Ground Segment Dimensioning Methodology for NGSO Constellations

Charilaos Kourogiorgas
Atheras Analytics SAS, 6 Place Thomas Woodrow Wilson, 31000 Toulouse, France,
charilaos.kourogiorgas @atherasanalytics.eu
Alexandra Prigent
Atheras Analytics SAS, 6 Place Thomas Woodrow Wilson, 31000 Toulouse, France,
alexandra.prigent@atherasanalytics.eu

Abstract

The rapid expansion of Non-Geostationary Satellite Orbit (NGSO) constellations has reshaped the landscape of satellite communications. With a growing demand for high-throughput, low-latency connectivity, operators must carefully design and optimise their ground infrastructure to ensure efficient service delivery while minimizing costs. Traditional satellite network planning approaches—often designed for Geostationary (GEO) systems—are not fully equipped to handle the dynamic nature of NGSO networks. Factors such as gateway placement, inter-satellite link (ISL) utilization, atmospheric attenuation, and regulatory constraints all add complexity to ground segment dimensioning. To address these challenges, Atheras Analytics has developed a Ground Segment Dimensioning Tool (GND Tool) designed specifically for NGSO ground segment optimisation. GND Tool uniquely integrates: a) sophisticated propagation models taking into account historical weather data to enable accurate performance evaluation and ground segment optimisation, b) comprehensive ISL and terrestrial network optimisation, eliminating excessive gateway deployments and c) flexible multi-objective optimisation algorithms, balancing cost-efficiency, network resilience, and performance targets. GND Tool has been developed under the ESA funded Programme Related to EU Secure Connectivity and it will be used to support ESA in its role of IRIS² Qualification and Validation Authority. In this paper, the methodology of the ground segment dimensioning is presented and explained and results are obtained with the GND Tool.

1. Introduction

The need for global broadband internet access and support of a variety of demanding applications and services has revived the idea of using the space segment as a direct access means and a backhaul to existing and new generation networks. The need of increased bandwidth to support high data rates and avoid congestion in lower bands favors the transition to higher frequencies (Q/V bands) than the currently used Ku and Ka bands. However, at these high frequencies, the atmospheric attenuation becomes a critical degrading factor [1] that cannot be economically mitigated by traditional methods like fade margin over-dimensioning or conventional site diversity.

NGSO constellations have the advantages of lower latency in comparison to GEO satellites, larger throughput that can be supported per link and, based on the size of constellation, global coverage including polar regions is feasible. NGSO constellations are already operated by SES, SpaceX and OneWeb at Ka-band. In addition, fillings have been submitted by Intelsat for a MEO constellation and Amazon Kuiper NGSO constellation is under development.

Within Europe, the Union Secure Connectivity Programme aims at deploying an EU satellite constellation - 'IRIS²' (Infrastructure for Resilience, Interconnectivity and Security by Satellite). IRIS² will provide a satellite-based, multi-orbital communication infrastructure for governmental use, while integrating and complementing existing and future national and European capacities in the frame of the GOVSATCOM component of the European Union Space Programme. IRIS² will develop further and gradually integrate the European Quantum Communication Infrastructure (EuroQCI) initiative which will support the distribution of quantum-based cryptographic keys (QKD).

These NGSO networks have differing numbers of satellites with differing orbits, employing diverse technologies across both space and ground segments, e.g. InterSatellite Links (ISL) presence or virtualisation of the gateway and digitisation of the Intermediate Frequency (IF) signal [2]. A large constellation poses great challenges for optimised network design of not only space segment but also of the gateway (GW) ground segment that connects with the terrestrial backbone. Ensuring ground connectivity to the different mega-constellation elements entails the need of multiple GWs distributed over the system coverage area. In NGSO dimensioning several criteria that have to be taken into account, like cost reductions by using the least number of GWs while maintaining Quality of Service (QoS) and satisfying availability requirements, rain attenuation and atmospheric impairments mitigation, Minimum Elevation Angle (MEA), visibility, coverage, geographical constraints, traffic demands, availability and usage of ISLs, number of beams, antennas, and proximity to the core network, require a balance among requirements for a multidimensional and computationally feasible optimisation.

