO satellite is passing through the main beam of a GSO earth station antenna	N_{hit}	–

D4.3   Description of the procedure for the determination of minimum uplink simulation time increment

High-level short-term uplink interference would be caused by emissions from a non-GSO earth station during an in-line event (when a GSO SS is in the main beam of a non-GSO earth station antenna). The required number N_{hit} of epfd↑ measurements should be effected within the period of the GSO satellite staying in the main beam of the non-GSO earth station antenna to ensure acquisition and definition of the in-line event. If the non-GSO earth station were directly below the GSO satellite (see Fig. 36) then the value of the minimum simulation time increment could be calculated using equations (1) and (2). In that case a width of the non-GSO earth station antenna main beam should be taken instead of that of the GSO earth station antenna main beam.

FIGURE 36

Calculation of epfd(up) time step size

GSO SS

non-GSO
SS

1 2 3 N_{hits}

θ_{3dB}

non-
GSO
ES

φ

SS: Space Station
ES: Earth Station

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TABLE 12

Input data

Parameter	Designation	Units
Orbit inclination	i	degree
Orbit altitude	h	km
Non-GSO earth station antenna 3 dB beamwidth	θ_{3dB}	degree
Number of epfd calculations required during the time a GSO satellite is passing through the main beam of a non-GSO earth station antenna	N_{hit}	–

D4.4 Description of the procedure for the determination of minimum inter-satellite simulation time increment

The time step size for epfd$_{is}$ calculations is derived by considering that there should be at least N_{hit} time steps during which the non-GSO satellite is within the main beam of the GSO satellite. Given

that the shortest time step is when the beam at the GSO is pointed as far as possible away from the sub-satellite point, and given the following:

R_e: radius of the Earth

h: height of non-GSO orbit

R_{geo}:   radius of geostationary orbit

θ_{3dB}:   half power beamwidth of GSO beam.

For elliptical orbit systems, calculate the height when the non-GSO satellite crosses the equator, i.e. when $\nu = -\omega$ or $+\omega$ such that $(\nu+\omega) = 0$ or integer multiples of π. In addition, it is necessary to consider the minimum operating height, so that the height to use is the maximum of {minimum operating height, height when crossing the equator}.

Then the time step can be calculated using the following algorithm (see Fig. 37).

FIGURE 37

Geometric parameters involved in the equations
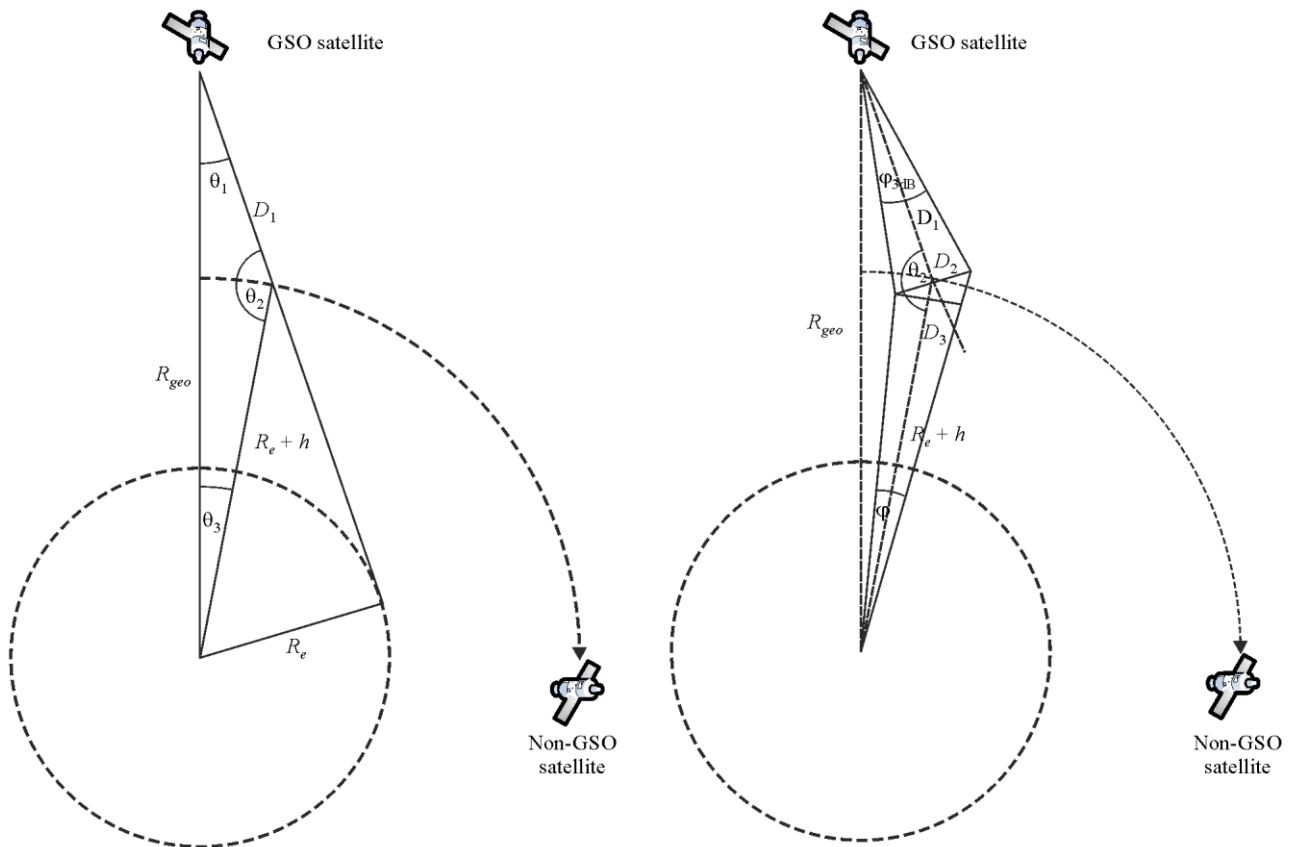
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Calculate:

$$\theta_1 = \arcsin\left(\frac{R_e}{R_{geo}}\right)$$

$$\theta_2 = 180 - \arcsin\left(\sin(\theta_1)\,\frac{R_{geo}}{R_e + h}\right)$$

$$\theta_3 = 180 - (\theta_1 + \theta_2)$$

$$D_1 = (R_e + h)\frac{\sin\theta_3}{\sin\theta_1}$$

$$D_2 = 2D_1\sin\left(\frac{\theta_{3dB}}{2}\right)$$

$$D_3 = D_2\cos(180 - \theta_2)$$

Then calculate the value:

$$\varphi = 2\arctan\left[\frac{D_3/2}{(R_e+h) - (D_2/2)\sin(180 - \theta_2)}\right]$$ (4)

which can be used in equation (2) to calculate the step size to use.

D4.5 Derivation of N_{hit}

The time step size is selected to ensure there is sufficient resolution of the epfd within the victim's main beam. The necessary resolution is driven by the bin size of 0.1 dB and from this the number of steps within the main beam can be derived.

N_{hit} should be selected so that the highest epfd will be detected in the simulation and identified to be within the right bin. This implies a resolution in the calculations of (0.1 dB)/2 = 0.05 dB.

The greatest error would occur when two-time steps are located equally spaced on either side of the main beam, as in Fig. 38.

FIGURE 38

Calculation of N_{hits}
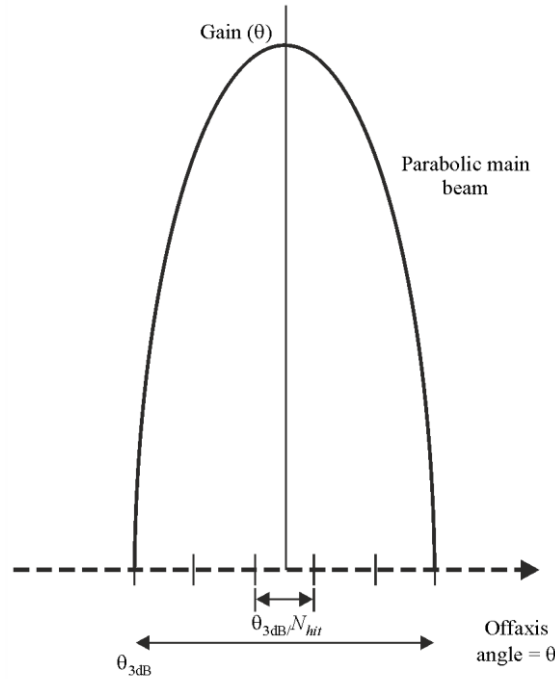
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The spacing between samples will be:

$$\Delta\theta = \frac{\theta_{3dB}}{N_{hit}}$$

The gain pattern within the main beam can be assumed to be parabolic and hence following:

$$G_{rel} = 12 \left(\frac{\theta}{\theta_{3dB}} \right)^2$$

The slope on this curve is:

$$\frac{\Delta G_{rel}}{\Delta \theta} = \frac{24}{\theta_{3dB}^2} \theta$$

Hence, N_{hit} required for a difference in gain of 0.05 dB can be derived as follows:

$$\Delta G_{rel} = 0.05 = 24 \cdot \frac{\theta}{\theta_{3dB}} \cdot \frac{\Delta \theta}{\theta_{3dB}} = 24 \cdot \frac{\theta}{\theta_{3dB}} \cdot \frac{1}{N_{hit}}$$

So:

$$N_{hit} = 480 \cdot \frac{\theta}{\theta_{3dB}}$$

Therefore for the time step nearest the main beam when:

$$\theta = \frac{1}{2} \frac{\theta_{3dB}}{N_{hit}}$$

Then:

$$N_{hit} = RoundUp\left[\sqrt{240} \right] = 16$$

This approach can also be used for cross-track sampling, and hence $N_{track} = N_{hit} = 16$.

D4.6   Total simulation run time

This section describes the calculation of number of time steps for the epfd↓ and epfd↑ algorithms specified in § D5. The basic approach first considers constellations with repeating and non-repeating ground track separately, where systems that use repeating ground tracks use station keeping to ensure that the satellites follow a single Earth trace. For example there will be minor launch errors and perturbations that would make the orbit drift unless station keeping was used operationally to ensure the track repeats. Administrations therefore must indicate to the BR whether station keeping is used to maintain a single track.

Some constellations have different values for inclination, height, or eccentricity between the planes. In this case, it is assumed that, to maintain coverage, the constellation would be designed so that the separation between planes does not change significantly. For the case of repeating ground tracks, this means that there will be a single repeat period for the constellation. This is the time for all satellites within the constellation to return to the same position relative to the Earth and each, within the constraints of station keeping. For the case of non-repeating ground tracks, there will be a single period for all the orbit planes to process around the equator.

This approach is to be used for constellations with both circular and elliptical orbits with orbit inclination non-zero. For equatorial orbit constellations in which all satellites have the same altitude, then it is sufficient to run for a single repeat period. This can be calculated as follows:

$$T_{run} = \frac{2\pi}{w_s - w_e}$$

$$N_{steps} = RoundDown \frac{T_{run}}{T_{step}}$$

where w_s and w_e are the rotation angular velocities of the satellite and Earth as given in § D2.

Table 13 shows the input parameters used in all other constellation types.

TABLE 13

Input data

Parameter	Designation	Units
Constellation repeats yes/no	Type	–
Minimum samples taken to get statistical significance	$N_S = 10$	–

In both cases the time step can be calculated using the method described above. The number of time steps should be at least:

N_{min} = $N_S \times 100/(100 - $ (maximum % in the Tables of Article **22** of the RR less than 100%))

So, for example, for the 99.999% case the number of steps would be:

$$N_{min} = 1\ 000\ 000$$

D4.6.1 Repeating orbits

For those orbits specified as being repeating, the orbit predictor has to be accurate to ensure repeatability. Thus, there is an option for administrations to specify the exact longitude precession rate with respect to a point mass orbit predictor that ensures the orbit would repeat. The definition and use of this parameter is described in § D6.3.

With this parameter, a simulated orbit would be repeated but in reality there would be a slight drift due to longitudinal station keeping errors. It is expected that station keeping changes within the orbit plane would make no difference and so are not included.

The result should be as shown in Fig. 39.

FIGURE 39

Track of repeating orbit non-GSO satellite through GSO ES beam
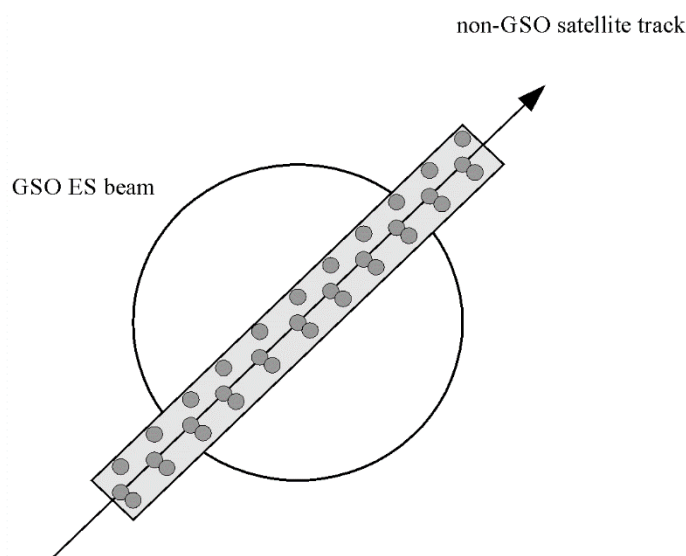
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In Fig. 39, it can be seen that the result would be a series of samples within the main beam of the GSO earth station that is sufficiently fine to resolve the main beam, includes station keeping drift and produces sufficient samples to generate the required statistics.

TABLE 14

Input data

Parameter	Designation	Units
Constellation repeat period	P_{repeat}	s

Given the following parameters:

N_{min}:   minimum number of time steps required for statistical significance

P_{repeat}:   time period that the constellation repeats (s)

T_{step}:   time step (s)

N_{tracks}:   number of tracks through the main beam, = 16, as specified in § D4.5.

For this case the time step should not exactly divide the constellation repeat period. If:

$$N_{repsteps} = P_{repeat}/T_{step}$$

is an integer, then calculate a revised time step (used in the following equations in place of T_{step}) equal to:

$$T'_{step} = T_{step}(1 + N_{repsteps})/ N_{repsteps}$$

Calculate the time period required to get the minimum number of time steps for statistical significance:

$$T_{sig} = N_{min} \cdot T_{step}$$

This corresponds to the following number of constellation repeats:

$$N_{rep} = \text{round } (T_{sig}/P_{repeat}) \text{ to nearest integer above.}$$

The number of repeats of the constellation is the largest of N_{rep} or N_{tracks} i.e.:

$$N_{run} = max (N_{rep}, N_{tracks})$$

Then the total run time is:

$$T_{run} = N_{run} \cdot P_{repeat}$$

So the number of time steps is then:

$$N_{steps} = \text{round } (T_{run}/T_{step}) \text{ to nearest integer below}$$

$$T_{run} = N_{steps} * T_{step}$$

D4.6.2 Non-repeating orbits

In this case the longitudinal spacing between successive ascending node passes must be examined so that there are sufficient tracks within the main beam. The time step size and number of time steps can be used to determine how far a particular orbit will have processed within the run. The same numbers can be used to determine how many time steps are required for the orbit to drift around the equator. The orbit period can then be used to work out the difference between tracks.

The constant that specifies the required number of points within the main beam can be used to specify the number of tracks though the main beam required (i.e. $N_{track} = N_{hits}$). If the gap between tracks is too large or too fine (resulting in either insufficient samples or excessive run times respectively) then artificial precession can be used.

It is expected that station keeping drift should cancel out in the long term and so would not be required for these calculations.

The result should be as shown in Fig. 40.

FIGURE 40

Track of non-repeating orbit non-GSO satellite through GSO ES beam
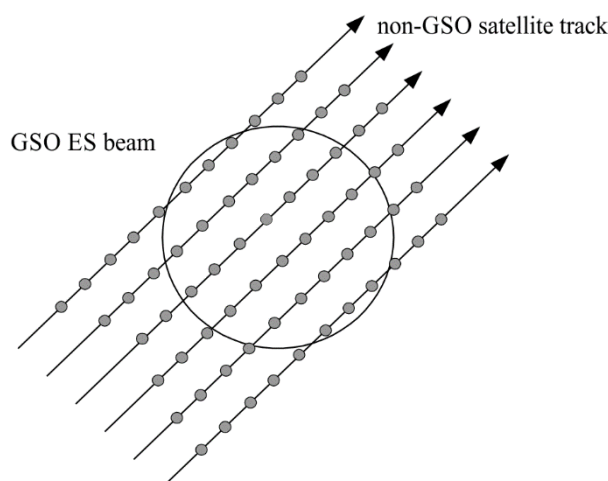
In Fig. 40, it can be seen that the result would be a series of tracks within the main beam of the GSO earth station that is sufficiently fine to resolve the main beam and produces sufficient samples to generate the required statistics.

TABLE 15

Input data

Parameter	Designation	Units
Orbit inclination	i	degree
Orbit semi-major axis	a	km
GSO earth station antenna 3 dB beamwidth[1]	φ_{3dB}	degree
Required number of tracks of a non-GSO satellite passing through the main beam of a GSO earth station antenna	N_{tracks}	–

[1] In the case of calculating run length for epfd↓. In the case of epfd$_{is}$ and epfd↑:

epfd↑: calculate φ using the beamwidth of the non-GSO earth station as specified in its e.i.r.p. mask using the calculation in equation (3)

epfd$_{is}$: calculate φ using the beamwidth of the GSO satellite in the calculation in equation (4).

Two parameters are required:

S_{pass}: longitudinal spacing between successive ascending passes through the equatorial plane

S_{req}: required resolution of passes through the equatorial plane based upon GSO earth station beam size.