In this paper, the methodology and the architecture of GND Tool developed by Atheras Analytics is presented. The GND Tool is a specialised software solution developed to evaluate and optimise NGSO constellation ground segment design. By integrating advanced simulation capabilities, multi-objective optimisation, and real-world constraints, the tool enables satellite operators and engineers to develop cost-efficient, scalable, and high-performance network architectures. Unlike conventional modeling tools that focus primarily on orbital dynamics and static link analysis, often ignoring weather effects, the GND Tool offers a holistic approach, taking into account: a) propagation effects at high-frequency bands (Ka/Q/V/W), incorporating two sophisticated propagation models, b) Inter-satellite link (ISL) characteristics and terrestrial network integration, enabling ground network optimisation and hence reduced infrastructure costs, c) dynamic gateway-satellite allocation, optimising network routing for maximum efficiency and d) extensive input parameters, allowing tailored simulations for diverse NGSO architectures.

2. System Architecture

The NGSO Ground Segment Dimension Tool (GND Tool) architecture is shown in Figure 1 below. It consists of 7 different modules. The Orbit Mechanics Module (OMM), Propagation Module, Traffic Demand Generation Module, Link Budget Module and NGSO Communication Module make up the Core Module. The User Interface and User Management modules are developed for ease of access and better user experience.

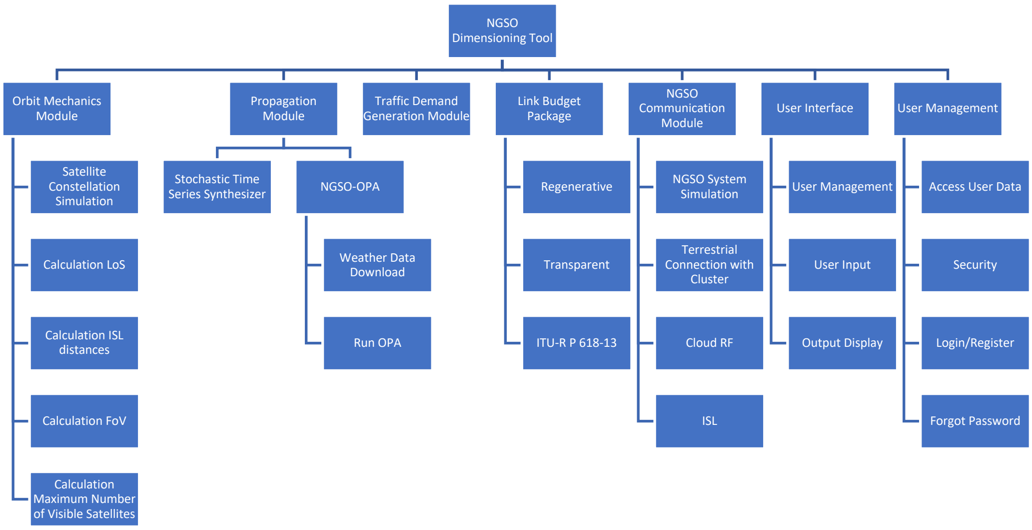

Figure 1 Atheras Analytics GND Tool product architecture

All the modules apart from the user interface are developed in Python3 environment. The user interface is developed in React. The landing pages of the GND Tool User Interface is shown in Figure 2.

The flow of the tool is shown in Figure 3. Once the algorithm starts, the input data is processed to be organised into a specific form to be used by the rest of the modules, and to check the values provided. In case the user has provided specific areas of interest for the gateways, the gateway locations are filtered. Then, the OMM produces the Field of View calculations, the intersatellite link distances and the elevation/azimuth time series between satellites and teleports. In parallel the link budget module produces the antenna dimensioning, the Site Switching Thresholds (if the NGSO-Outage Prediction Algorithm (OPA) is chosen as a method to produce propagation time series) and the spectral efficiencies for different elevation angles starting from 5° up to 90°. Subsequently the Propagation Module runs to produce either outage time series with the NGSO-OPA method or total attenuation time series with ITU-R method. The Traffic Demand Generation Module provides traffic demand for each time step for each satellite taking into account the service area (which is provided as input from the user in the form of a bounding box). Finally, the NGSO Communication Module either evaluates or optimises the system and can take into account ISLs, capacity over the satellite, the percentage of capacity that a satellite operates, and terrestrial network limitations regarding clusters and cloud RF options with different data centres either manually provided as input from the user or derived from a database. In addition, it considers the switching outage due to the need to repoint a feeder antenna because of an insufficient number of redundant feeder antennas and it can filter out gateway locations or service areas that are not of interest.