These are calculated using the following steps:

Step 1: Using the equations in § D6.3.2, calculate the $\overline{n}, \Omega_r, \omega_r$ in radians / second

Step 2: Convert the $\overline{n}, \Omega_r, \omega_r$ into degrees per minute

Step 3: Calculate the nodal period of the orbit in minutes using:

$$P_n = \frac{360}{w_r + \bar{n}}$$

Step 4: Calculate the longitudinal spacing between successive ascending passes through the equatorial plane, *S*, given the Earth's rotation rate ($\Omega_e = 0.250684$ degrees/min):

$$S_{pass} = (\Omega_e - \Omega_r) \cdot P_n \qquad \text{degrees}$$

The equations above apply to circular orbits. For elliptical orbit systems where the calculations above would be significantly different, the value of S_{pass} should be supplied by the administration.

Step 5: From the GSO earth station beamwidth and height, S_{req} can be calculated using equation (3):

$$S_{req} = \frac{2\varphi}{N_{tracks}}$$

Step 6: Calculate the number of orbits to fully populate around the equator, taking into account that each plane has ascending and descending nodes:

$$N_{orbits} = \frac{180}{S_{req}}$$

Step 7: Round N_{orbits} to next highest integer.

Step 8: Calculate total angle orbit has rotated round during this time:

$$S_{total} = N_{orbits} \cdot S_{pass}$$

Step 9: Calculate the number of multiples of 360° that this corresponds to, rounding to nearest integer below:

$$N_{360} = \text{int}\left(\frac{S_{total}}{360}\right)$$

Step 10: Calculate the separation between planes that this corresponds to:

$$S_{actual} = \frac{360 N_{360}}{N_{orbits}}$$

Step 11: To ensure that the orbit drifts with the required precession rate, the following additional artificial precession should be included:

$$S_{artificial} = S_{actual} - S_{pass} \qquad \text{degrees/orbit}$$

or:

$$D_{artificial} = \frac{S_{artificial}}{T_{period}} \qquad \text{degrees/s}$$

Step 12: Part D gives more information on how this parameter is used. The total run time is then the time to process around the equator using the orbit period from either §§ D6.3.1 or D6.3.2 depending upon or bit model, namely:

$$T'_{run} = T_{period} \cdot N_{orbits}$$

Step 13: The total number of time steps is then:

$$N_{steps} = \text{Round } (T'_{run} / T_{step}) \text{ to nearest integer below}$$
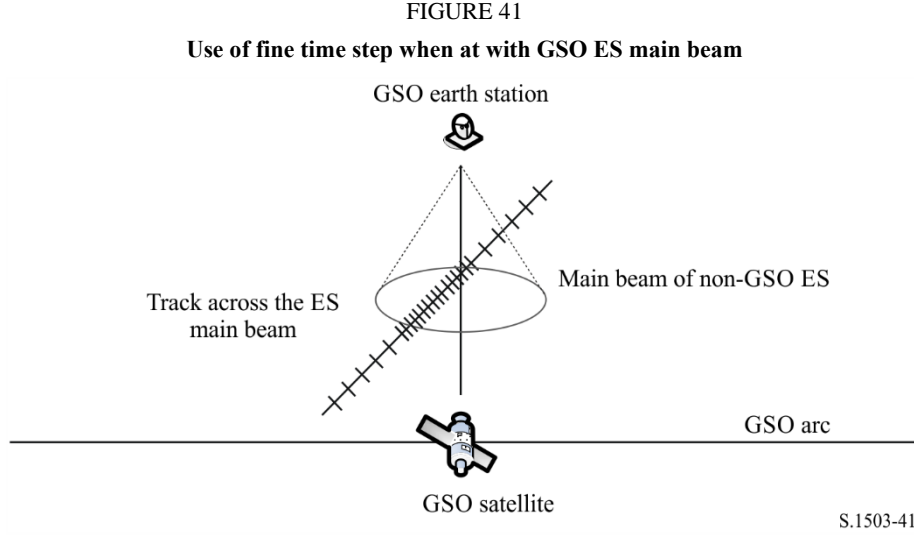
$$T_{run} = N_{steps} * T_{step}.$$

D4.7 Dual time step option

D4.7.1 Dual time step option epfd(down)

In order to improve simulation performance an option to the algorithm is to implement two time steps. A coarse time step would be used except when any non-GSO satellite is near the main beam of the GSO ES or edge of exclusion zone, defined as:

$$G_{RX}(\varphi) > \min[\text{Gmax} - 30 \text{ dB}, G_{RX}(\alpha_0[\text{Latitude}])]$$

Figure 41 shows where to use the finer time step:

FIGURE 41

Use of fine time step when at with GSO ES main beam

GSO earth station

Main beam of non-GSO ES

Track across the ES
main beam

GSO arc

GSO satellite

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A coarse step size is used for non-critical regions far from the GSO earth station main beam. This step size is defined as a topocentric angle:

$$\varphi_{coarse} = 1.5°$$

This coarse step size is used for all antenna beamwidths and all non-GSO systems.

The size of the coarse step needs to be an integer multiple of fine steps for statistical purposes. Since the coarse step size is constant, the ratio of coarse steps to fine steps is dependent only upon the beamwidth of the GSO earth station (φ_{3dB}). This ratio is defined as:

$$N_{coarse} = Floor((N_{hits} * \varphi_{coarse})/\varphi_{3dB})$$

where floor is a function that truncates the decimal part of the ratio and outputs the integer part of the ratio. This produces a conservative ratio of fine steps to coarse steps to ensure that a coarse step is never larger than the target topocentric size of 1.5°.

D4.7.2 Dual time step option epfd(up)

In order to improve simulation performance an option to the algorithm is to implement two-time steps. A coarse time step would be used except when the gain from any non-GSO ES towards the GSO satellite is greater than −30 dB.

A coarse step size is used for non-critical regions when the non-GSO earth station main beam is pointing away from the GSO satellite. This step size is defined as a topocentric angle:

$$\varphi_{coarse} = 1.5°$$

This coarse step size is used for all antenna beamwidths and non-GSO systems.

The size of the coarse step needs to be an integer multiple of fine steps for statistical purposes. Since the coarse step size is constant, the ratio of coarse steps to fine steps is dependent only upon the beamwidth of the non-GSO earth station (φ_{3dB}). This ratio is defined as:

$$N_{coarse} = Floor((N_{hits} * \varphi_{coarse})/\varphi_{3dB})$$

where floor is a function that truncates the decimal part of the ratio and outputs the integer part of the ratio. This produces a conservative ratio of fine steps to coarse steps to ensure that a coarse step is never larger than the target topocentric size of 1.5 degrees.

D5 epfd calculation description

D5.1 epfd↓ software description

This section describes the algorithm to calculate the epfd↓ from a non-GSO constellation into a GSO downlink. It is assumed that each non-GSO satellite has a pfd mask. From the pfd for each satellite the aggregate epfd↓ at an earth station of a GSO system is calculated. This is repeated for a series of time steps until a distribution of epfd↓ is produced. This distribution can then be compared with the limits to give a go/no go decision.

Figure 42 shows the geometry with constellation of non-GSO satellites and test GSO satellite transmitting to a GSO earth station.

FIGURE 42

Example of epfd(down) scenario

S.1503-42
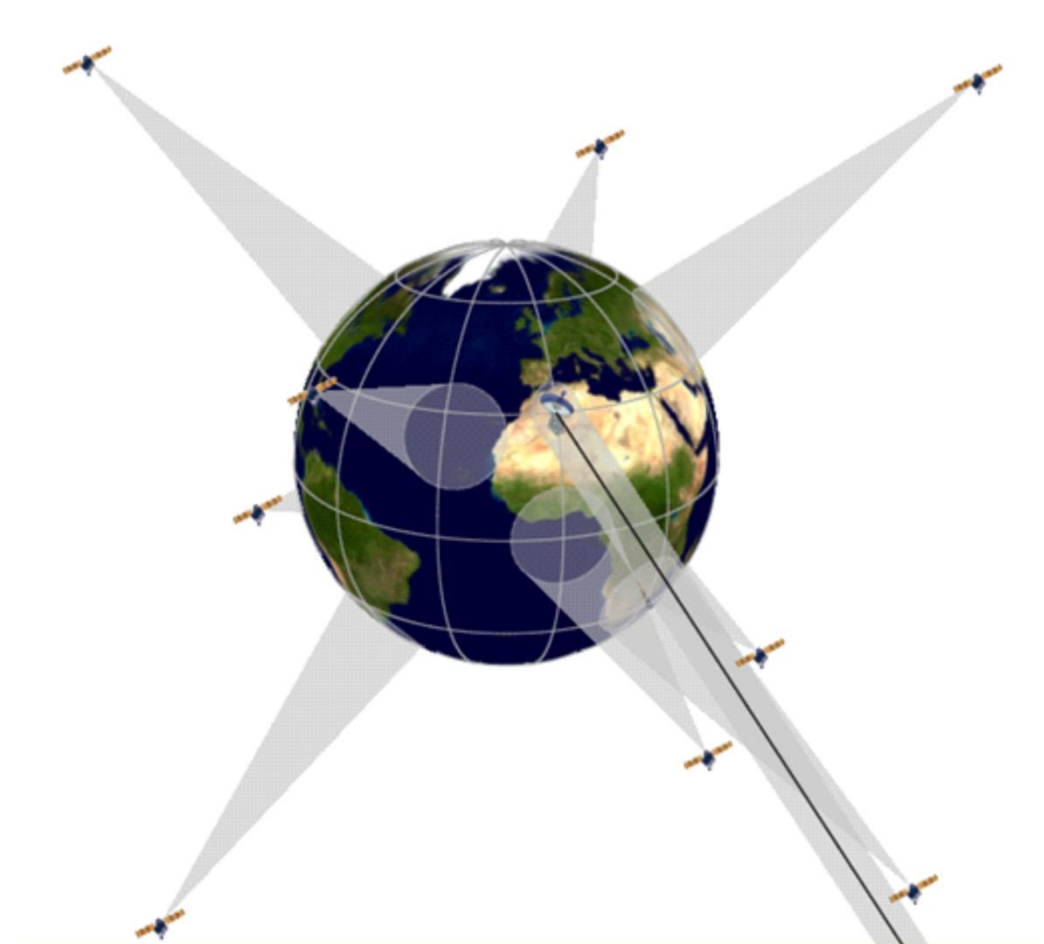
D5.1.1 Configuration parameters

These run definition parameters are:

Parameter name	Parameter value	Parameter units and ranges
Frequency	F_DOWN	MHz
GSO satellite longitude	GSO_LONG	degree
GSO earth station latitude	GSO_ES_LAT	degree
GSO earth station longitude	GSO_ES_LONG	degree
GSO earth station dish size	GSO_ES_D_ANT	m
GSO earth station gain pattern	GSO_ES_PATTERN	One of those in § D6.5
Reference bandwidth	REFBW	kHz
Number of epfd↓ points	Nepfd_DOWN	–
Array of Nepfd_DOWN epfd↓ values	epfd_DOWN[I]	$dB(W/(m^2 \cdot BW_{ref}))$
Array of Nepfd_DOWN percentages	PC[I]	%

D5.1.2 Non-GSO system parameters

The following parameters, as specified in § B3.1 would be used.

Parameter description	Parameter name	Parameter units
Satellite pfd mask	See Part C for definition and format	
Number of non-GSO satellites	N_{sat}	–
Transmit centre frequency	F_DOWN$_{sat}$	MHz
Exclusion zone angle by latitude, potentially varying by satellite	MIN_EXCLUDE[Latitude]	degree
Minimum satellite tracking duration by latitude	MIN_DURATION [Latitude]	second
Maximum number of satellites operating co-frequency at Earth location, potentially varying by latitude	MAX_CO_FREQ [Latitude]	–
Orbit has repeating ground track maintained by station keeping	Yes or No	–
Administration is supplying specific node precession rate	Yes or No	–
Station keeping range for ascending node as half total range	W_{delta}	degree
Minimum operating height	H_MIN	km
Minimum operating elevation angle by latitude and azimuth	ES_MINELEV[Latitude] [Azimuth]	degree
Minimum angle between active non-GSO satellites at ES	MIN_ANGLE_AT_ES	degree

For each satellite the following parameters specified in § B3.2 would be used, where the definitions of the parameters are specified in § D6.3.1 at the time of the start of the simulation.

Note that in the Table below, the indices [N] are present to indicate that there would be a different value for each satellite, and the N-th value corresponds to the N-th satellite. For the pfd mask it indicates that the pfd data is structured in such a way that the pfd[N] entry is a reference that points

to a particular sub-set. For example each satellite in the constellation could reference the same pfd(lat, az, el), pfd(lat, X, Δlong), or pfd(lat, α, Δlong) table.

Parameter description	Parameter name	Parameter units
pfd mask to use	pfd[N]	–
Semi-major axis	A[N]	km
Eccentricity	E[N]	–
Inclination	I[N]	degree
Longitude of ascending node	O[N]	degree
Argument of perigee	W[N]	degree
True anomaly	V[N]	degree

D5.1.3 Run time step parameters

The following run parameters should be calculated using the algorithm in § D4:

Parameter description	Parameter name	Parameter units
Time step	TSTEP	s
Number of time steps	NSTEPS	–

The time step and statistics take account of the time windows as shown in Fig. 43.

FIGURE 43

Run time, fine and course time steps and time windows
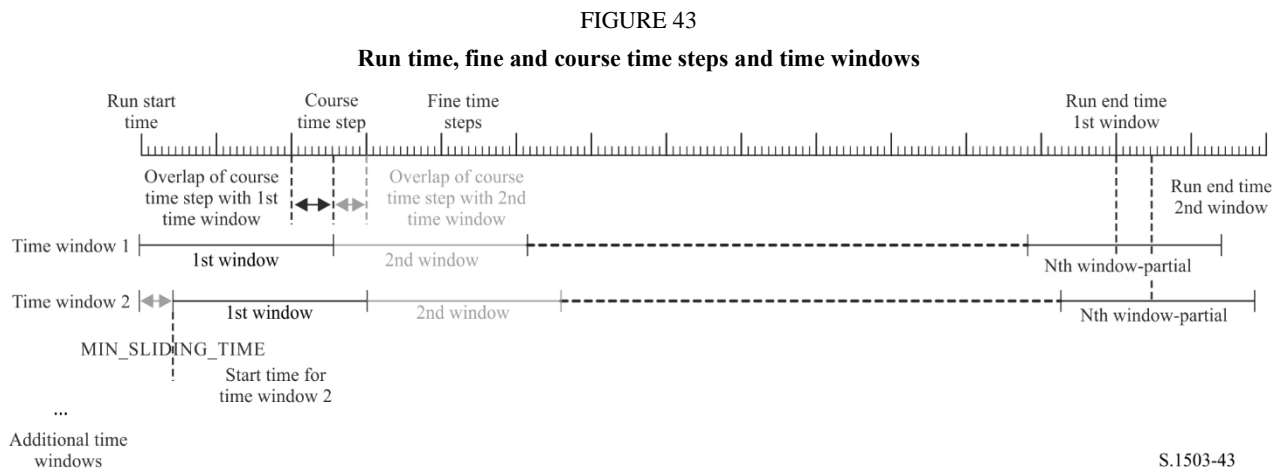
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The following are calculated in § D4:

–   Run duration

–   Fine time step

–   Course time step.

In the case that the non-GSO satellite selection method is defined by track duration (e.g. for the MIN_DURATION [Latitude] to be non-zero for at least one latitude), then it is also necessary to consider a set of time windows to ensure all combinations of satellite selection are analysed.

The MIN_DURATION is provided for the constellation (possibly dependent upon latitude, which in this case of the ES). The length of the time window in fine time steps is calculated as the integer ratio of this track duration divided by fine time step size. The MIN_SLIDING_TIME is also calculated as an integer number of fine time steps.

The minimum sliding time is:

$$\text{MIN\_SLIDING\_TIME} = \max\left\{1\ second, \frac{MinimumOrbitalPeriod}{100.N_{satellites}}\right\}$$

Where *MinimumOrbitalPeriod* is the smallest orbit period over all sub-constellations.

The run duration is derived in § D4 so that the constellation has returned to the initial conditions and hence statistics are complete. This could require that the last time window is only partially included: i.e. only those time steps within the run duration would be included in the epfd statistics. However the simulation would continue until the time window is complete to determine the satellites to track. In addition, as each window starting time is offset it is necessary to run for other windows additional steps beyond that used by the first-time window.

The length of the sliding window in number of fine time steps is:

$N_{SW} = \text{RoundDown}(\text{MIN\_DURATION} / T_{fine})$

The number of fine time steps for the MIN_SLIDING_TIME can be calculated as:

$N_{MSL} = \text{RoundUp}(\text{MIN\_SLIDING\_TIME} / T_{fine})$

The number of time windows to use in the calculations is then:

$N_{TW} = \text{RoundUp}(N_{sw} / N_{MSL})$

The number of repeats of the time window for the run duration is then:

$N_{Repeat} = \text{RoundUp}(N_{step} / N_{SW})$

The total number of fine time steps required to simulate is the run duration plus the time required to complete all the time windows, namely:

$N_{TotalSteps} = N_{repeat} * N_{SW} + (N_{TW} - 1) * N_{MSL}$

The total run duration required to get all the sliding windows to complete is then:

$T_{TotalDuration} = N_{TotalSteps} * T_{fine}$

D5.1.4 Algorithms and calculation procedures

In the case that the non-GSO satellite selection method is defined by track duration (e.g. for the MIN_DURATION [Latitude] to be non-zero for at least one latitude) then the algorithm and calculation procedures are as in § D5.1.4.2, otherwise they are as in § D5.1.4.1.

The operating non-GSO satellites are those outside the exclusion zone, above their minimum operating elevation angle and transmitting towards (i.e. height above or equal to MIN_OPERATING_HEIGHT) the GSO earth station. The maximum number of operating non-GSO satellites is the maximum number of non-GSO satellites allowed to transmit co-frequency towards the same area on the ground.

D5.1.4.1 Algorithms and calculation procedures when not using track duration

To calculate epfd↓ values from a non-GSO system that is not using the track duration into one GSO system earth station the following algorithm should be used. The algorithm can be used on multiple GSO systems in parallel if required.

Step 1: Read in parameters for non-GSO system as specified in § D5.1.2.

Step 2: Read in GSO parameters as specified in § D5.1.1.

Step 3: If required, calculate the maximum epfd GSO location using the algorithm in § D3.1 otherwise use the GSO satellite and ES location requested.

Step 4: Calculate the number of time steps and time step size using algorithm in § D4 and hence calculate end time.

Step 4bis: Initialize statistics by zeroing all bins of epfd↓ values.

Step 5: If a dual time step algorithm is included then use Sub-step 5.1, otherwise $N_{coarse} = 1$ all the time.

    Sub-step 5.1: Calculate coarse step size $T_{coarse} = T_{fine} * N_{coarse}$.

Step 6: If a dual time step algorithm is included then repeat Sub-step 6.1 to Step 22 until end time is reached, otherwise repeat Steps 7 to 22 until end time is reached.

    Sub-step 6.1: If it is the first time step then set $T_{step} = T_{fine}$.

    Sub-step 6.2: Otherwise if there are less than N_{coarse} steps remaining then set $T_{step} = T_{fine}$.

    Sub-step 6.3: Otherwise, if any of the $G_{RX}(\varphi)$ for the last time step were within 30 dB of peak then set $T_{step} = T_{fine}$; otherwise, set $T_{step} = T_{coarse}$.

Step 7: Update position vectors of all earth stations based on coordinate system in § D6.1.

Step 8: Update position vectors of all GSO satellites based on coordinate system in § D6.2.

Step 9: Update position and velocity vectors of all non-GSO satellites based on coordinate system, orbit prediction model and station keeping algorithm in § D6.3.

Step 10: Set epfd↓ = 0.

Step 11: Select all non-GSO satellites visible to the GSO earth station using the algorithm in § D6.4.1.

Step 12: Repeat Steps 13 to 18 for each visible non-GSO satellite.

Step 13: Calculate the parameters required by the pfd mask, either (lat, α, Δlong) or (lat, azimuth, elevation) as required, using the definition of angles in § D6.4.4 or § D6.4.5.

Step 13bis: Calculate the (Azimuth$_{NGSO}$, ε$_{NGSO}$) of the non-GSO satellite as seen at the GSO ES location using the definition of angles in § D6.4.4.

Step 14: Using the pfd mask for the selected non-GSO satellite, calculate pfd(lat, α, Δlong) or pfd(lat, azimuth, elevation) at the GSO earth station using the non-GSO satellite pfd mask as specified in § D5.1.5.

Step 15: Calculate the off-axis angle φ at GSO earth station between line to the GSO satellite and the non-GSO satellite.

Step 16: Calculate $G_{RX}(\varphi)$ = Receive gain (dB) at GSO earth station using relevant gain pattern specified in algorithms in § D6.5.

Step 17: Calculate epfd↓$_i$ for this non-GSO satellite using:

$$epfd{\downarrow}_i = pfd + G_{RX}(\varphi) - G_{max}$$

where G_{max} is the peak gain of the GSO earth station antenna.

Step 18: Store the epfd↓$_i$ entries for each satellite that:

    • either has an α ≥ α$_0$[latitude] for that satellite and has an ε$_{NGSO}$ ≥ ε$_0$[latitude][Azimuth$_{NGSO}$]

    • or for which $G_{RX}(\varphi) > \min[G_{max} - 30$ dB, $G_{RX}(\alpha_o[\text{Latitude}])]$

Step 19: Repeat Steps 20 and 21 for each time step as long as no more than MAX_CO_FREQ[lat] satellites are included in Step 23.

    MAX_CO_FREQ[lat] is the maximum number of operating non-GSO satellites at the latitude of GSO_ES considered corresponding to the maximum number of satellites allowed to transmit at the same frequency towards the same area on the ground, fulfilling

the GSO exclusion zone, the minimum elevation angle and the MIN_ANGLE_AT_ES requirements as defined for the non-GSO system.

Step 20: Apply Step 23 for the satellite which has an $\alpha \geq \alpha_0$[latitude] and an $\varepsilon_{NGSO} \geq \varepsilon_0$[latitude][Azimuth$_{NGSO}$] and with the highest single epfd$\downarrow_i$.

Step 21: If the MIN_ANGLE_AT_ES between non-GSO satellites has been specified, then remove the non-GSO satellites from those in Step 18 which have an $\alpha \geq \alpha_0$[latitude] and an $\varepsilon_{NGSO} \geq \varepsilon_0$[latitude][Azimuth$_{NGSO}$] that do not meet this criterion with respect to the satellite used in Step 20.

Step 22: Repeat Step 23 for those satellites for which $G_{RX}(\varphi) > min[G_{max} - 30\ dB, G_{RX}(\alpha_o[Latitude]])$.

Note: There should be no double-counting of satellites in Step 23. In particular, if a satellite is on the list of the highest MAX_CO_FREQ[lat] satellites and also for which $G_{RX}(\varphi) > min[G_{max} - 30\ dB, G_{RX}(\alpha_o[Latitude]])$ it should be included only once as part of the MAX_CO_FREQ[lat] satellites in Step 20.

Step 23: Increment epfd$\downarrow$ by the epfd$\downarrow_i$ value in linear.

Step 24: Increment epfd$\downarrow$ statistics by epfd$\downarrow$ for this time step by (T_{step}/T_{fine}) entries.

Step 25: Generate the epfd$\downarrow$ CDF from the epfd$\downarrow$ PDF using the algorithm in § D7.1.2.

Step 26: Compare epfd$\downarrow$ statistics with limits using the algorithm in § D7.1.

Step 27: Output results in format specified in § D7.3.

D5.1.4.2 Algorithms and calculation procedures when using track duration

To calculate epfd$\downarrow$ values from a non-GSO system that is using the track duration into one GSO system earth station the following algorithm should be used. The algorithm can be used on multiple GSO systems in parallel if required.

Step 1: Read in parameters for non-GSO system as specified in § D5.1.2.

Step 2: Read in GSO parameters as specified in § D5.1.1.

Step 3: If required, calculate the maximum epfd GSO location using the algorithm in § D3.1 otherwise use the GSO satellite and ES location requested.

Step 4: Calculate the number of time steps and time step size using algorithm in § D4 and hence calculate end time. As described in § D5.1.3, adjust the MIN_SLIDING_TIME and MIN_DURATION to be an integer number of fine time step and hence calculate the NUM_SLIDE_WINDOWS. Increment the run duration by the integer number of fine time steps so that all sliding windows will have complete statistics.

Step 4bis: Initialize statistics by zeroing all bins of epfd$\downarrow$ values for each of the NUM_SLIDE WINDOWS.

Step 5: If a dual time step algorithm is included then use Sub-step 5.1, otherwise $N_{coarse} = 1$ all the time.

    Sub-step 5.1: Calculate coarse step size $T_{coarse} = T_{fine} * N_{coarse}$.

Step 6: If a dual time step algorithm is included then repeat Sub-step 6.1 to Step 22 until end time is reached, otherwise repeat Steps 7 to 22 until end time is reached.

    Sub-step 6.1: If it is the first time step then set $T_{step} = T_{fine}$.

    Sub-step 6.2: Otherwise if there are less than N_{coarse} steps remaining then set $T_{step} = T_{fine}$.

Sub-step 6.3: Otherwise, if any of the $G_{RX}(\varphi)$ for the last time step were within 30 dB of peak then set $T_{step} = T_{fine}$; otherwise, set $T_{step} = T_{coarse}$.

Step 7: Update position vectors of all earth stations based on coordinate system in § D6.1.

Step 8: Update position vectors of all GSO satellites based on coordinate system in § D6.2.

Step 9: Update position and velocity vectors of all non-GSO satellites based on coordinate system, orbit prediction model and station keeping algorithm in § D6.3.

Step 10: Set epfd↓ = 0.

Step 11: Select all non-GSO satellites visible to the GSO earth station using the algorithm in § D6.4.1.

Step 12: Repeat Steps 13 to 18 for each visible non-GSO satellite.

Step 13: Calculate the parameters required by the pfd mask, either (lat, α, Δlong) or (lat, azimuth, elevation) as required, using the definition of angles in § D6.4.4 or § D6.4.5.

Step 13bis: Calculate the (Azimuth$_{NGSO}$, ε_{NGSO}) of the non-GSO satellite as seen at the GSO ES location using the definition of angles in § D6.4.4.

Step 14: Using the pfd mask for the selected non-GSO satellite, calculate pfd(lat, α, Δlong) or pfd(lat, azimuth, elevation) at the GSO earth station using the non-GSO satellite pfd mask as specified in § D5.1.5.

Step 15: Calculate the off-axis angle φ at GSO earth station between line to the GSO satellite and the non-GSO satellite.

Step 16: Calculate $G_{RX}(\varphi)$ = Receive gain (dB) at GSO earth station using relevant gain pattern specified in algorithms in § D6.5.

Step 17: Calculate epfd↓$_i$ for this non-GSO satellite using:

$epfd↓_i = pfd + G_{RX}(\varphi) - G_{max}$

where G_{max} is the peak gain of the GSO earth station antenna.

Step 18: Store the epfd↓$_i$ entries for each satellite that:

• either has an $\alpha \geq \alpha_0$[latitude] for that satellite and has an $\varepsilon_{NGSO} \geq \varepsilon_0$[latitude][Azimuth$_{NGSO}$]

• or for which $G_{RX}(\varphi) > min[G_{max} - 30\ dB,\ G_{RX}(\alpha_0[Latitude]])$

Step 19: If a window is closing this time step then identify which non-GSO satellites met the α_0, ε_0 constraints for the full duration of the window.

Step 19bis: For each of those satellites that met the α_0, ε_0 constraints for the full duration of the window, calculate the highest epfd↓[nSat] over the time window and sort this list of satellites by maximum epfd↓[nSat] per satellite.

Step 20: Repeat Steps 21 and 22 for each time step in the window for the MAX_CO_FREQ[lat] satellite's epfd↓[nSat] contributions on this list plus those satellites for which $G_{RX}(\varphi) > min[G_{max} - 30\ dB,\ G_{RX}(\alpha_0[Latitude]])$, where MAX_CO_FREQ[lat] is the maximum number of operating non-GSO satellites at the latitude of GSO_ES considered corresponding to the maximum number of satellites allowed to transmit at the same frequency towards the same area on the ground, fulfilling the GSO exclusion zone and minimum elevation angle requirements as defined by for the non-GSO system.

Note: There should be no double-counting of satellites in Step 21. In particular, if a satellite is on the list of the highest MAX_CO_FREQ[lat] satellites and also for which $G_{RX}(\varphi) > min[G_{max} - 30\ dB,\ G_{RX}(\alpha_0[Latitude]])$ it should be included only once as part of the MAX_CO_FREQ[lat] satellites in Step 21.

Step 21: Increment epfd↓ by the epfd↓$_i$ value in linear.

Step 22: Increment epfd↓ statistics for the relevant slide window by epfd↓ for this time step by (T_{step}/T_{fine}) entries. If last time step was a course time step and the window closed during that time step, then the epfd↓ statistics should be updated by that part of T_{step} that was in the window and the remaining part stored for the following window. If the run since start time for this slide window exceeds the run duration then only include that part of the time window that is within the run duration in the statistics.

Step 23: Generate the epfd↓ CDF for all slide windows from the epfd↓ PDF using the algorithm in § D7.1.2.

Step 24: Compare epfd↓ statistics for all slide windows with limits using the algorithm in § D7.1.

Step 25: Output results in format specified in § D7.3.

D5.1.5 pfd mask calculation

The pfd mask is defined as a table of pfd values for various angles and latitudes.

Note that the latitude range should be:

Minimum: $-i$

Maximum: $+i$

where i is the inclination of the non-GSO satellite's orbit.

In general, the (azimuth, elevation) or (α, $\Delta long$) angles calculated at each time step will be between two values in the arrays. In this case bilinear interpolation between pfd values should be used with equations:

$$pfd = (1 - \lambda_x)(1 - \lambda_y)pfd_{11} + \lambda_x(1 - \lambda_y)pfd_{21} + (1 - \lambda_x)\lambda_y pfd_{12} + \lambda_x\lambda_y pfd_{22}$$

where:

$$\lambda_x = \frac{x - x_1}{x_2 - x_1}$$

$$\lambda_y = \frac{y - y_1}{y_2 - y_1}$$

And (x, y) are the two dimensions of the pfd mask.

If the angles are outside the pfd mask, the software calculates pfd from the highest angle in the mask (i.e. at the mask edge).

The mask that is closer in latitude to that of the reference satellite should be used. Part C gives more information about the format and sampling of the pfd mask.

D5.1.6 Outputs

The result of the algorithm is two arrays in format:

Array of epfd↓ values	epfd_DOWN_CALC[I]	dB(W/(m^2 · BW$_{ref}$))
Array of percentages	PC_CALC[I]	%

where PC_CALC[I] is the percentage of time epfd_DOWN_CALC[I] is exceeded.

D5.2 epfd↑ software description

This section describes the algorithm to calculate epfd↑ from non-GSO earth stations into a GSO uplink. The locations of the ES can be defined in one of two ways:

1)   It is assumed that the Earth is populated with a uniform distribution of non-GSO earth stations. In this case the ES_ID in the e.i.r.p. mask should be set to −1.

2)   The locations of specific ES are used via a field in the ES e.i.r.p. mask. In this case the density field is not used.

Each earth station points towards a non-GSO satellite using pointing rules for that constellation, and transmits with a defined e.i.r.p. From the e.i.r.p. and off-axis gain pattern for each earth station, the epfd↑ at the GSO can be calculated. This is repeated for a series of time steps until a distribution of epfd↑ is produced. This distribution can then be compared with the limits to give a go/no go decision.

Figure 44 shows the geometry with population of non-GSO earth stations transmitting to a constellation of non-GSO satellites, together with a test GSO satellite receiving from a GSO earth station.

FIGURE 44

Example of epfd(up) scenario
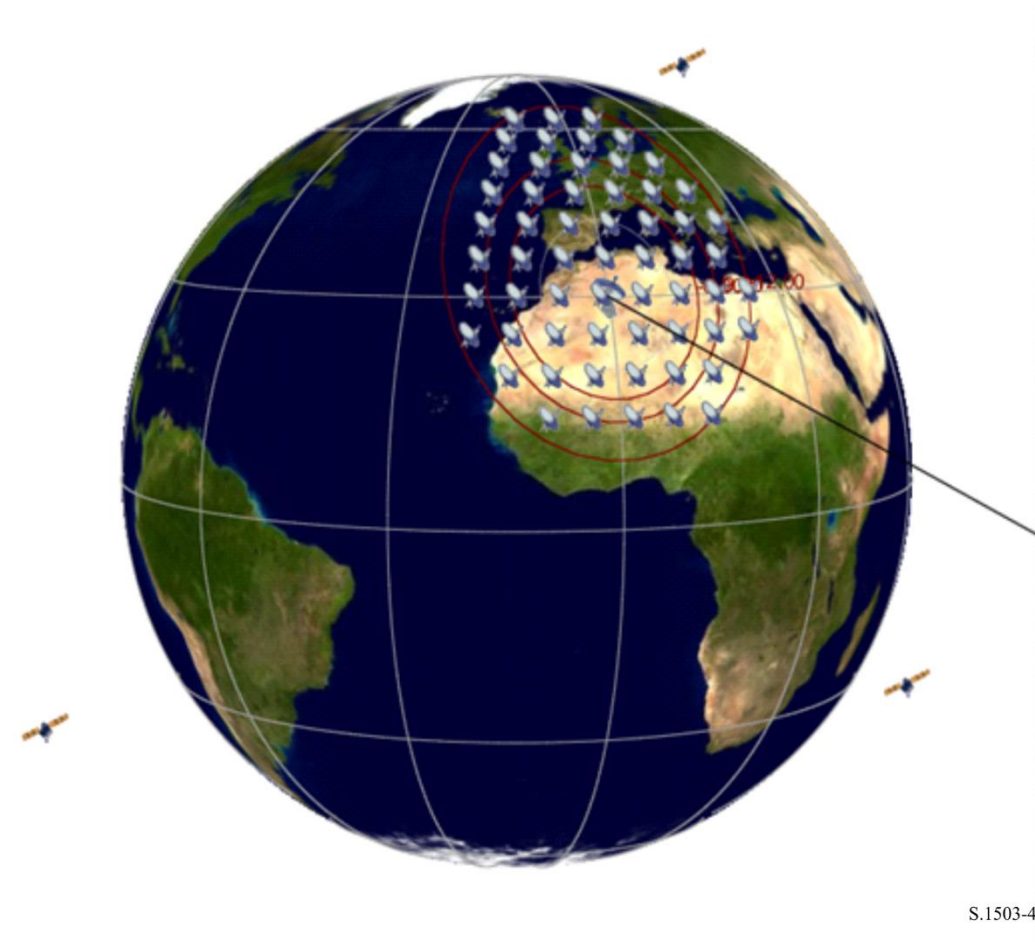
S.1503-44

D5.2.1 Configuration parameters

This sub-section specifies the parameters required for all epfd↑ calculations defined in the RR. This would be a data-set of N sets of limits that can be shared between runs. The Table could be queried so that the required values can be used depending upon non-GSO system frequency.

For each set of limits the following would be defined as generated by in § D2.1.

Parameter name	Parameter value	Parameter units and ranges
Frequency	FREQ	MHz
GSO gain pattern	FEND_UP	One of those in § D6.5
GSO peak gain	GSO_SAT_PEAKGAIN	dBi
GSO half power beamwidth	GSO_SAT_BEAMWIDTH	degree
Reference bandwidth	RAFBW	kHz
Number of epfd↑ points	Nepfd_UP	–
Array of Nepfd_UP epfd↑ values	epfd_UP[I]	$dB(W/(m^2 \cdot BW_{ref}))$
Array of Nepfd_UP percentages	PC_UP[I]	%

D5.2.2 Determination of maximum epfd configuration

The maximum epfd location of the GSO satellite and beam centre is defined in § D3.2.

D5.2.3 Calculation of run steps

The time step and number of time steps are calculated using the algorithm in § D4 which also describes the optional dual time step option.

D5.2.4 Inputs

D5.2.4.1 Input parameters

This section defines the input parameters for a particular non-GSO system scenario. In this case, input is a generic term that could include files or user input. Information is required for:

– non-GSO system;
– GSO system;
– run configuration.