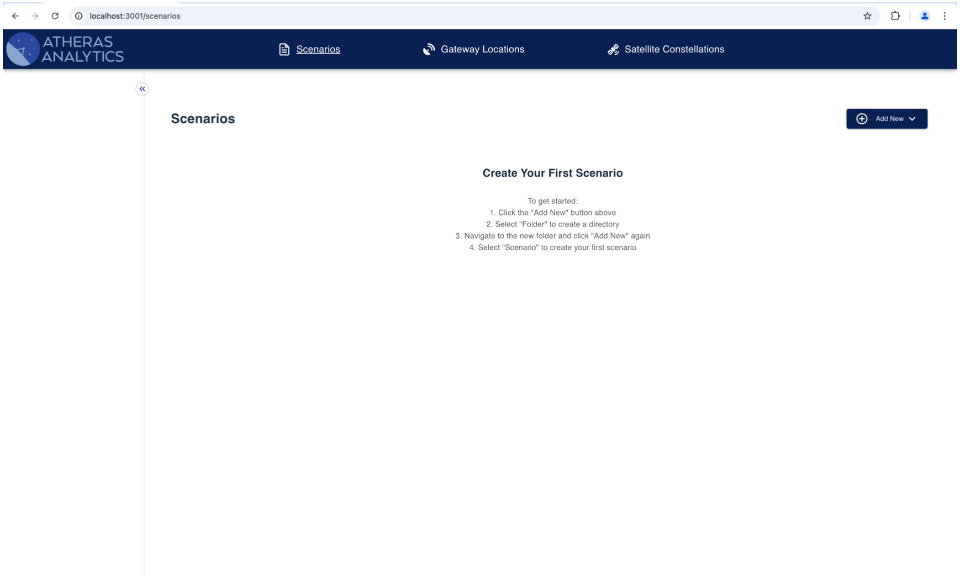

Figure 2 Landing Page of GND Tool UI

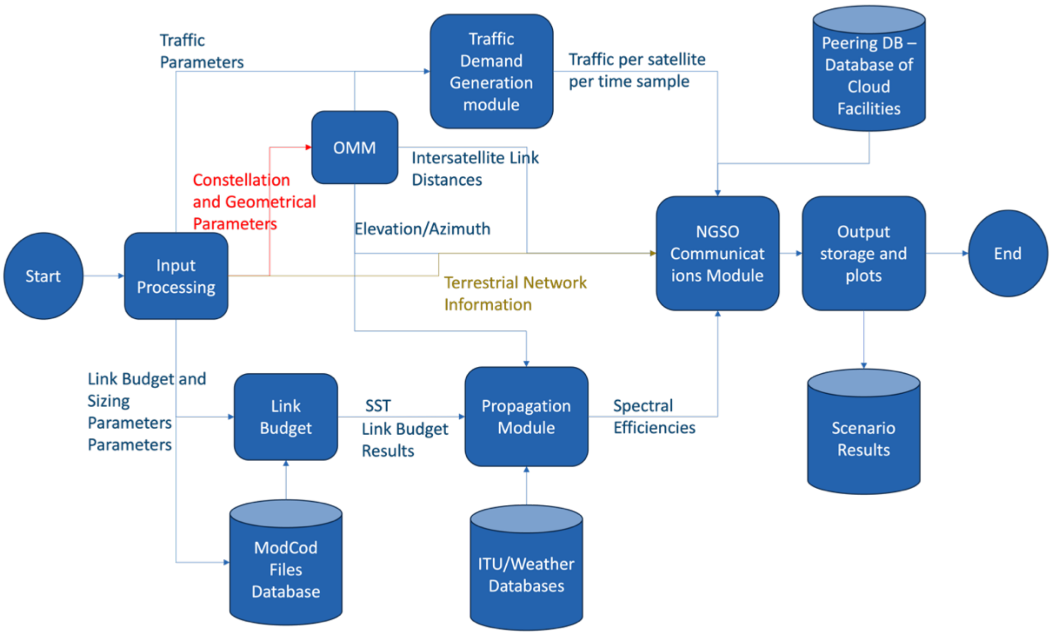

Figure 3 GND Tool Algorithmic Flow

3. Orbit Mechanics Module

The Orbit Mechanics Module (OMM) is the initial component of the system simulation, defining the geometric relationships between stations and satellites. This foundational module generates essential data for subsequent modules, including for the propagation, traffic, and inter-satellite link modules.

OMM first calculates the time series of visibility from each station to each satellite and in particular, the distance, elevation angle and azimuth by first computing the satellite positions for the specified timeframe and time resolution; then the earth station location positions are computed; and finally the relative vector is computed by subtracting the stations' position vector from the satellite positions vector. Doing this, we have the relative vector between all stations and all satellites for all the time samples for the desired timeframe. After computing all the elevation and azimuth timeseries for every station-satellite pair these are stored for usage in the next modules. It is possible to build the polar elevation-azimuth histograms for every station. Figure 4 shows an example of this histogram for a station located in Madrid tracking a MEO constellation.

The OMM also produces station-to-all-satellites visibility distributions and this information can be used to define the maximum number of antennas per station for the optimisation module, as there is no need to have more antennas on the gateways than the maximum number of satellites that can be seen since only a single gateway antenna can connect to a single satellite. In addition, the tool considers as well, the exclusion zone for avoiding interference to GEO systems.OMM calculates the FoV as the area on the Earth's surface that sees the given satellite above a given Minimum Elevation Angle (MEA). For the traffic demand generation, the OMM generates a new output that defines, for every satellite, the FoV area percentage inside the service area as provided as input by the user. This feature can be used to limit the traffic served by satellites passing unwanted regions. The service area is defined by the rectangular boundary of southwest and northeast points. The intersatellite link visibility is established between two satellites if the line of sight between them does not cross the atmosphere. Figure 5 shows the intersatellite visibility for one satellite at a given time, from which the closest ones will be chosen as candidates to establish the ISL. The output of the ISL computation is for every satellite the visible satellites and their respective distance. The distance is used later on for the latency calculations.

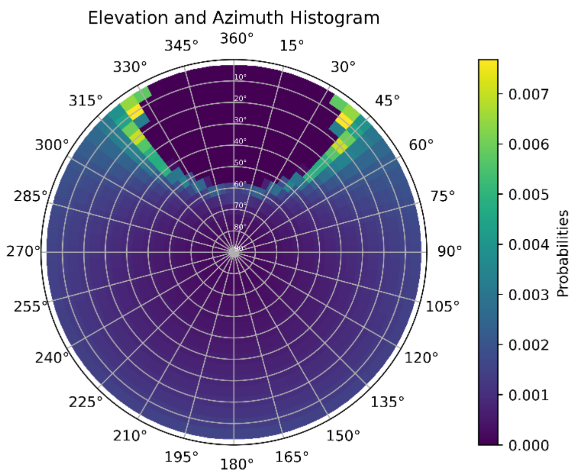

Figure 4 Polar elevation-azimuth histogram for Madrid

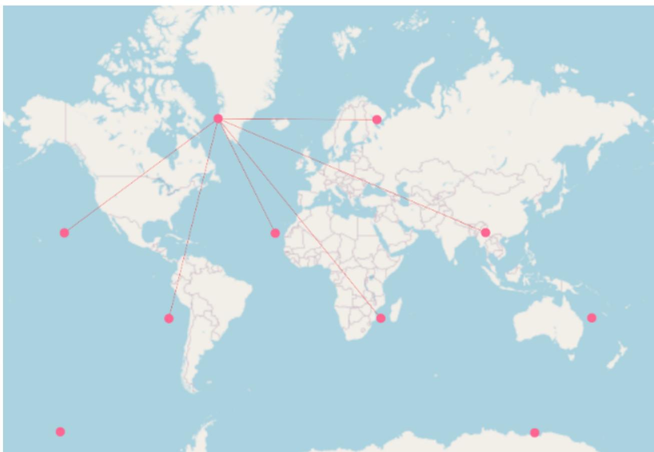

Figure 5 ISL Visibility representation

4. Link Budget Module

The Link Budget Module implements the main link budget equations for the system parameters and provides the following functionalities:

1. Gateway Sizing: calculates the required antenna size and transmit power to be used at a gateway to achieve the required datarate and availability based on user inputs.

2. Site Switching Threshold (SST): Based on the constellation and the gateway parameters the module calculates the Free Space Path Loss and the SSTs for each gateway. The SST is used in case that NGSO-OPA method is chosen to generate propagation time series in the propagation module.