D5.2.4.2 Non-GSO system parameters

The following parameters, as specified in § B3.1 would be used:

Parameter description	Parameter name	Parameter units
Number of non-GSO satellites	N_{sat}	–
Orbit has repeating ground track maintained by station keeping	Yes or No	–
Administration is supplying specific node precession rate	Yes or No	–
Station keeping range for ascending node as half total range	W_{delta}	degrees

For each satellite the following parameters specified in § B3.2, would be used, where the definitions of the parameters are specified in § D6.3.1 at the time of the start of the simulation.

Note that in the Table below, the indices [*N*] are present to indicate that there would be a different value for each satellite, and the *N*-th value corresponds to the *N*-th satellite.

Parameter description	Parameter name	Parameter units
Semi-major axis	A[*N*]	km
Eccentricity	E[*N*]	–
Inclination	I[*N*]	degrees
Longitude of ascending node	O[*N*]	degrees
Argument of perigee	W[*N*]	degrees
True anomaly	V[*N*]	degrees

Each satellite must have an independent set of six orbital parameters for orbit definition and subsequent propagation.

To define the characteristics of non-GSO earth stations, the following parameters, as specified in § B4.2 would be used:

Parameter description	Parameter name	Parameter units
Maximum number of co-frequency tracked non-GSO satellites	MAX_CO_FREQ [Latitude]	–
Earth station e.i.r.p. mask by latitude	ES_e.i.r.p.[lat]	$dB(W/BW_{ref})$
Minimum elevation angle	ES_MINELEV[Latitude] [Azimuth]	degree
Exclusion zone angle by latitude, potentially varying by satellite	MIN_EXCLUDE [Latitude]	degree
Average number of non-GSO ES active at the same time per km^2	ES_DENSITY	km^2
Average distance between cell or beam foot-print centres	ES_DISTANCE	km
The maximum number of non-geostationary earth stations tracked co-frequency by a non-geostationary satellite within the EPFD(up) calculation. If a value is not provided, it is assumed that the maximum number of earth stations tracked co-frequency by a non-geostationary satellite is equal to the number of earth stations created for the epfd↑ run	MAX_CO_FREQ_SAT	–
The minimum angle in degrees at the non-GSO satellite between the lines to any two active non-GSO earth stations. Assumed to be zero if not provided	MIN_ANGLE_AT_SAT	degree
Minimum angle in degrees at the surface of the Earth between the lines to any two active non-GSO satellites. Assumed to be zero if not provided. Not applicable if the MIN_DURATION[Latitude] is non-zero	MIN_ANGLE_AT_ES	degree

Note that the minimum track duration is not used for the epfd(up) case.

D5.2.4.3 GSO system parameters

The GSO system can be either calculated or use worst-case parameters using the algorithm in § D3.2 or entered values. The required parameters as specified are:

Parameter description	Parameter name	Parameter units
GSO satellite longitude	GSO_SAT_LONG	degree
GSO boresight latitude	BS_LAT	degree
GSO boresight longitude	BS_LONG	degree
GSO reference gain pattern	GSO_SAT_PATTERN	One of those in § D6.5

These parameters are defined in §§ D6.1 and D6.2.

D5.2.4.4 Run parameters

The following run parameters should be calculated using the algorithm in § D4:

Parameter description	Parameter name	Parameter units
Time step	TSTEP	s
Number of time steps	NSTEPS	–

D5.2.5 Production of non-GSO earth station distribution

In the case that the non-GSO ES locations are defined by a distribution, the following method should be used:

Step 1: Calculate the number of actual operating non-GSO earth stations that the representative earth station will represent using:

$$NUM\_ES = ES\_DISTANCE * ES\_DISTANCE * ES\_DENSITY$$

Step 2: Calculate e.i.r.p. to use for each representative non-GSO earth station using:

$$REP\_e.i.r.p. = ES\_e.i.r.p. + 10\log_{10}(NUM\_ES)$$

Step 3: Define the GSO service area as the region enclosed by the contour representing a relative gain of 15 dB.

Step 4: For every distance ES_DISTANCE in latitude and distance ES_DISTANCE in longitude within the service area defined in Step 3, locate a representative non-GSO earth station with radiating with REP_e.i.r.p.

If the supplied ES_DISTANCE is zero, then in Step 1 set NUM_ES = 1 and at Step 4 locate a single non_GSO ES at the boresight of the GSO satellite.

The NUM_ES is typically 1 for TDMA and FDMA systems and for CDMA systems equal to the number of co-frequency ES all operating on the same frequency at the same time and location. The ES_DISTANCE relates to the average distance between co-frequency beams.

The deployment method should be symmetric around the (latitude, longitude) of the GSO satellite's boresight, as shown in Fig. 45.

FIGURE 45

Deployment method for non-GSO earth stations
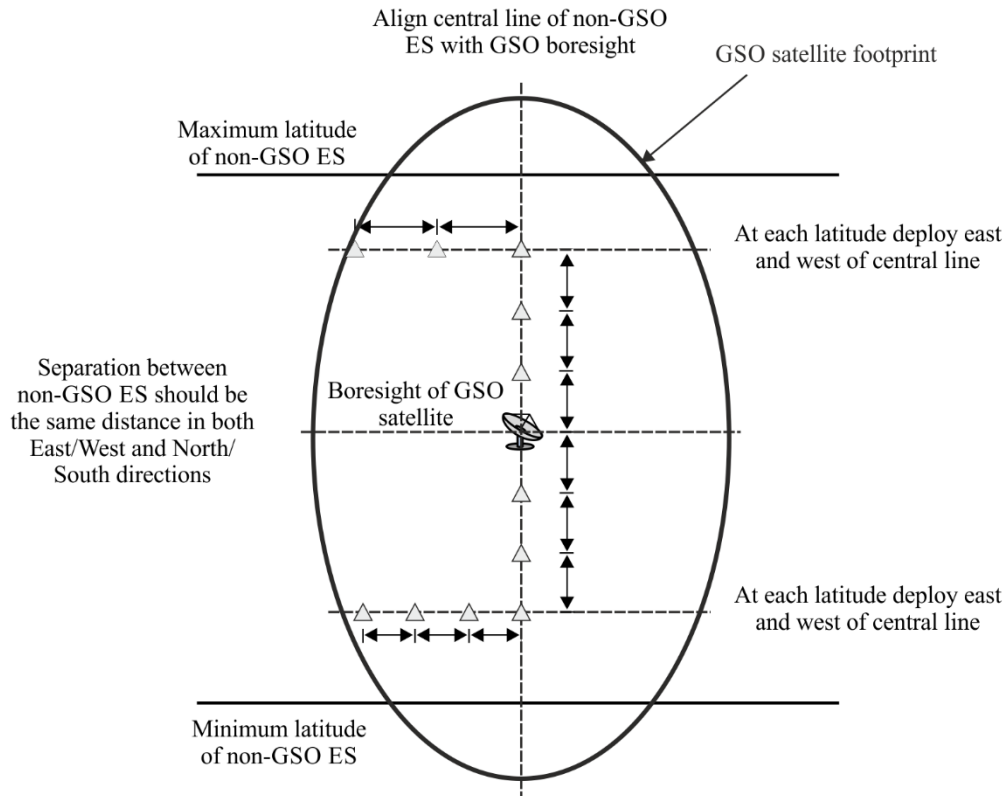
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No non-GSO ESs should be deployed below the minimum latitude or above the maximum latitude, where these two extreme values are derived using the methodology in § D3.2.3.

The separation in latitude in radians between non-GSO ES can be calculated from the distance using:

$$\Delta lat = \frac{d}{R_e}$$

The separation in longitude in radians between non-GSO ES can be calculated using:

$$\Delta long = \frac{d}{R_e \cos lat}$$

D5.2.6 Algorithms and calculation procedures

To calculate epfd↑ values from one non-GSO system into one GSO system satellite the following algorithm should be used. The algorithm can be used on multiple GSO systems in parallel if required:

Step 1: Read in parameters for non-GSO system as specified in § D5.2.4.2.

Step 2: Read in GSO parameters as specified in § D5.2.4.3.

Step 3: If required calculate maximum epfd GSO location using the algorithm in § D3.2 otherwise use the GSO satellite and ES location requested.

Step 4: If required calculate locations of non-GSO earth stations using the algorithm in § D5.2.5.

Step 5: Initialize statistics by zeroing all bins of epfd↑ values.

Step 6: If required calculate number of time steps and time step size using the algorithm in § D4 and hence calculate end time.

If a dual time step algorithm is included then use Sub-step 6.1, otherwise $N_{coarse} = 1$ all the time.

Sub-step 6.1: Calculate coarse step size $T_{coarse} = T_{fine} * N_{coarse}$.

Step 7: Repeat Steps 8 to 24 for all time steps.

If a dual time step algorithm is included, then repeat Sub-step 7.1 to Step 22 until end time is reached.

Sub-step 7.1: If it is the first-time step then set $T_{step} = T_{fine}$.

Sub-step 7.2: Otherwise if there are less than N_{coarse} steps remaining then set $T_{step} = T_{fine}$.

Sub-step 7.3: Otherwise if any of the α angles for the last time step were within φ_{coarse} of the exclusion zone angle then set the $T_{step} = T_{fine}$; otherwise, use $T_{step} = T_{coarse}$.

Step 8: Update position vectors of all earth stations using algorithm in § D6.1.

Step 9: Update position and velocity vectors of all non-GSO satellites using algorithm in § D6.3.2.

Step 10: Update position vectors of GSO satellite using algorithm in § D6.2.

Step 11: Initialise a list of possible links comprising triples of {non-GSO satellite, non-GSO ES, $epfd{\uparrow}_I$ } to be an empty list.

Step 12: Set the counter of times each satellite is used to zero for all satellites.

Step 13: Set the counter of times each non-GSO ES is used to zero for all non-GSO ES.

Step 14: Repeat Steps 15 to 24 for all non-GSO earth stations.

Step 15: Determine if this non-GSO earth station is visible to the GSO satellite using the algorithm in § D6.4.1.

Step 16: If the non-GSO earth station is visible to the GSO satellite then do Steps 17 to 24.

Step 17: For all non-GSO satellites repeat Steps 18 to 24.

Step 18: If this non-GSO satellite is a) visible to the non-GSO ES and b) above the minimum elevation angle ε_0[latitude][Azimuth$_{NGSO}$] at the non-GSO for this latitude and the non-GSO satellite's azimuth and c) outside the exclusion zone for this latitude α_0[latitude], undertake Steps 19 to 24.

Step 19: Calculate ES_e.i.r.p.[lat] (dB(W/BW$_{raf}$)) of non-GSO earth station at its given latitude in direction of GSO satellite using non-GSO earth station e.i.r.p. mask in § C3.

$$REP\_e.i.r.p. = ES\_e.i.r.p.[lat, off\text{-}axis\ angle] + 10\log_{10}(NUM\_ES)$$

Step 20: Calculate G_{RX} = receive relative gain (dB) at GSO satellite using relevant gain pattern specified in the algorithms in § D6.5.

Step 21: Calculate D = distance (km) between the non-GSO earth station and the GSO satellite using the algorithm in § D6.4.1.

Step 22: Calculate the spreading factor $L_{FS} = 10\log(4\pi D^2) + 60$.

Step 23: Calculate $epfd{\uparrow}_i$ for this non-GSO satellite:

$$epfd{\uparrow}_i = REP\_e.i.r.p. - L_{FS} + G_{RX} - G_{max}$$

Step 24: Add to the list of possible links this {non-GSO Satellite, non-GSO ES, $epfd{\uparrow}_i$ }.

Step 25: Sort the list of possible links by $epfd{\uparrow}_i$ with the highest $epfd{\uparrow}_i$ at the top.

Step 26: Set $epfd{\uparrow} = 0$.

Step 27:   If the list of possible links is empty jump to Step 35 otherwise repeat Steps 28 to 34 for the link {non-GSO satellite, non-GSO ES, epfd↑$_i$ } on the list of possible link with the highest epfd↑$_i$

Step 28:   Increment the epfd↑ by this link's epfd↑$_i$

Step 29:   Increment the counter of the number of times this link's non-GSO satellite has been used.

Step 30:   If this non-GSO satellite counter is equal to MAX_CO_FREQ_SAT then remove all remaining links on the list of possible links that use this non-GSO satellite.

Step 31:   Increment the counter of the number of times this link's non-GSO ES has been used.

Step 32:   If this non-GSO ES counter is equal to MAX_CO_FREQ then remove all remaining links on the list of possible links that use this non-GSO ES.

Step 33:   If the MIN_ANGLE_AT_ES is non-zero, then remove all links from the list that have an angle at the ES to this link's non-GSO satellite is less than MIN_ANGLE_AT_ES.

Step 34:   If the MIN_ANGLE_AT_SAT is non-zero, then remove all links from the list that have an angle at the satellite to this link's non-GSO satellite is less than MIN_ANGLE_AT_SAT.

Step 35:   Increment epfd↑ statistics by this epfd↑.

         If a dual time step algorithm is included, then the step below should be used:

         Sub-step 35.1:   Increment epfd↑ statistics by the epfd↑ for this time step by T_{step}/T_{fine} entries.

Step 36:   Generate the epfd↑ CDF from the epfd↑ pdf using the algorithm in § D7.1.2.

Step 37:   Compare epfd↑ statistics with limits using the algorithm in § D7.1.

Step 38:   Output results in format specified in § D7.2.

D5.2.7   Calculation of e.i.r.p.

If the ES_e.i.r.p. mask is of the form ES_e.i.r.p.(lat)(θ) then find the table with the nearest latitude to the non-GSO ES under consideration, and then use that to undertake linear interpolation in ES_e.i.r.p. against the off-axis angle at the non-GSO ES towards the GSO satellite.

If the ES_e.i.r.p. mask is of the form ES_e.i.r.p.(lat)(az)(el)(DeltaLongES) then find the table with the nearest latitude to the non-GSO ES under consideration. Within that table, find the (az)(el) array with the smallest angular offset to the (azimuth, elevation) of the non-GSO satellite as seen by the non-GSO ES. Use that array to undertake linear interpolation in ES_e.i.r.p. against the difference in longitude between the non-GSO ES and the GSO satellite.

D5.2.8   Outputs

The result of the algorithm is two arrays of size Nepfd↑ in format:

Array of Nepfd_UP epfd↑ values	epfd_UP_CALC[I]	dB(W/(m^2 · BW$_{ref}$))
Array of Nepfd_UP percentages	PC_CALC[I]	%

where PC_CALC[I] is the percentage of time epfd_UP_CALC[I] is exceeded.

D5.3   epfd$_{is}$ software description

This section describes the algorithm to calculate epfd$_{is}$ from non-GSO space stations into a GSO uplink. From the e.i.r.p. and off-axis angle for each space station, the epfd$_{is}$ at the GSO space station

can be calculated. This is repeated for a series of time steps until a distribution of $epfd_{is}$ is produced. This distribution can then be compared with the limits to give a go/no go decision.

D5.3.1 Configuration parameters

This sub-section specifies the parameters required for all $epfd_{is}$ calculations. This would be a data-set of N sets of limits that can be shared between runs. The Table could be queried so that the required values can be used depending upon non-GSO system frequency.

For each set of limits the following would be defined as derived in § D2.1.

Parameter name	Parameter value	Parameter units and ranges
Frequency band start	FREQ	MHz
GSO gain pattern	FEND_IS	One of those in § D5.5
GSO peak gain	GSO_SAT_PEAKGAIN	dBi
GSO half power beamwidth	GSO_SAT_BEAMWIDTH	degrees
Reference bandwidth	RIFBW	kHz
Number of $epfd_{is}$ points	Nepfd_IS	–
Array of Nepfd_IS $epfd_{is}$ values	epfd_IS[I]	$dB(W/(m^2 \cdot BW_{rif}))$
Array of Nepfd_IS percentages	PC_IS[I]	%

D5.3.2 Determination of maximum epfd configuration

The maximum epfd location of GSO satellite and beam centre is defined in § D3.3.

D5.3.3 Calculation of run steps

A single time step and number of time steps are calculated using the algorithm in § D4.

D5.3.4 Input parameters

This sub-section defines the input parameters for a particular non-GSO system scenario. In this case, input is a generic term that could include files or user input. Information is required for:

– non-GSO system;

– GSO system;

– run configuration.

D5.3.4.1 Non-GSO system parameters

The following parameters, as specified in § B2.1 would be used:

Parameter description	Parameter name	Parameter units
Number of non-GSO satellites	N_{sat}	–
Orbit has repeating ground track maintained by station keeping	Yes or No	–
Administration is supplying specific node precession rate	Yes or No	–
Station keeping range for ascending node as half total range	W_{delta}	degrees

For each satellite the following parameters specified in § B2.1 would be used, where the definitions of the parameters are specified in § D6.3.1 at the time of the start of the simulation.

Note that in the Table below, the indices [*N*] are present to indicate that there would be a different value for each satellite, and the *N*-th value corresponds to the *N*-th satellite.

Parameter description	Parameter name	Parameter units
Semi-major axis	A[*N*]	km
Eccentricity	E[*N*]	–
Inclination	I[*N*]	degrees
Longitude of ascending node	O[*N*]	degrees
Argument of perigee	W[*N*]	degrees
True anomaly	V[*N*]	degrees

Each satellite must have an independent set of six orbital parameters for orbit definition and subsequent propagation.

To define the characteristics of non-GSO space stations, the following parameters, as specified in § B4.3 would be used:

Parameter description	Parameter name	Parameter units
e.i.r.p. per space station by latitude	non-GSO_SS_e.i.r.p.[Lat][φ]	dB(W/BW$_{rif}$)
Minimum transmit frequency[1]	IS_F	GHz

[1]   The filing administration can supply a set of space station e.i.r.p. masks and associated frequency range for which the mask is valid.

D5.3.4.2 GSO system parameters

The GSO system can either use worst-case parameters using the algorithm in § D5.2 or entered values. The required parameters are:

Parameter description	Parameter name	Parameter units
GSO satellite longitude	GSO_SAT_LONG	degrees
GSO boresight latitude	BS_LAT	degrees
GSO boresight longitude	BS_LONG	degrees
GSO reference gain pattern	GSO_SAT_PATTERN	One of those in § D5.5

These parameters are defined in §§ D6.1 and D6.2.

D5.3.4.3 Run parameters

The following run parameters should be calculated using the algorithm in § D4:

Parameter description	Parameter name	Parameter units
Time step	TSTEP	s
Number of time steps	NSTEPS	–

D5.3.5 Algorithms and calculation procedures

In the calculation of the dual time step for the epfd$_{is}$ computation, $N_{coarse} = 1$.

To calculate epfd$_{is}$ values from one non-GSO system into one GSO system satellite the following algorithm should be used. The algorithm can be used on multiple GSO systems in parallel if required:

Step 1:   Read in parameters for non-GSO system as specified in § D5.3.4.2.

Step 2:   Read in GSO parameters as specified in § D5.3.4.3.

Step 3:   If required calculate worst-case GSO location using algorithm in § D3.3.

Step 4:   Initialize statistics by zeroing all bins of epfd$_{is}$ values.

Step 5:   If required calculate number of time steps and time step size using algorithm in § D4 and hence calculate end time.

   If a dual time step algorithm is included then use Sub-step 5.1, otherwise $N_{coarse} = 1$ all the time.

   Sub-step 5.1: Calculate coarse step size $T_{coarse} = T_{fine} * N_{coarse}$.

Step 6:   Repeat Steps 7 to 19 for all time steps.

   If a dual time step algorithm is included, then repeat Sub-step 6.1 to Step 17 until end time is reached.

   Sub-step 6.1: If it is the first-time step then set $T_{step} = T_{fine}$.

   Sub-step 6.2: Otherwise if there are less than N_{coarse} steps remaining then set $T_{step} = T_{fine}$.

   Sub-step 6.3: Otherwise, if any of the α angles for the last time step were within φ_{coarse} of the exclusion zone angle then set the $T_{step} = T_{fine}$; otherwise, use $T_{step} = T_{coarse}$.

Step 7:   Update position and velocity vectors of all non-GSO satellites using algorithm in § D6.3.

Step 8:   Update position vectors of GSO satellite using algorithm in § D6.2.

Step 9:   Set epfd$_{is} = 0$.

Step 10: Repeat Steps 10 to 18 for all non-GSO space stations.

Step 11: Determine if this non-GSO space station is visible to the GSO satellite using the algorithm in § D6.4.1.

Step 12: If the non-GSO space station is visible to the GSO satellite then do Steps 13 to 18.

Step 13: Calculate e.i.r.p. (dB(W/BW$_{rif}$)) of non-GSO space station in direction of GSO satellite using the e.i.r.p. mask in § C3 for the non-GSO space station's latitude.

Step 14: Calculate G_{RX} = receive relative gain (dB) at GSO satellite using relevant gain pattern specified in algorithms in § D6.5.

Step 15: Calculate D = distance (km) between the non-GSO space station and the GSO satellite using the algorithm in § D6.4.1.

Step 16: Calculate the spreading factor $L_{FS} = 10 \log(4\pi D^2) + 60$.

Step 17: Calculate epfd$_{isi}$ for this non-GSO satellite:

$$epfd_{isi} = e.i.r.p. - L_{FS} + G_{RX} - G_{max}$$

Step 18: Increment epfd$_{is}$ by epfd$_{isi}$.

   Sub-step 19:   Increment epfd$_{is}$ statistics by this epfd$_{is}$.

   If a dual time step algorithm is included then the step below should be used:

   Sub-step 19.1: Increment epfd$_{is}$ statistics by the epfd$_{is}$ for this time step by T_{step}/T_{fine} entries.

Step 20: Generate the epfd$_{is}$ CDF from the epfd$_{is}$ pdf using the algorithm in § D7.1.2.

Step 21: Compare epfd$_{is}$ statistics with limits using algorithm in § D7.1.

Step 22: Output results in format specified in § D7.2.

D5.3.6 Outputs

The result of the algorithm is two arrays in format:

Array of Nepfd_IS epfd$_{is}$ values	epfd_IS_CALC[I]	dB(W/(m^2 · BW$_{rif}$))
Array of Nepfd_IS percentages	PC_CALC[I]	%

where PC_CALC[I] is percentage of time epfd_IS_CALC[I] is exceeded.

D6 Geometry and algorithms

This section describes the geometry that defines the core algorithms used in the software. One aspect is the conversion into a generic cartesian vector-based coordinate system. The precise orientation of the *X* vector is not specified in this Recommendation to allow alternative implementations by developers. The axis chosen should not impact the results as satellite and Earth coordinates are defined relative to the Earth.

To aid developers examples coordinate systems are used to show how to convert to and from generic vectors.

D6.1 Earth coordinates system

Figure 46 shows the reference coordinate system for earth stations.

FIGURE 46

Definition of latitude
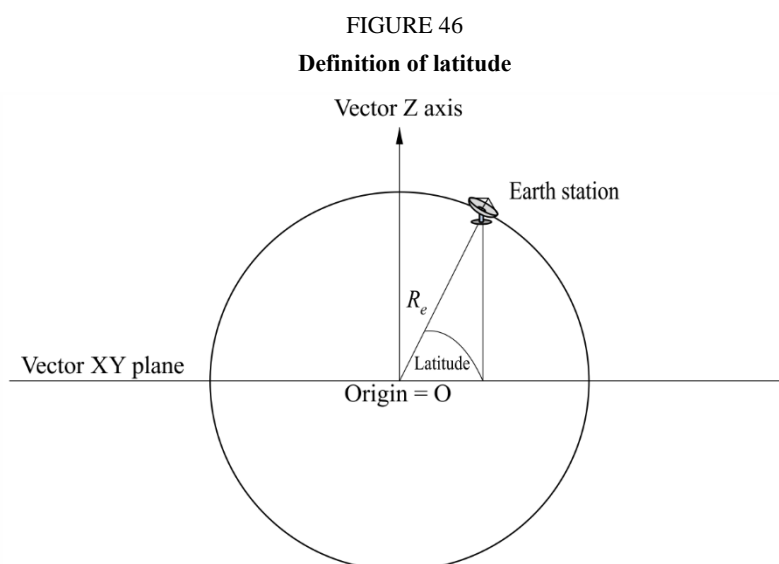
S.1503-46

The Earth is defined as a sphere with radius as specified in § A2.2 = R_e. The Earth rotates around an axis, the Z axis, at a rate defined in § A2.2 = Ω_e. Perpendicular to the Z axis, crossing the Earth at the Equator, is the XY plane.

Earth stations are located on this sphere based upon two angles:

Latitude: angle between line from centre of Earth to earth station and XY plane;

Longitude: angle as shown in Fig. 47.

FIGURE 47

Definition of longitude
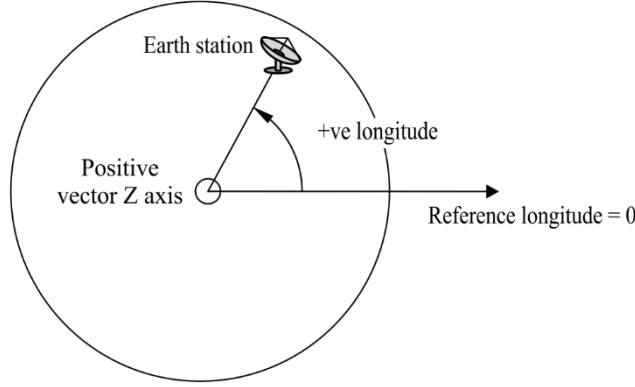
S.1503-47

Earth stations are assumed to have constant (latitude, longitude) positions in time.

The orientation within the XY plane of the X and Y axes is not specified in this Recommendation as all locations are referenced to the Earth rather than one particular inertial frame. This allows different implementations to use different reference points if required without impacting on the results.

One possible implementation is what is described as the geocentric inertial system. For this example case, conversion from geographic coordinates is achieved using:

$$\text{Long} = \arccos\left(\frac{x}{\sqrt{x^2+y^2}}\right) \qquad \text{if } y \geq 0 \tag{5}$$

$$\text{Long} = -\arccos\left(\frac{x}{\sqrt{x^2+y^2}}\right) \qquad \text{if } y < 0 \tag{6}$$

$$\text{Lat} = \arctan\left(\frac{z}{\sqrt{x^2+y^2}}\right) \tag{7}$$

If this example coordinate system is used, then the conversion from geographic coordinates into geocentric inertial system coordinates is:

$$x = R_e \cos(\text{lat}) \cos(\text{long}) \tag{8}$$

$$y = R_e \cos(\text{lat}) \sin(\text{long}) \tag{9}$$

$$z = R_e \sin(\text{lat}) \tag{10}$$

where:

(x, y, z): coordinates in the geocentric inertial system

long: geographic longitude

lat: geographic latitude.

In this example geocentric inertial reference system, the equation for motion of a mass point on the Earth's surface would be as:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} R_e \cos(\text{lat}) \cos(\text{lon} + \Omega_e t) \\ R_e \cos(\text{lat}) \sin(\text{lon} + \Omega_e t) \\ R_e \sin(\text{lat}) \end{bmatrix} \tag{11}$$

where:

lat: geographic latitude of the mass point on the Earth's surface

lon: geographic longitude of the mass point on the Earth's surface

t: time

Ω_e: angular rate of rotation of the Earth.

D6.2   GSO satellite coordinate system

The geostationary arc is a circle in the XY plane at a distance of R_{geo} from the Earth's centre where R_{geo} is specified in § A2.2. Individual geostationary satellites have location on this circle defined by a longitude as shown in Fig. 48.

FIGURE 48

Definition of GSO satellite longitude
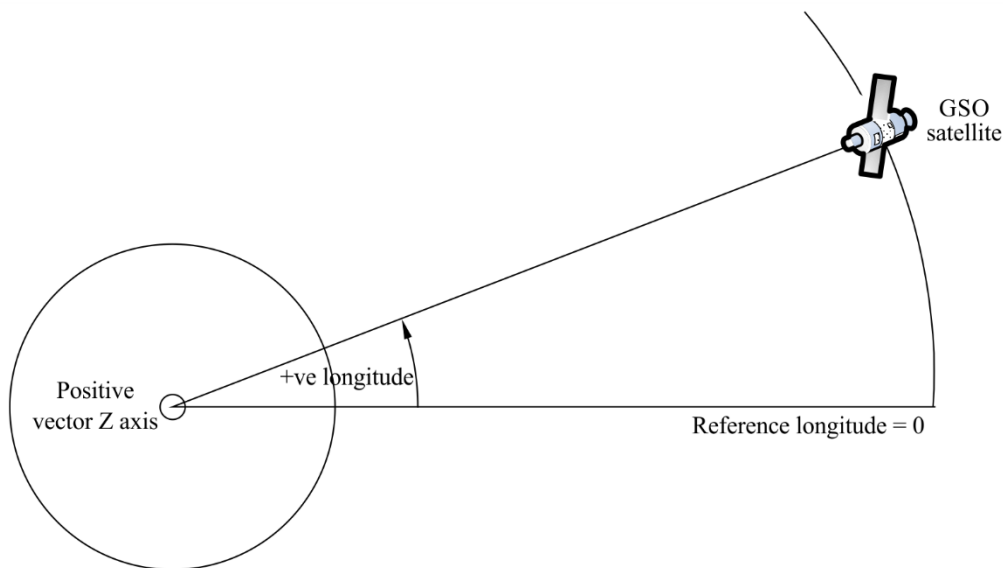
S.1503-48

Geostationary satellites are assumed to have constant longitude in time. The conversion to and from vectors can use the same algorithms as in the section above by setting the latitude to zero.

D6.3   Non-GSO satellite coordinate system

D6.3.1 Non-GSO satellite orbit parameters

This section defines the parameters that specify an orbit for non-GSO satellites. Non-GSO satellites move in a plane as shown in Fig. 49.

FIGURE 49

Orbit plane angles
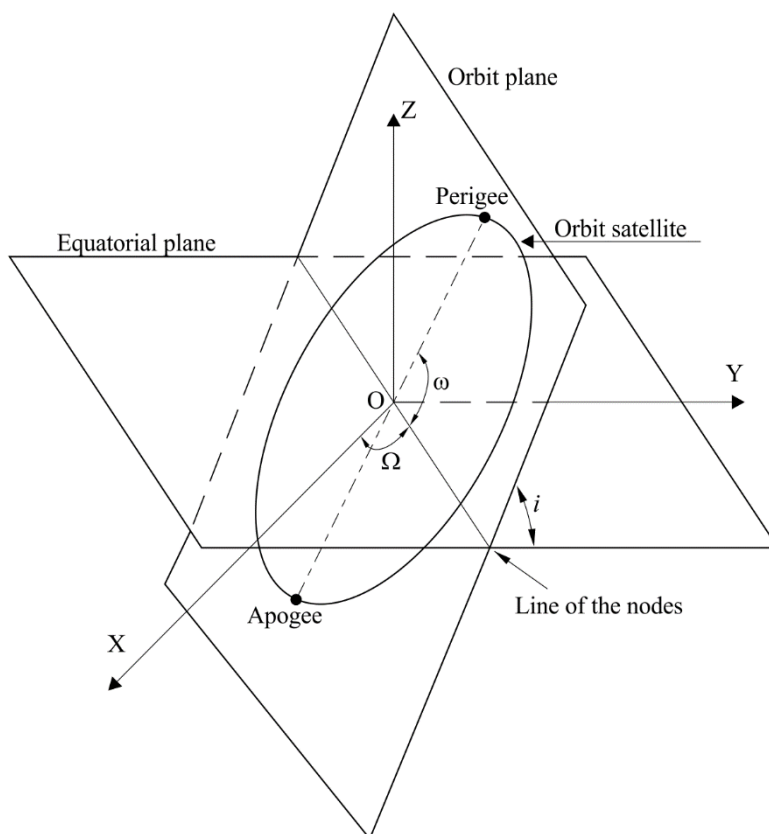
S.1503-49

The plane of the orbit is referenced to the Earth by two angles:

Ω: longitude of ascending node: This defines where the ascending orbit plane intersects the equatorial plane. As the orbit is fixed in inertial space while the Earth rotates, a time reference for which this angle is valid must be given. In this case it is the start of the simulation

i: inclination angle: This is defined as the angle between the plane of the orbit and the equatorial plane.

The orbit and position of the non-GSO satellite within the orbit is then defined by further parameters as shown in Fig. 50.
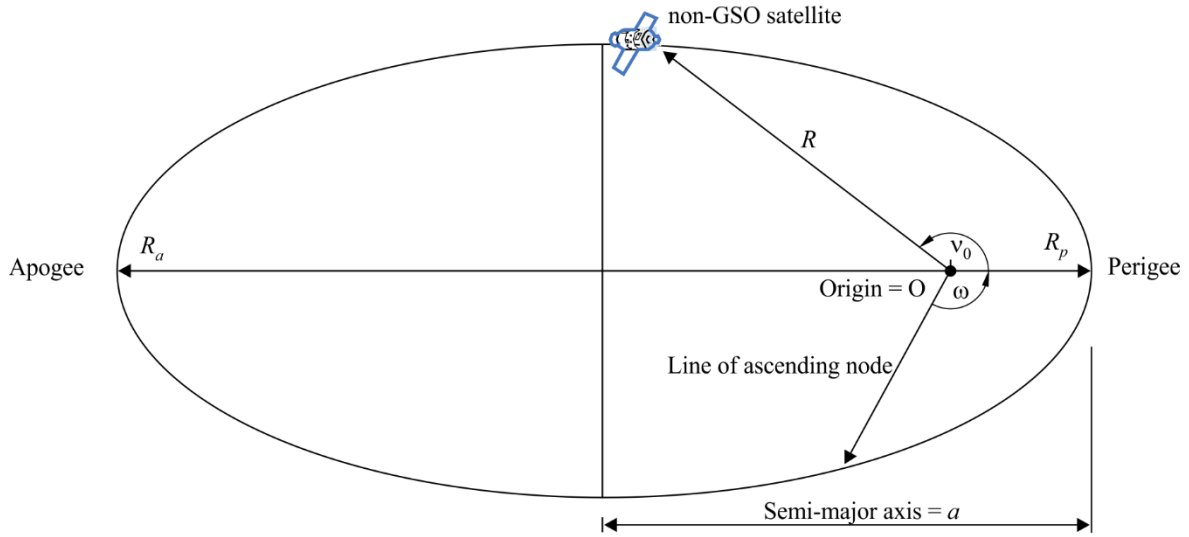
S.1503-50

The shape of the orbit is defined by:

$$a = (R_a + R_p)/2 \tag{12}$$

$$e = (R_a - R_p) / (R_a + R_p) \tag{13}$$

where:

    a: semi-major axis

    e: eccentricity

    R_a: distance from the centre of the Earth to the satellite at apogee

    R_p: distance from the centre of the Earth to the satellite at perigee.

The position of the perigee within the orbit plane is defined by:

    ω: argument of perigee, angle between the line of the nodes and perigee.

The position of a non-GSO satellite within the plane at a particular time is defined by:

    v_0:   angle between perigee and specified point on orbit.

For circular orbits, ω can be set to zero and v_0 assumed to be the same as the argument of latitude defined as:

$$\mu_0 = \omega + \upsilon_0 \tag{14}$$

Other useful terms are:

$$p = a(1 - e^2) \tag{15}$$

$$M = E - e \sin E \tag{16}$$

$$\tan\frac{v}{2} = \sqrt{\frac{1+e}{1-e}} \tan\frac{E}{2} \tag{17}$$

$$R = \frac{p}{1 + e\cos(v)} \tag{18}$$

$$T = 2\pi\sqrt{a^3/\mu} \tag{19}$$

where:

        p: focal parameter

        E: eccentric anomaly

        M: mean anomaly

        T: period of orbit

        R: distance from centre of Earth to satellite when satellite is at position ν.

These can be used by the algorithm to predict the future position of the non-GSO satellite as described in § D5.

D6.3.2 Non-GSO satellite orbit predictor

Given the orbital elements in the section above, standard orbit mechanics can be used to predict the position of the satellite at future times. In addition there are three additional precession factors for the ascending node and argument of perigee as described below.