3. Spectral Efficiency calculation: Given the attenuation on each link based on weather conditions/modeling, the module calculates the available spectral efficiencies for the selected Modulation and Coding Schemes (MODCODs).

The link budget module considers both non-regenerative and regenerative payloads based on the user input. If the satellite amplifies and retransmits the received uplink signal to the downlink without demodulating the system, it is characterized as a bent-pipe nonregenerative payload. Alternatively, if the satellite is able to demodulate the signal and regenerate it with error correction, the payload is a regenerative one. For a non-regenerative hop both uplink and downlink impact final C/(N+I), whereas for regenerative the uplink is “cleaned” by the onboard demod-remod, so (presuming uplink closed) only downlink C/(N+I) has effect.

5. Propagation Module

In the Propagation Module, the time series of the tropospheric attenuation are produced and then fed into the NGSO System Module. Traditionally, the slant path between a ground location and a GEO satellite is constant. However, for NGSO satellites the slant path changes continuously, and it is important to analyse the propagation attenuation in all the directions that the slant path will sweep, since it may not have the same attenuation in all directions.

Two methods are used, and the user can either select either of them. The first method relies on the NGSO-OPA [3] to provide the outage time series for the specific time series of elevation and azimuth taking into account both the spatial and temporal correlation of the weather effects using weather databases, combined with the slant path changes. The OPA uses as input historical weather data which can come from multiple sources. The second method generates time series of tropospheric attenuation using long-term statistics from ITU-R P. 618-13 [4], the elevation angle of the link and the fade dynamics which are captured using a model of the dynamic rain attenuation which takes into account the geometric characteristics of the link.

5.1. NGSO-OPA

The Outage Prediction Algorithm (OPA) forms the basis of the Atheras Analytics Tools. The OPA is an AI-model that was initially derived from analysis of a series of propagation measurements taken from the Ka-band and Q-band experimental payloads on the Alphasat geostationary satellite. The OPA AI-models are trained for different link parameters so by applying weather data, either historic or forecast, to determine if a link is impaired or not for those specific meteorological conditions [5], [6].

To operate a satellite network, we need to understand the attenuation threshold at which a participating gateway is no longer capable of supporting commercial traffic and at which the traffic needs to be switched to an alternative gateway. We refer to this point as the SST and it is defined as the point at which the gateway has employed all the available Fade Mitigation Techniques (FMTs) such as Fade Margin, Uplink Power Control (UPC), Adaptive Coding and Modulation (ACM) etc. and is about to go into outage. The SST may be determined using either link budget calculations or using empirical methods.

The OPA generates a Propagation Impairment Flag (PIF) when, for a specific frequency, SST and meteorological conditions, an outage is predicted to occur. Two possible states exist for the PIF: 1 (one) indicating that an outage is predicted to occur, i.e., attenuation induced on the gateway-satellite link is predicted to be larger than the SST and 0 (zero) indicating that no outage is predicted, i.e., attenuation induced on the gateway-satellite link is predicted to lower than the SST.

Atheras Analytics’ NGSO-OPA enables the OPA to be applied over the entire communication link. This offers two primary advantages. Firstly, explicitly considering weather conditions along the slant-path renders a more accurate picture of the fading that is likely to be induced on the link. Occasionally, a weather event may occur along the slant path, without impacting the weather directly over the gateway. As the elevation angle decreases, this becomes increasingly common, as the path through the atmosphere below the 0°C isotherm can be several kilometres. Secondly, as the slant path is defined by the elevation angle and azimuth of the satellite with respect to the gateway, it becomes possible to analyse the availability of the system as a function of these parameters. This is of particular use for NGSO systems, in which both elevation angle and azimuth vary over time.

The NGSO-OPA is created by taking a discretised list of coordinates corresponding to the projection of the 3D slant-path onto a 2D grid of geodetic coordinates in the vicinity of the gateway. The slant-path is considered up to the average height of the 0°C isotherm (also known as the rain height) for that location. The OPA is then applied to create a PIF for each point, and a logical OR operation is used to generate the overall PIF for the link. In Figure 6, a snapshot of the outage time series is shown for a station connected to two satellites.

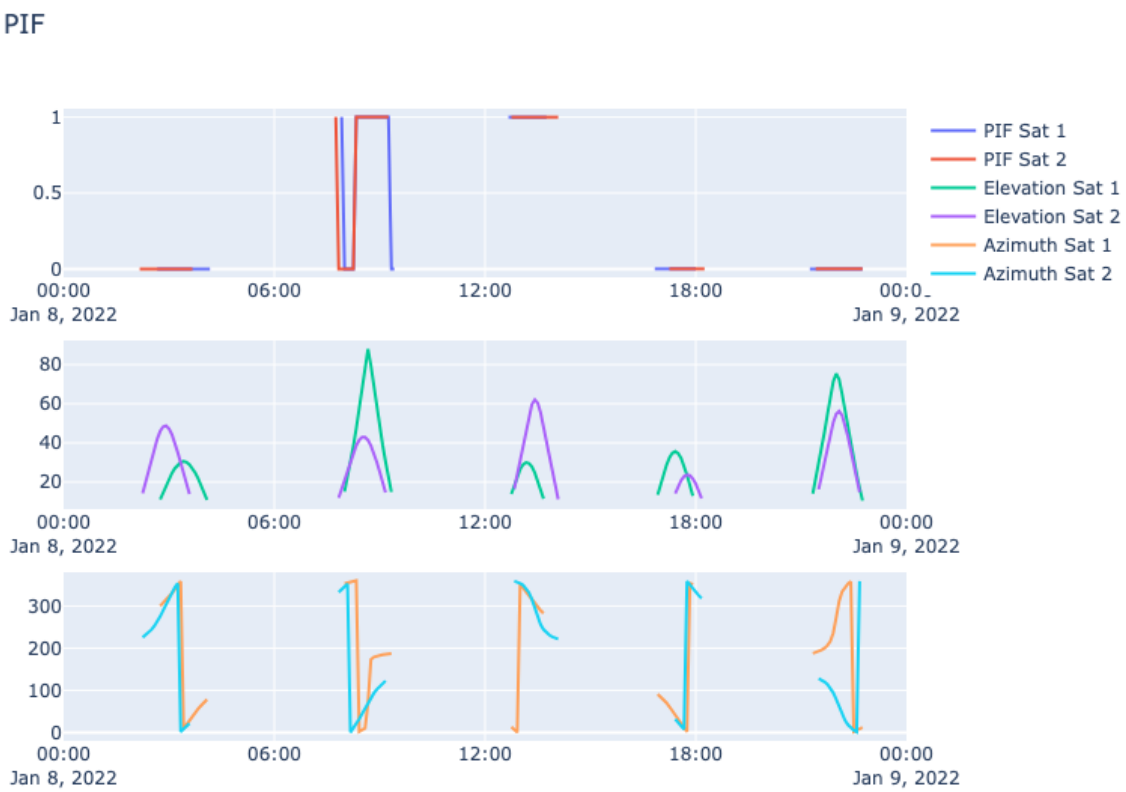

Figure 6 Snapshot of PIF Time Series

5.2 Use of Stochastic Differential Equations (SDEs) with ITU-R methods

The model uses ITU-R statistics for the long-term modelling of the attenuation from the different attenuation components, while for the second-order statistics relies on a modification of ITU-R P. 1853-1 and ITU-R P. 1853-2 to include the time dependency of the link parameters due to the movement of the satellites. The foundation of this methodology is to generate time series of each component that capture the first order statistics of each attenuation component and total attenuation when the elevation angle varies with time. It considers a realistic temporal correlation, realistic spatial correlation for each component and the correlation between the different components. It is based on the model presented in [7].

In Figure 7, example time series as generated by the SDE methodology of all attenuation components are shown for an uplink for a single link to a MEO satellite.