Line of nodes

$$\overline{n} = n_0\left(1 + \frac{3}{2}\frac{J_2 R_e^2}{p^2}\left(1 - \frac{3}{2}\sin^2(i)\right)(1 - e^2)^{1/2}\right) \tag{20}$$

where:

    $J_2 = 0.001082636$

    $n_0 = \sqrt{\dfrac{\mu}{a^3}}$

Orbit precession in ascending node longitude

The rate of ascending node longitude secular drift is defined as:

$$\Omega_r = -\frac{3}{2}\frac{J_2 R_e^2}{p^2}\overline{n}\cos(i) \tag{21}$$

It follows from the above that polar orbits have zero precession rate and equatorial ones have a maximum precession rate. With direct satellite motion ($i < 90°$) the ascending node shifts to the west (to Ω decreasing) and with reverse satellite motion ($i > 90°$) it shifts to the east (to Ω increasing).

Perigee argument precession

Perigee argument secular shift rate is defined as:

$$\omega_r = \frac{3}{2}\frac{J_2 R_e^2}{p^2}\overline{n}\left(2 - \frac{5}{2}\sin^2(i)\right) \tag{22}$$

Perigee argument precession rate at $i = 0$ and $i = 180$ is maximum. For $i_1 = 63°26'06''$ or $i_2 = 116°33'54''$ the precession rate is zero. If $i < i_1$ or $i > i_2$, then the perigee precession is along a satellite motion direction, and if $i_1 < i < i_2$, then it is in the opposite direction.

Use of precession terms

Perigee argument is defined as:

$$\omega = \omega_0 + \omega_r t \tag{23}$$

where:

        ω_0:   perigee argument at an initial moment

ω_r: perigee argument precession rate.

A current value of an ascending node longitude is defined as:

$$\Omega = \Omega_0 + \Omega_r t \tag{24}$$

where:

Ω_0: ascending node longitude at an initial moment

Ω_r: ascending node longitude precession rate.

The revised orbit period is then:

$$T_P = \frac{2\pi}{w_r + \bar{n}} \tag{25}$$

The conversion to generic cartesian-based vector would depend upon the direction of the X vector. For an example coordinate system and for circular orbits, the satellite motion expression in the geocentric inertial reference system could be defined as:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} R(\cos(v + \omega)\cos(\Omega) - \sin(v + \omega)\sin(\Omega)\cos(i)) \\ R(\cos(v + \omega)\sin(\Omega) + \sin(v + \omega)\cos(\Omega)\cos(i)) \\ R\sin(v + \omega)\sin(i) \end{bmatrix} \tag{26}$$

And the velocity vector could be defined as:

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \end{bmatrix} = \begin{bmatrix} \frac{xhe}{Rp}\sin(v) - \frac{h}{R}(\cos(\Omega)\sin(\omega + v) + \sin(\Omega)\cos(\omega + v)\cos(i)) \\ \frac{yhe}{Rp}\sin(v) - \frac{h}{R}(\sin(\Omega)\sin(\omega + v) - \cos(\Omega)\cos(\omega + v)\cos(i)) \\ \frac{zhe}{Rp}\sin(v) + \frac{h}{R}\sin(i)\cos(\omega + v) \end{bmatrix} \tag{27}$$

$$h = \sqrt{\mu p}$$

h: specific angular momentum

ECF (Earth Centered and Fixed) components of the position and velocity vectors could be defined as:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix}_{ECF} = \begin{bmatrix} x\cos(\theta) + y\sin(\theta) \\ -x\sin(\theta) + y\cos(\theta) \\ z \end{bmatrix} \tag{28}$$

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \end{bmatrix}_{ECF} = \begin{bmatrix} \dot{x}\cos(\theta) + \dot{y}\sin(\theta) + \Omega_e y_{ECF} \\ -\dot{x}\sin(\theta) + \dot{y}\cos(\theta) - \Omega_e x_{ECF} \\ \dot{z} \end{bmatrix} \tag{29}$$

where Ω_e is a rotation rate of the earth $\left(7,2921158553 * 10^{-5} \frac{rad}{sec}\right)$ and θ is the Greenwich hour angle of the Earth's prime meridian, i.e. the angle between the inertial x axis and ECF x axis.

A satellite motion in an elliptical orbit is non-uniform; therefore, the Kepler expression and a concept of a mean anomaly would be used in the model to define the real anomaly as a function of time. Since an explicit dependence of the true anomaly on time is unavailable; the numerical methods of solving the below expressions were used for its definition. The expression is:

$$M = M_0 + \bar{n}t \tag{30}$$

Kepler's equation $M = E - esin(E)$ can be solved with Newton-Raphson method to obtain the true anomaly:

$$E_0 = M_0 = \arccos\left(\frac{e+\cos(v_0)}{1+\cos(v_0)}\right) \tag{31}$$

$$E_{i+1} = E_i - \frac{E_i - e\sin(E_i) - M}{1 - e\cos(E_i)} \tag{32}$$

D6.3.3 Conversion to Generic Cartesian-based Vectors

The conversion to generic Cartesian-based vector would depend upon the direction of the X vector, but an approach based upon the X vector aligned with the direction in which the ascending node longitude is zero is as follows:

1. For the relevant time t in seconds since simulation start, calculate the values of the processing terms (ω, Ω, M) as required using the decision tree in § D6.3.5.

2. From M calculate the eccentric anomaly E using equation (16) and iteration.

3. From E calculate the true anomaly v using equation (17).

4. Hence calculate the radius vector R using equation (18).

5. Calculate the position of the satellite within the orbital plane in (P, Q) coordinates defined as in Fig. 51 below using:

$$\begin{pmatrix} p \\ q \\ 0 \end{pmatrix} = \begin{bmatrix} R\cos(v) \\ R\sin(v) \\ 0 \end{bmatrix} \tag{33}$$

6. Create the rotation matrix from satellite orbit coordinates to inertial xyz coordinates using:

$$\tilde{R} = \begin{bmatrix} R_{11} & R_{12} & R_{13} \\ R_{21} & R_{22} & R_{23} \\ R_{31} & R_{32} & R_{33} \end{bmatrix} \tag{34}$$

where:

$$R_{11} = \cos(\Omega)\cos(\omega) - \sin(\Omega)\sin(\omega)\cos(i) \tag{35}$$

$$R_{12} = -\cos(\Omega)\sin(\omega) - \sin(\Omega)\cos(\omega)\cos(i) \tag{36}$$

$$R_{13} = \sin(\Omega)\sin(i) \tag{37}$$

$$R_{21} = \sin(\Omega)\cos(\omega) + \cos(\Omega)\sin(\omega)\cos(i) \tag{38}$$

$$R_{22} = -\sin(\Omega)\sin(\omega) + \cos(\Omega)\cos(\omega)\cos(i) \tag{39}$$

$$R_{23} = -\cos(\Omega)\sin(i) \tag{40}$$
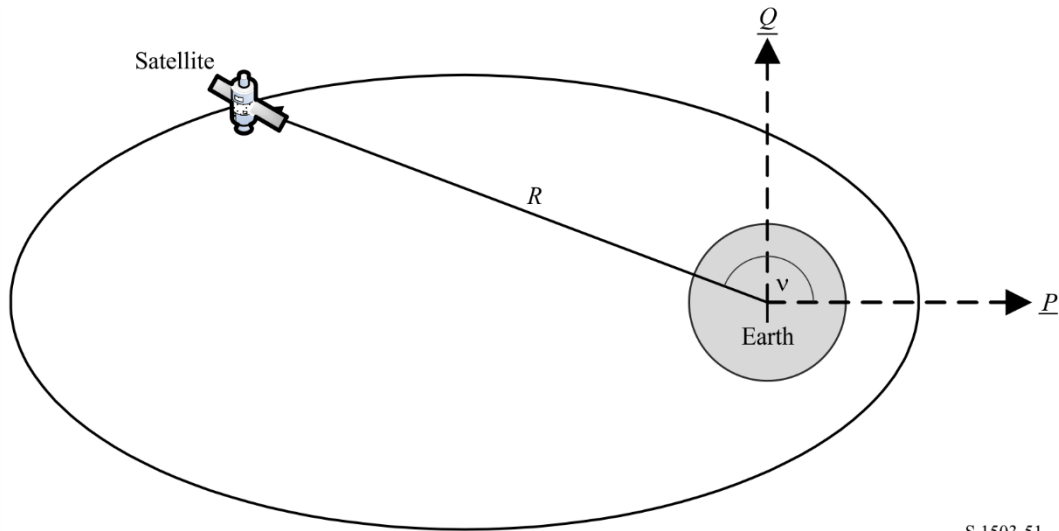
$$R_{31} = \sin(\omega)\sin(i) \tag{41}$$

$$R_{32} = \cos(\omega)\sin(i) \tag{42}$$

$$R_{33} = \cos(i) \tag{43}$$

7. Hence calculate the position of the satellite in xyz coordinates using:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \tilde{R}\begin{pmatrix} p \\ q \\ 0 \end{pmatrix} \tag{44}$$

FIGURE 51

Definition of satellite P, Q coordinates

S.1503-51

D6.3.4 Non-GSO satellite orbit station keeping

An important aspect to station keeping is to simulate multiple passes of the non-GSO satellite through an earth station's main beam with slightly different crossing directions. As changing the position within the plane does not affect this, then the main parameter to vary is the longitude of the ascending node.

The approach proposed is to give range $\pm W_{delta}$ in longitude of ascending node. At the start of the simulation all stations in the constellation have this parameter offset by $-W_{delta}$. During the simulation this field would increase to 0 (at the run's mid-point) and then increase to $\pm W_{delta}$.

This is implemented by rotating the station's position and velocity vectors around the Z axis by the required angle as specified in § D6.3.4.

D6.3.5 Forced orbit precession

The standard orbit prediction algorithm is based upon point Earth mass plus correcting factors for J_2 perturbations. There are two cases where this requires to be over-ridden:

a)   where administrations supply a detailed value of the orbit precession rate with respect to a point Earth mass to ensure a repeat ground track;

b)   for non-repeat orbits where an artificial precession rate is used to ensure the required spacing between equatorial passes.

D6.3.6 Combining the orbit models

The various options for the orbit model can be combined in three ways as shown Fig. 52.

FIGURE 52
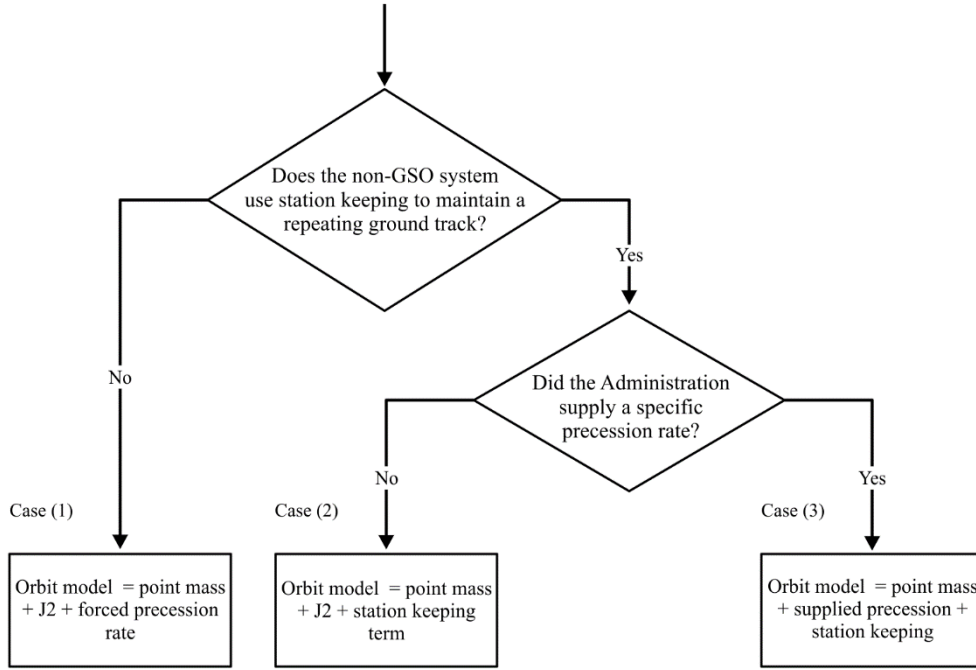
S.1503-52

Note that the equatorial orbit $i = 0$ constellation is a special case in that there is no station keeping but the ground track of each satellite repeats just after one orbit. It should therefore be treated as Case (1) but with forced precession set to zero as described in § D4.

The three cases have their key orbit angles in radians updated as follows:

Case 1

$$\omega(t) = w_0 + \omega_r t \tag{45}$$

$$\Omega(t) = \Omega_0 + \Omega_r t + \frac{\pi}{180} D_{artificial} t \tag{46}$$

$$M(t) = M_0 + \bar{n} t \tag{47}$$

Case 2

$$\omega(t) = w_0 + \omega_r t \tag{48}$$

$$\Omega(t) = \Omega_0 + \Omega_r t + \frac{\pi}{180} \cdot W_{delta} \left(\frac{2t}{T_{run}} - 1 \right) \tag{49}$$

$$M(t) = M_0 + \bar{n} t \tag{50}$$

Case 3

$$\omega(t) = w_0 \tag{51}$$

$$\Omega(t) = \Omega_0 + \frac{\pi}{180} D_{admin} t + \frac{\pi}{180} \cdot W_{delta} \left(\frac{2t}{T_{run}} - 1 \right) \tag{52}$$

$$M(t) = M_0 + n_0 t \tag{53}$$

where:

$\Omega_r =$ J_2 precession of longitude of the ascending node in radians / second

$\omega_r =$ J_2 precession of the argument of perigee in radians / second

$\overline{n} =$ orbit motion including the J_2 term in radians / second

$n_0 =$ orbit motion for point mass in radians / second

$D_{artificial} =$ artificial precession in degrees / second

$D_{admin} =$ admin supplied precession in degrees / second

$W_{\text{delta}} =$ station keeping range in degrees

$t =$ simulation time in seconds

$T_{run} =$ total run time of the simulation in seconds.

D6.3.7 Mapping orbit parameters from SRS data

The following orbit parameters are given in the SRS / IFIC database:

Table *orbit*:

– Apogee height (km) = h_a

– Perigee height (km) = h_p

– Inclination angle (degrees) = INC

– Right ascension (degrees) = RA

– Longitude of ascending node (degrees) = LAN

– Argument of perigee (degrees) = AP.

Table *phase*:

– Phase angle (degrees) = PA.

For most of these fields it is possible to map nearly directly to the orbit parameters required, such as:

$$a = R_e + \frac{h_a + h_p}{2}$$

$$e = \frac{h_a - h_p}{2a}$$

$$i = \text{INC}$$

$$\Omega = \text{LAN}$$

$$\omega = \text{AP}$$

Note that this algorithm uses the ascending node definition based upon longitude rather than right ascension to ensure the orbit is correctly referenced to earth station longitude.

The last field to define is the true anomaly, ν, which can be derived from the phase angle. The phase angle is defined in RR Appendix **4** as:

A.4.b.5.b: *the initial phase angle (ω_i) of the i-th satellite in its orbital plane at reference time t = 0, measured from the point of the ascending node ($0° \leq \omega_i < 360°$)*

The phase angle is shown in Fig. 53.

FIGURE 53
Definition of phase angle
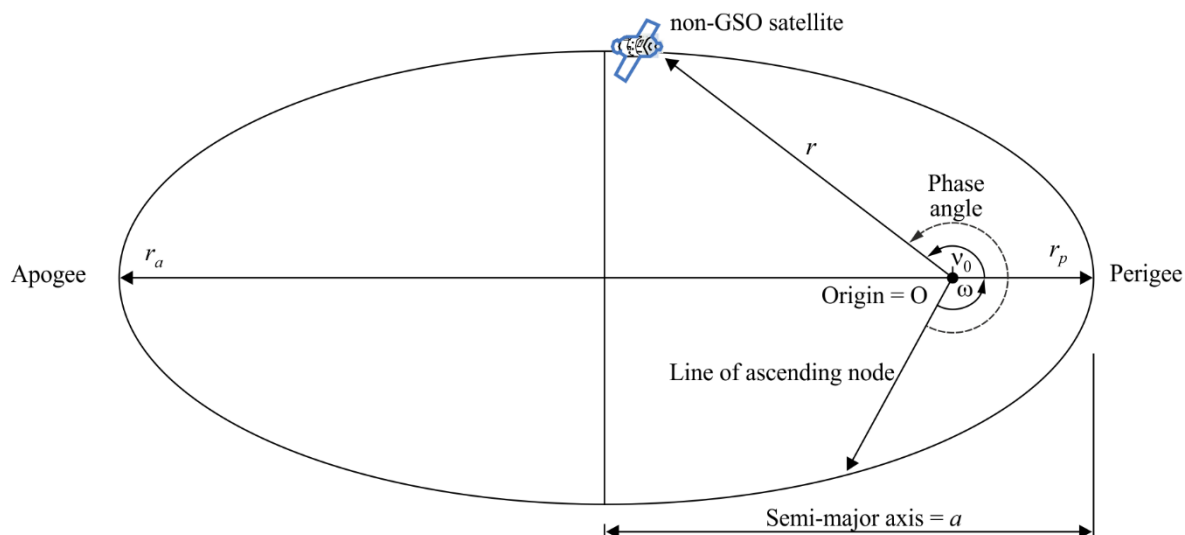
S.1503-53

The true anomaly can therefore be derived from the phase angle as follows:

$$\nu_0 = PA - \omega$$

or:

$$PA = \omega + \nu_0 = \mu_0$$

D6.4 Geometry

D6.4.1 Distance between two stations

Given two station's position vectors in the form (x, y, z), the distance D between them can be calculated using:

$$D = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2 + (z_1 - z_2)^2}$$

D6.4.2 Distance to Earth horizon

The distance to the horizon D_h for a station with Earth centred position vector of magnitude R can be calculated as follows:

$$D_h = \sqrt{R^2 - R_e^2}$$

D6.4.3 Satellite visibility check

Two stations, whether earth stations or satellites, are visible if the direct distance between them is less than the sum of the distance to the horizon for each station, using the spherical Earth model described in § D6.1.

D6.4.4 Angle to GSO arc and ΔLongitude

D6.4.4.1 Definition

Figure 54 shows the definition of the α angle.