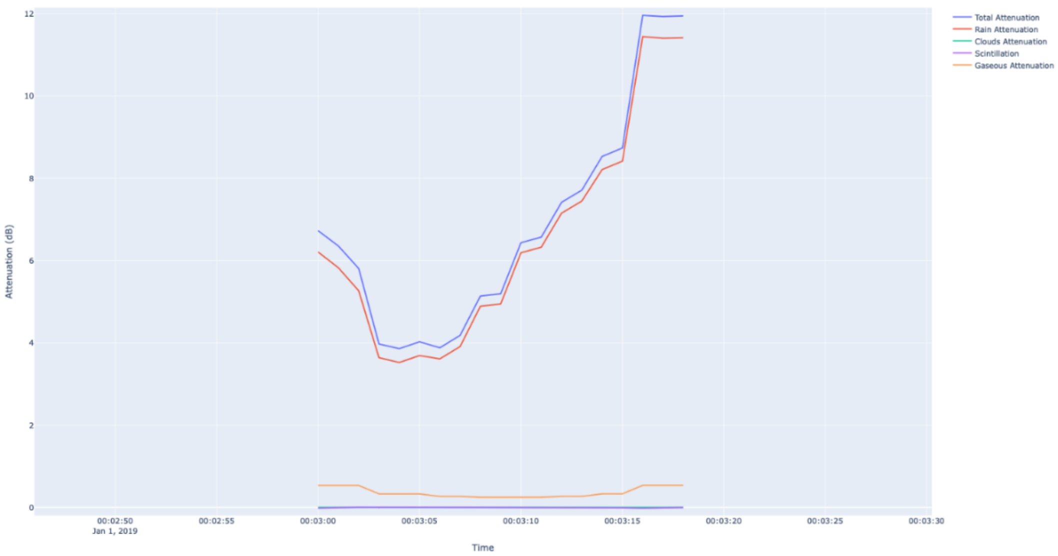

Figure 7 Attenuation time series

6. NGSO Communications Module

The tool operates in two modes: a) Evaluation of the user defined ground segment with all the inputs well defined or b) optimise over number of antennas of teleports. Both modes require the system simulation. The outputs of the NGSO communications module for a system simulation are divided into average table metrics and plots and also based on whether these refer to teleports, satellites or the system, while in case of optimisation the output is actually a set of possible solutions as this is a multi-objective optimisation problem and the user may then select the appropriate configuration based on certain criteria, e.g. required average capacity and can run an evaluation.

6.1 System Simulation

For both modes the system first needs to be simulated for a long time period and the system metrics that are of importance need to be calculated for each candidate configuration. The system simulation is one part of the NGSO communications module and uses the outputs of the OMM module, the Link Budget Module and the Propagation Module.

The system simulation does calculations for each time step. There are 4 stages on the simulation algorithm and each time a stage is finished the connection status is updated. In summary, three different link establishment strategies have been implemented based on the selection of the best link available, i.e. selecting the links with the highest spectral efficiencies and the duration of visibility. If the link is already established, then the link is retained. If due to visibility or weather conditions the link is on outage (spectral efficiency less than the minimum desired), a switchover takes place and a new link that can provide a better spectral efficiency is established, if available. As the tool takes into account the clustering of teleports, for the link establishment first the satellites that were connected to the same cluster with the gateway under consideration are iterated. If not available then a satellite connected previously to a different cluster may switch to continue serving the ground segment. In the link establishment logic the residual satellite capacity and the free feeder antennas on both the satellites and the gateways are of importance. The tool also introduces a switching outage to account for the number of redundant feeder beams. When all satellites have been iterated and if any residual traffic is not delivered, then if ISL is available, the network is solved by the ISL algorithm to find additional ISL paths and deliver the required traffic. The tool also integrates terrestrial connectivity features including the data rate required for cloud modules. A user can enter either manually the cluster centres or use PeeringDB database in order to find the closest datacentre to the location of each candidate gateway.

The output of the simulation mode includes a number of average metrics and distributions of capacity, throughput, number of antennas used per gateway and satellite and for the whole system. In addition, the number of handovers and switches are calculated, the distribution of the latency including the latency due to ISL.

6.2 Optimisation

Evolution is an optimisation process and nature provides an example how it has been used to solve difficult problems. This paradigm is used in evolutionary computation, a relatively recent discipline in order to find solutions in various kind of engineering problems like design, planning, scheduling, control etc.

In the current setting, the metrics that can be used for the optimisation are values that describe on one hand the capability of the system to deliver the capacity in different weather conditions over a long simulated time span and on the other hand the number and location of gateways used. A trade-off is needed to satisfy requirements while also keeping the number of gateways (and thus infrastructure cost) at acceptable levels. This is a multi-objective optimisation problem. A set of candidate solutions to support this trade-off decision is provided based on the NGSA-II algorithm.

The metrics that are used in the multi-objective optimisation include the total capacity of the system (System Capacity) and the total number of antennas. The capacity metrics are straightforward. Based on the constellation positions and the weather conditions, the link budget equations are solved and links are established between the satellites and the gateways with the data rate provided by the achieved spectral efficiency. A statistic can be calculated or an aggregate value for the complete simulation time. In the tool, the average value of capacity is used. The tool targets the required number and location of teleports in a particular geographical area and the number of GW antennas required at each teleport, given the inputs of the constellation and certain other user settings.