FIGURE 54

Definition of α angle
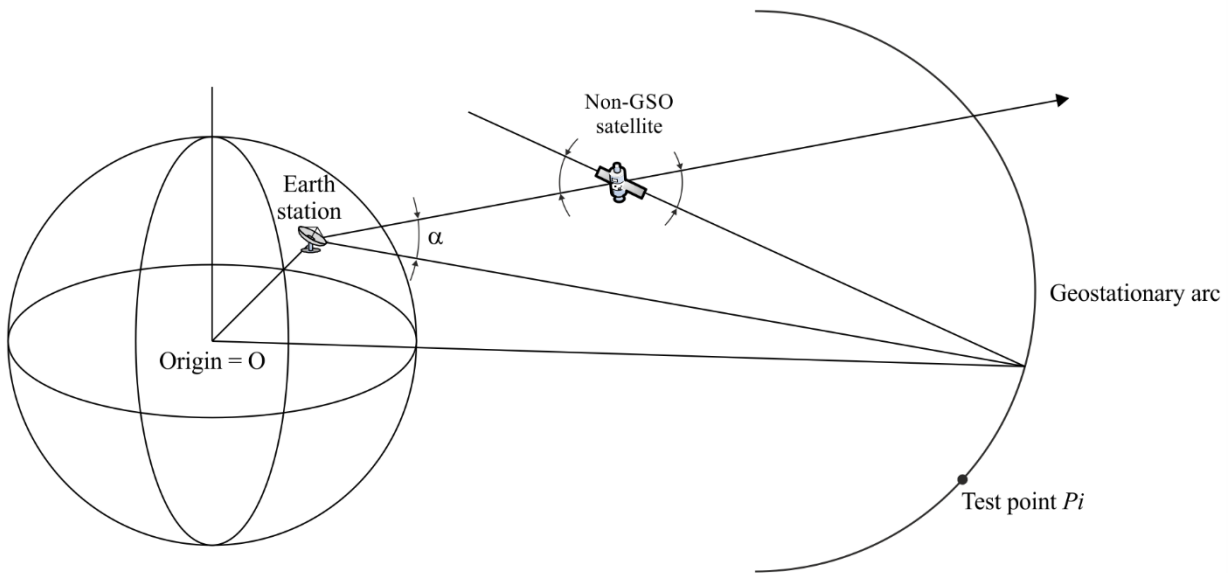
S.1503-54

The Figure shows a test earth station and non-GSO satellite.

For each test point P_i on the GSO arc, there is a line from the earth station that intersects that point. There is then an angle α_i between that line and a line from the earth station to the non-GSO satellite.

The α angle is the minimum of all the test points for which the line does not intersect the Earth, i.e.

$$\alpha = \min(\alpha_1)$$

The sign of α is determined by whether the line from the earth station to the non-GSO satellite intersects the XY plane at a distance less than or greater than the GSO radius as follows:

Given:

        Earth station position vector: $\underline{R}_{ES}$

        Non-GSO satellite position vector: $\underline{R}_{NS}$

        Construct line:

$$\underline{R} = \underline{R}_{ES} + \lambda \underline{R}_{EN}$$

where:

$$\underline{R}_{EN} = \underline{R}_{NS} - \underline{R}_{ES}$$

        This line crosses the XY plane when:

$$R(z) = 0$$

        i.e. when

$$\lambda_{z=0} = \frac{-R_{ES}(z)}{R_{EN}(z)}$$

Hence:

$$\underline{R}_{z=0} = \underline{R}_{ES} + \lambda_{z=0} \underline{R}_{EN}$$

The sign of α, X is then determined by:

If $\lambda_{z=0} < 0$ then $R_{z=0} =$ Infinity

In the case when the ES is in the northern hemisphere:

If $R_{z=0} < R_{geo}$ then α is positive

If $R_{z=0} = R_{geo}$ then α is zero

If $R_{z=0} > R_{geo}$ or if $\lambda_{z=0} \leq 0$ then α is negative.

In the case when the ES is in the southern hemisphere:

If $R_{z=0} > R_{geo}$ then α is positive

If $R_{z=0} = R_{geo}$ then α is zero

If $R_{z=0} < R_{geo}$ or if $\lambda_{z=0} \geq 0$ then α is negative.

In the case when the ES is at the equator:

α is the negative of the sign of $R_{EN}(z)$

From the test point identified to give the α angle, the Δlongitude can be calculated between the non-GSO sub-satellite point and the point on the GSO arc where the α angle is minimised, as shown in Fig. 55.

FIGURE 55

Definition of Δlongitude
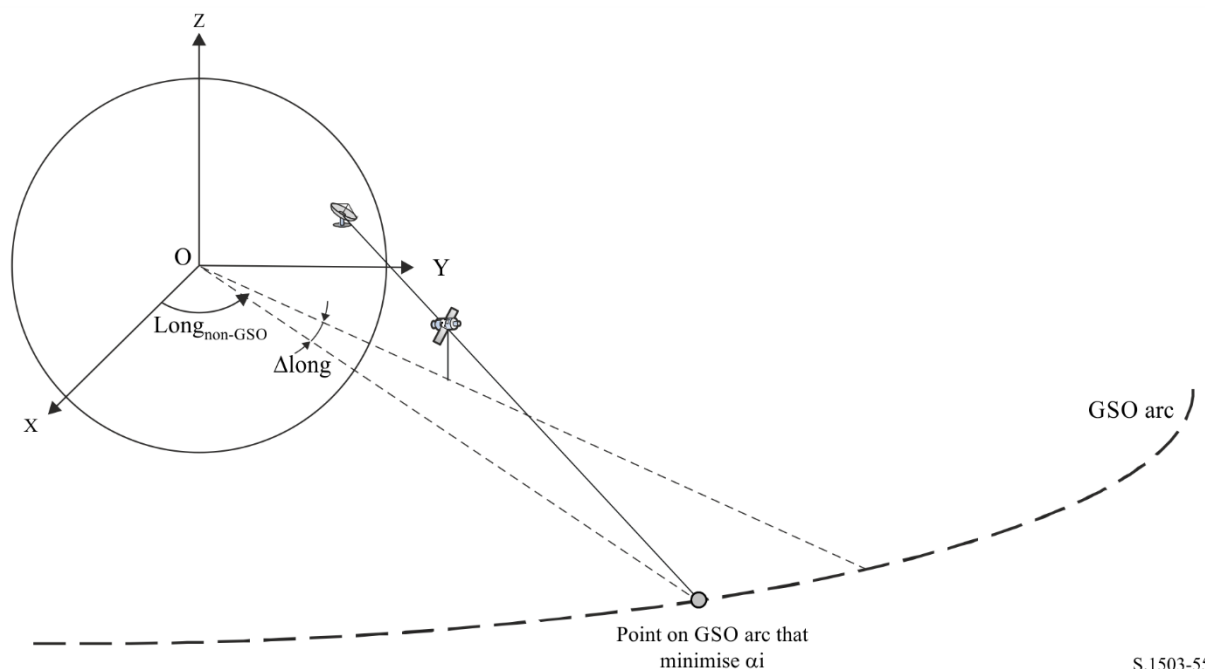
Hence:

$$\Delta Long = LongAlpha - LongNGSO$$

The α iteration should use test points that meet the requirements in § D1.4.

If there are two points on the GSO arc that give the same α (possibly the two edge of visibility points), then the one with the minimum absolute ΔLong should be selected. If both have the same ΔLong but with different signs, then the positive one should be used.

D6.4.4.2 Alpha search range

Note that the GSO arc will be visible to the non-GSO at a height of h_{nGSO} and latitude lat_{nGSO} if the difference in longitude is less than:

$$\cos \Delta long = \frac{\cos x}{\cos lat_{nGSO}}$$

where:

$$x = x_1 + x_2$$

and:

$$\cos x_1 = \frac{R_e}{R_{gso}}$$

$$\cos x_2 = \frac{R_e}{R_e + h_{nGSO}}$$

The range of the GSO arc that will be visible to an ES can be calculated in a similar manner by setting $x_2 = 0$.

D6.4.4.3 Sign of Alpha

Figures 56 and 57 below are provided to give clarity as to the sign of α as seen from the perspective of a non-GSO satellite or non-GSO ES in the northern and southern hemispheres.

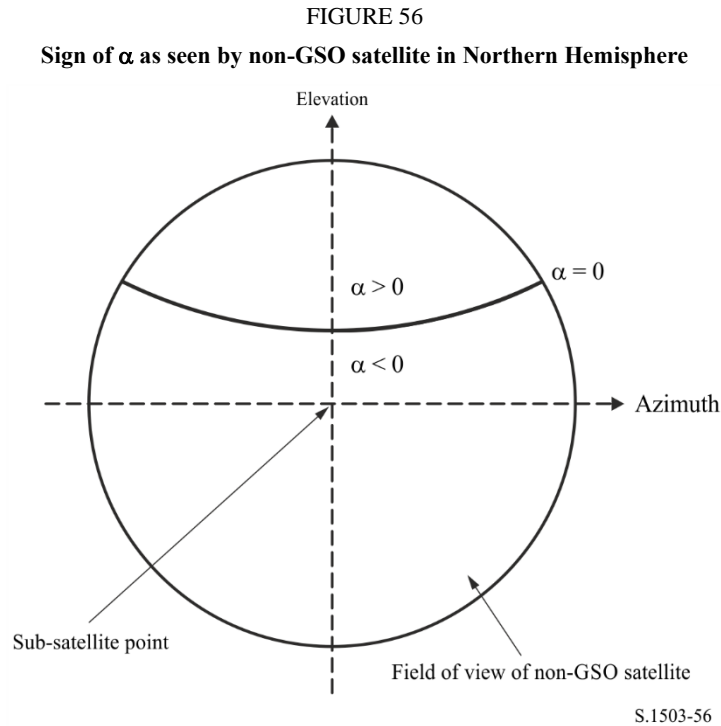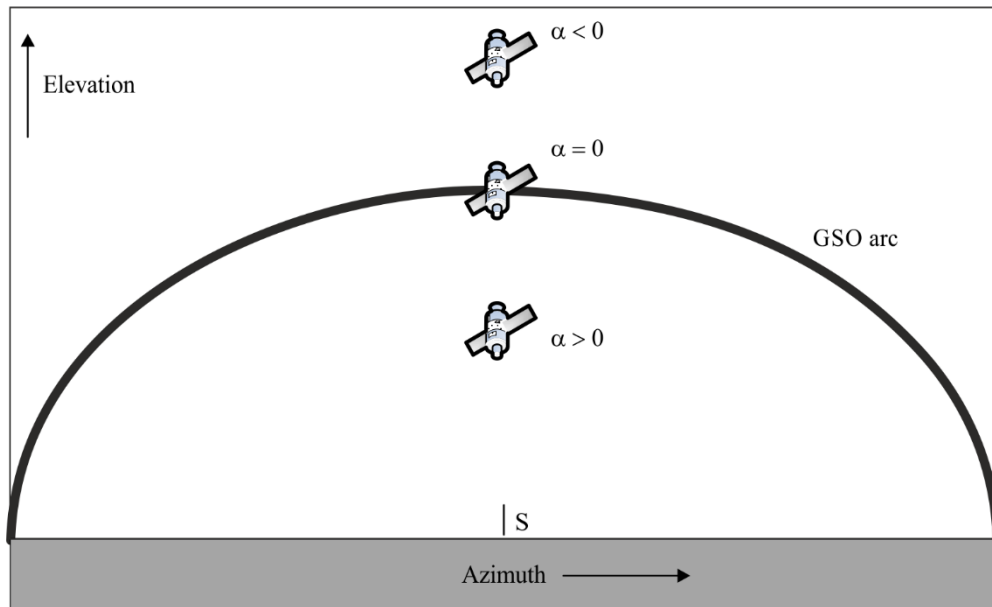When the non-GSO satellite is in the northern hemisphere:

FIGURE 56

Sign of α as seen by non-GSO satellite in Northern Hemisphere

S.1503-56

FIGURE 57

Sign of α as seen by non-GSO ES in Northern Hemisphere looking South
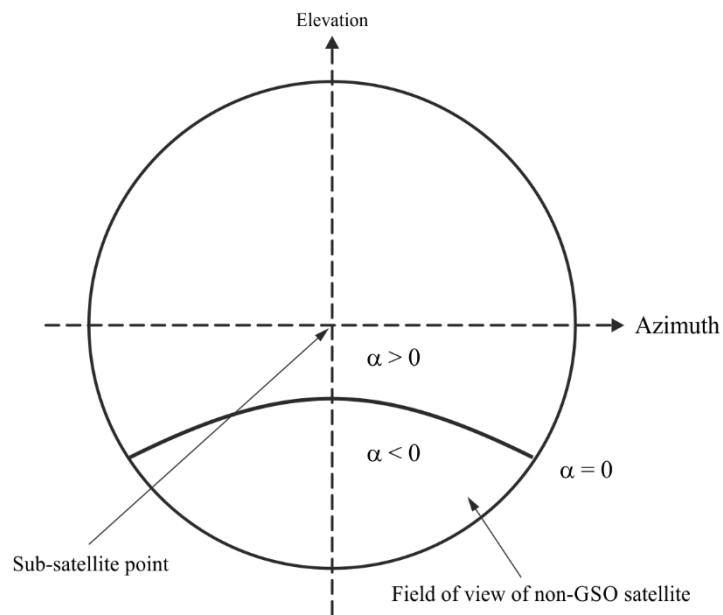

S.1503-57

The geometry for the case when the non-GSO satellite is in the southern hemisphere is shown in Figs 58 and 59 below.
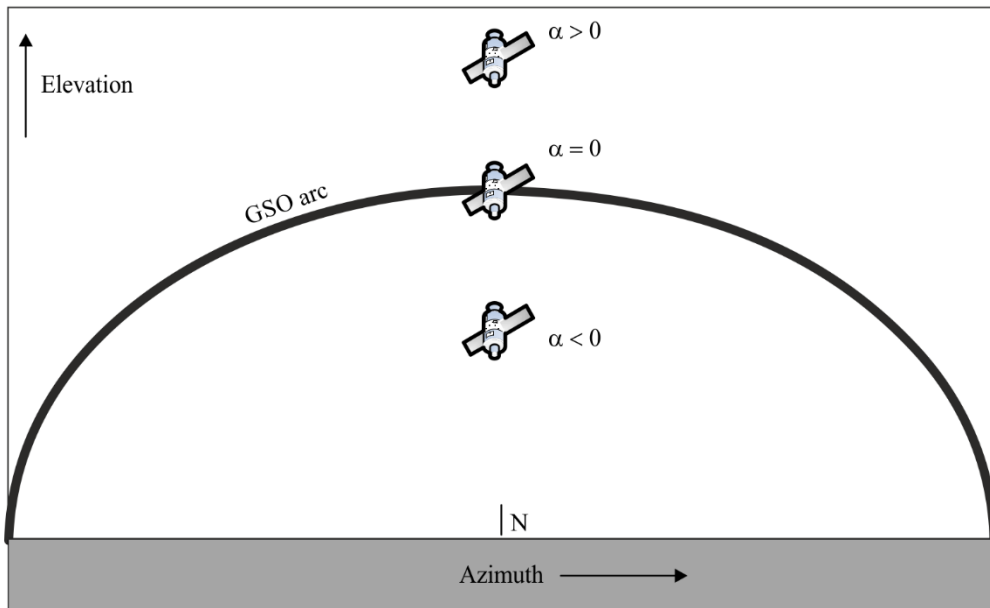
FIGURE 58

Sign of α as seen by non-GSO satellite in Southern Hemisphere

S.1503-58

FIGURE 59

Sign of α as seen by non-GSO ES in Southern Hemisphere looking North

S.1503-59

D6.4.4.4 Analytic method to calculate α and β

This section describes an analytic method to calculate the alpha angle and also associated β angles.

Analytic calculation of α

The analytic method to calculate α starts with the following two inputs:

P = Position vector of GSO ES, typically with magnitude = radius of the Earth = R_e

N = Position vector of non-GSO satellite

These are defined as:

$$P = \begin{pmatrix} x_p \\ y_p \\ z_p \end{pmatrix}$$

$$N = \begin{pmatrix} x_n \\ y_n \\ z_n \end{pmatrix}$$

Then assume:

G = Position vector of a point on GSO arc specified by angle θ and radius of geostationary orbit R_{geo}:

$$G = \begin{pmatrix} R_{geo} \cos\theta \\ R_{geo} \sin\theta \\ 0 \end{pmatrix}$$

Then α is the minimum over all θ of the angle between the lines PN and PG where:

$$PN = \begin{pmatrix} x_n - x_p \\ y_n - y_p \\ z_n - z_p \end{pmatrix}$$

$$PG = \begin{pmatrix} R_{geo} \cos \theta - x_p \\ R_{geo} \sin \theta - y_p \\ -z_p \end{pmatrix}$$

This can be calculated using:

$$\cos \alpha = \frac{PN.PG}{|PN||PG|}$$

This will be minimised over θ when:

$$\frac{d\alpha}{d\theta} = 0$$

Which is also when:

$$\frac{d}{d\theta} \left[\frac{PN.PG}{|PN||PG|} \right] = 0$$

Writing this as:

$$\frac{d}{d\theta} \left[\frac{f}{g} \right] = 0$$

Then f can be written as:

$$f = A + B \cos \theta + C \sin \theta$$

where:

$$A = -\left[(x_n - x_p)x_p + (y_n - y_p)y_p + (z_n - z_p)z_p \right]$$
$$B = (x_n - x_p)R_{geo}$$
$$C = (y_n - y_p)R_{geo}$$

And g can be written:

$$g = \sqrt{E + F \cos \theta + G \sin \theta}$$

where:

$$E = R_{geo}^2 + R_e^2$$
$$F = -2x_p R_{geo}$$
$$G = -2y_p R_{geo}$$

Note that D = magnitude of PN is not dependent upon θ and so is a constant which need not be considered further.

using:

$$g = \sqrt{g_r}$$

and noting that:

$$\frac{d}{d\theta} \left[\frac{f}{g} \right] = 0$$

when:

$$\frac{d}{d\theta} \left[\left(\frac{f}{g} \right)^2 \right] = 0$$

i.e. when:

$$\frac{d}{d\theta}\left[\frac{f^2}{g_r}\right] = 0$$

using f' to represent f differentiated by θ, this can be expanded using standard methods as:

$$\frac{2ff'g_r - g_r'f^2}{g_r^2} = 0$$

This can be simplified to:

$$2f'g_r = g_r'f$$

using:

$$x = \sin\theta$$

Note there is an alternative solution that uses $\cos\theta$ instead of $\sin\theta$.

Simplified using a new set of parameters $\{a, b, c, d, e\}$ this is:

$$[a + bx]^2(1 - x^2) = [c + dx + ex^2]^2$$

where:

$$a = AG - 2CE$$
$$b = BF - CG$$
$$c = 2CF - BG$$
$$d = AF - 2BE$$
$$e = -BG - CF$$

This can be expanded and then re-arranged into:

$$a_4 x^4 + a_3 x^3 + a_2 x^2 + a_1 x + a_0 = 0$$

where:

$$a_4 = e^2 + b^2$$
$$a_3 = 2de + 2ab$$
$$a_2 = d^2 + 2ce + a^2 - b^2$$
$$a_1 = 2cd - 2ab$$
$$a_0 = c^2 - a^2$$

This quartic equation can be solved using a number of techniques, including the use of the Newton-Raphson method[1]. This approach aims to solve a function f of a variable x, using iteration, given an initial value and f' = the derivative of f using:

$$x_{n+1} = x_n - \frac{f(x_n)}{f'(x_n)}$$

where:

$$x = \sin\theta$$
$$f(x) = a_4 x^4 + a_3 x^3 + a_2 x^2 + a_1 x + a_0$$
$$f'(x) = 4a_4 x^3 + 3a_3 x^2 + 2a_2 x + a_1$$

---

[1]   https://en.wikipedia.org/wiki/Newton%27s_method

The Newton-Raphson method is considered to have converged when the absolute difference between x_n and x_{n+1} is less than 1e-6.

For the starting value, both x = +1 and x = −1 can be used and two solutions derived, matching the two cases of the line from the GSO ES position P to the non-GSO satellite N forward or backwards.

This analytic method does not take account of the range of visibility of the GSO arc as seen by the GSO ES. It is therefore necessary to identify the maximum range of the visible GSO arc, using:

$$\cos \theta_{max} = \frac{R_e}{R_{geo} \cos Lat_{ES}}$$

The points on the GSO arc that correspond to $\pm\theta_{max}$ can be considered additional possible solutions. The solution to use is one that is within the range $-\theta_{max}$ to θ_{max} that results in the smallest alpha angle.

The iterative method may be used as a fall-back should these methods fail to derive suitable solutions to the quartic equation but the preferred approach is analytic.

Analytic calculation of β

The beta angle is defined in a similar way to that for α but is minimised over all possible positions of the non-GSO satellite with radius vector R_n and at latitude = lat but unknown longitude, for a given position of the GSO satellite.

The analytic method to calculate β starts with the following two inputs:

P = Position vector of GSO ES, typically with magnitude R_p = radius of the Earth = R_e

G = Position vector of GSO satellite with magnitude R_g

These are defined as:

$$P = \begin{pmatrix} x_p \\ y_p \\ z_p \end{pmatrix}$$

$$G = \begin{pmatrix} x_g \\ y_g \\ 0 \end{pmatrix}$$

Then assume:

N = Position vector of non-GSO satellite at latitude = lat and angle θ and radius of geostationary orbit R_n:

$$N = \begin{pmatrix} R_n \cos lat \cos \theta \\ R_n \cos lat \sin \theta \\ R_n \sin lat \end{pmatrix}$$

Then β is the minimum over all θ of the angle between the lines *PN* and *PG* where:

$$PN = \begin{pmatrix} R_n \cos lat \cos \theta - x_p \\ R_n \cos lat \sin \theta - y_p \\ R_n \sin lat - z_p \end{pmatrix}$$

$$PG = \begin{pmatrix} x_g - x_p \\ y_g - y_p \\ -z_p \end{pmatrix}$$

This can be calculated using as similar approach above, with f and g_r functions:

$$f = A + B \cos \theta + C \sin \theta$$

$$g_r = E + F \cos \theta + G \sin \theta$$

where:

$$A = R_P^2 - \left(x_G x_P + y_G y_P + z_p R_N \sin lat\right)$$
$$B = (x_G - x_P)R_N \cos lat$$
$$C = (y_G - y_P)R_N \cos lat$$

and:

$$E = R_N^2 + R_P^2 - 2z_P R_N \sin lat$$
$$F = -2x_P R_N \cos lat$$
$$G = -2y_P R_N \cos lat$$

Note that D = magnitude of $\boldsymbol{PG}$ is not dependent upon θ and so is a constant which need not be considered further.

When the parameter set $\{A, B, C, E, F, G\}$ has been defined then a similar methodology can be used to solve for θ as for α above. There can be cases, such as its use in the worst case geometry algorithm, where it is not required to check for visibility.
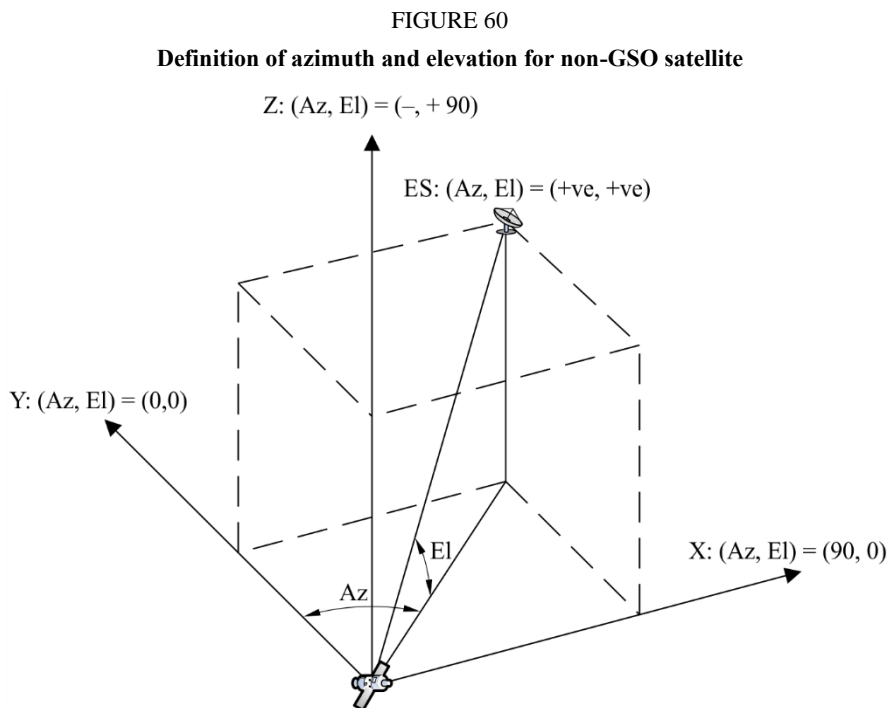
D6.4.4.5 DeltaLongES

The difference in longitude for a non-GSO ES and a point on the GSO arc, as used in the definition of the ES_e.i.r.p. mask, is defined as follows:

DeltaLongES = Longitude(GSO point) – Longitude(Non-GSO ES)

D6.4.5 Satellite and earth station azimuth and elevation

Figure 60 shows the definition of the azimuth and elevation angles used for the non-GSO satellite:

FIGURE 60
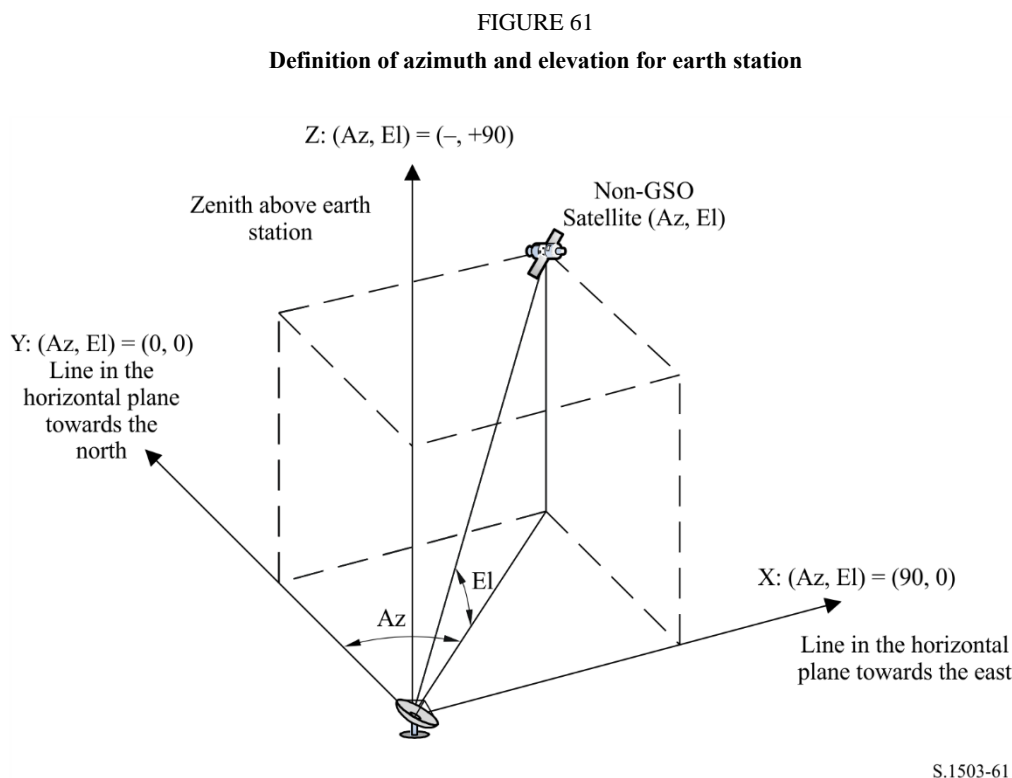
Definition of azimuth and elevation for non-GSO satellite

It should be noted that direction of the cartesian *X*, *Y*, *Z* vectors in this diagram are:

    X: +ve in the East direction from the non-GSO satellite

 Y: towards the centre of the Earth from the non-GSO satellite

 Z: +ve towards the North direction from the non-GSO satellite.

For the earth station, the definition of the azimuth and elevation angles are as in Fig. 61.

FIGURE 61

Definition of azimuth and elevation for earth station

S.1503-61

It should be noted that direction of the cartesian *X*, *Y*, *Z* vectors in this diagram are:

 X: +ve in the East direction from the earth station in the horizontal plane

 Y: towards the North direction from the earth station in the horizontal plane

 Z: +ve towards the Zenith of the earth station perpendicular to the horizontal plane.

Furthermore, the normalized coordinates, u and v, can be computed from the azimuth and elevation angles as follows:

$$u = \cos(El) * \cos(Az)$$

$$v = \cos(El) * \sin(Az)$$

D6.5 Gain patterns

This section defines the gain patterns used in the algorithms for earth stations and satellites. Note that all formula includes the peak gain, so where relative gain is required, the peak gain should be subtracted.

D6.5.1 GSO earth station gain patterns

D6.5.1.1 FSS earth station gain pattern

The FSS earth station gain pattern to use is specified in Recommendation ITU-R S.1428.

D6.5.1.2 BSS earth station gain pattern

The BSS earth station gain pattern to use is specified in Recommendation ITU-R BO.1443.

D6.5.2　GSO satellite gain pattern

The values of peak gain and half power beamwidth and the antenna reference radiation pattern to use are specified in RR Article **22** based upon Recommendation ITU-R S.672.

The peak gain to use in analysis should be selected using Table 16.

TABLE 16

Peak gain to use with Recommendation ITU-R S.672

Half power beamwidth in Article 22	Peak gain to use in analysis
1.5°	41.0 dBi
1.55°	40.7 dBi
4°	32.4 dBi

D7　　Structure and format of results

D7.1　Go/No-go decision

D7.1.1　Overall description of the decision process

The simulation produces a probability distribution function (PDF) of the pfd. The PDF records, for each pfd level, the number of simulation time-steps at which that pfd level occurred divided by the sum of all bins. The PDF should be converted into a cumulative distribution function (CDF) which records for each pfd level the number of simulation time-steps at which that pfd level was exceeded normalized by the total number of simulation time steps.

Note that the term cumulative distribution function is meant to include the concept of the complementary cumulative distribution function depending upon context.

D7.1.2　Production of the CDF

The process detailed in § D5 generated a PDF of the pfd values. This PDF should be converted into a CDF which records for each pfd level an estimate of the percentage of time during which that pfd level is exceeded.

For each pfd value, the CDF should be calculated by:

$$CDF_i = 100\,(1 - SUM\,(PDF_{min}: PDF_i))$$

where:

$\quad\quad PDF_x$:　PDF table entry for a pfd value of X dB, normalized so that the total sum for all PDF_x is 1.

D7.1.3　Comparison procedure

The next stage is the comparison of the pfd limit values in the RR with those in the probability table.

Step 1:　Perform Steps 2 through 4 for each specification limit *i*.

Step 2:　Read the pfd value/probability pair (J_i and P_i) from the database.

Step 3:　If the pfd value J_i has a higher precision than S_B (currently 0.1 dB) round J_i to a lower value with a maximum precision of 0.1 dB.

Step 4:　From the CDF find P_t, the probability that pfd value J_i was exceeded as obtained by the software.

Step 5: If $P_i < P_t$ then record Pass: the CDF complies with this specification point. Else record Fail: the CDF does not comply with this specification point.

The final stage is the comparison of the maximum pfd value recorded during the software run with the limit specified for 100% time (if any).

From the CDF, find the maximum pfd value recorded during the software run, J_{max}. Compare it with the pfd limit specified for 100% time, J_{100}. If $J_{max} < J_{100}$ then record Pass: the CDF complies with this specification point. If $J_{max} \geq J_{100}$ then record Fail: the CDF does not comply with this specification point.

D7.1.4 Decision process

If a Pass result was recorded for all of the specification limits, then the non-GSO network complies with the specification. If any Fail results were recorded, then the non-GSO network does not comply with the specification.

D7.2 Background information to decision

The background information required is:

– pfd data generated in the software run (including antenna diameter) and reference antenna pattern;

– table of specification limits for various antenna diameters and reference antenna pattern.

D7.3 Format for output

The output format should be:

– statement of the result of the test;

– summary table;

– CDF table (for information only).

D7.3.1 Statement of the result of the compliance test

The overall conclusion of the evaluation (Pass or Fail) as defined in § D7.1.4 should be output.

D7.3.2 Summary table

The summary table should show the following data (see Table 17):

TABLE 17

Summary table

Specification point		Result	Simulation point
pfd value	Probability		Probability
$J_1 dB(W/(m^2 \cdot BW_{ref}))$	P_1	Pass/fail	P_y
:	:	:	:
$J_i dB(W/(m^2 \cdot BW_{ref}))$	P_i	Pass/fail	P_y

where:

J_i and P_i: pfd value/probability specification values from the database

Pass/fail: test result

P_y: probability value from the probability table.

D7.3.3 Probability table

The output should include for information the calculated CDF which was used in the decision-making process.

PART E

Testing of the reliability of the software outputs

E1 Evaluation of the computation accuracy of the candidate software

These tests could be performed by the software developer, and the results supplied to the BR along with the candidate software.

Software functions to be evaluated:

Orbit projection – Using a set of simplified parameters which result in a defined repeat period, run the software for the required simulation interval and check the actual (satellite vectors) against the predicted values.

Offset angles – Using appropriate sets of earth station and satellite locations, check the actual beam offset angle values against the predicted values. The sets of test data should cover the most complex trigonometrical cases: for example sites around longitude zero and longitude 180°.

Time step and simulation duration – Using appropriate sets of non-GSO network parameters, check the time step and simulation duration values generated by the software against the predicted values.

CDF generation – Using sets of test input files with known CDF results, verify the CDF generation software.

Go/no-go decision process – Using sets of CDF test input files, verify the accuracy of the go/no-go decision process.

Should multiple implementations be available then sensitivity analysis could be used to evaluate them, and their output can be compared to ensure consistency.

E2 Evaluation of the epfd(↓/↑) statistics obtained by the BR

These are tests which will be performed automatically by the software as part of each run, to confirm that the run did find the worst-case interference events.

epfd value for 100% time – the epfd↓ value for 100% time obtained during the run should be compared with a value calculated from analysis of the non-GSO constellation. The obtained value should be within ±0.X dB of the expected value.

E3 Verification of the pfd masks

The pfd masks are inputs to the BR validation tool to be provided by the notifying administration to the BR together with the software used for its calculation, the complete software description and

parameters. The information required to generate the pfd mask could be made available to interested administrations to be used in case of dispute.

E4   Re-testing of the BR software after any modifications or upgrades

A set of tests should be defined for use on any occasions when the BR software or its operating environment has been modified or upgraded. Such tests could include:

a)   some or all of the tests defined in § E1 for the initial evaluation of the computational accuracy of the candidate software;

b)   repetition of a representative set of evaluations of actual non-GSO filings, and comparison of the results obtained by the original and modified software systems.

PART F

Software implementing this Recommendation

F1   Operating system

The software should run on Microsoft platforms under the Windows 10 or higher operating system.

F2   Interfaces to existing software and databases

The BR captures all incoming notices related to space services into one central database for alphanumeric data (SNS) and into another database for graphical data (GIMS) such as antenna diagrams and service areas. These databases are used for the publication of the data on DVD, in the Weekly Circular and its Special Sections. They are also used to provide input data to software packages performing RR Appendix **8** and pfd examinations. Graphical Interface for Batch Calculations (GIBC) is used to carry out examination using these different modules. This guarantees that the data published are also the data used in these examinations. The BR considers this important for both the notifying administration and for administrations the services of which may be affected by the new station. This is not only for the convenience of the BR, but to ensure consistency and transparency towards administrations.

F3   User manual

The purpose of the user manual is to tell the user how to run different tests to obtain certain results. Given the complexity of these tests, they need to be given in detail.

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