7. Numerical Application

The first simulation scenario is a set of 7 stations and 300 LEO satellites with full mesh ISL. In Table 1, the gateway metrics are shown while in Table 2 the satellite metrics and in Table 3 the system metrics. In Figure 8, the distribution of capacity is shown for the whole system.

Table 1 - Teleport metrics

Name	Capacity (Gbps)	Throughput (Gbps)	Antenna Diameter (m)	Availability (%)	Output Power Ka - band (W)	Terrestrial Data Rate (Gbps))
GW 1	81.94	81.94	1.00	99.89	12.28	1296.00
GW 2	71.06	71.06	1.00	83.78	17.75	1296.00
GW 3	54.51	54.51	1.00	61.21	78.10	1296.00
GW 4	48.77	48.77	1.00	56.69	26.18	1296.00
GW 5	53.89	53.89	1.00	61.77	25.58	1296.00
GW 6	58.43	58.43	1.00	65.60	35.98	1296.00
GW 7	59.62	59.62	1.00	66.94	166.99	1296.00

Table 2 - Satellite metrics for 10 out of 300 satellites

Name	Capacity (Gbps)	Throughput (Gbps)	Feeder Link Availability (%)
SAT 1	1.42	1.48	3.30
SAT 2	1.43	1.42	3.30
SAT 3	1.42	1.43	3.29
SAT 4	1.43	1.42	3.31
SAT 5	1.43	1.43	3.31
SAT 6	1.42	1.43	3.30
SAT 7	1.43	1.43	3.30
SAT 8	1.43	1.43	3.31
SAT 9	1.43	1.43	3.30
SAT 10	1.42	1.43	3.30

Table 3 - System metrics

Capacity (Gbps)	Throughput (Gbps)
428.22	428.22

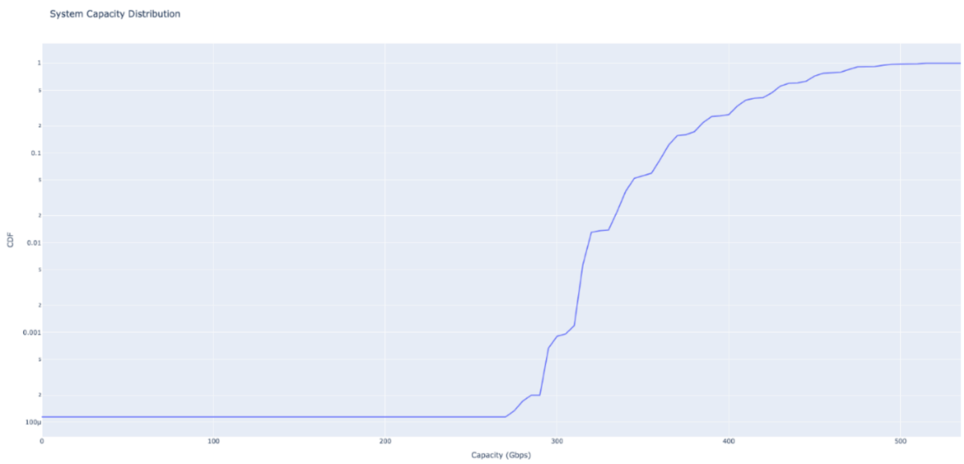

Figure 8 - System capacity distribution

In Optimisation mode, as explained, a multi-objective genetic algorithm is used to identify the Pareto front. From the output of the simulation, the 5 gateway configurations with the highest capacity are shown in Table 4 while the Pareto front is shown in Figure 9.

Table 4 - System metrics : 5 first gateway configurations

Configuration No	Number of Antennas										Capacity (Gbps)
	GW 1	GW 2	GW 3	GW 4	GW 5	GW 6	GW 7	GW 8	GW 9	GW 10	
1	5	5	5	5	5	5	5	5	5	6	1069.12
2	5	5	4	5	5	5	5	5	5	6	1069.06
3	5	5	4	3	5	5	5	5	5	6	1069.05
4	5	5	4	3	4	5	5	5	5	6	1066.78
5	4	0	5	5	5	5	5	5	5	6	1065.95

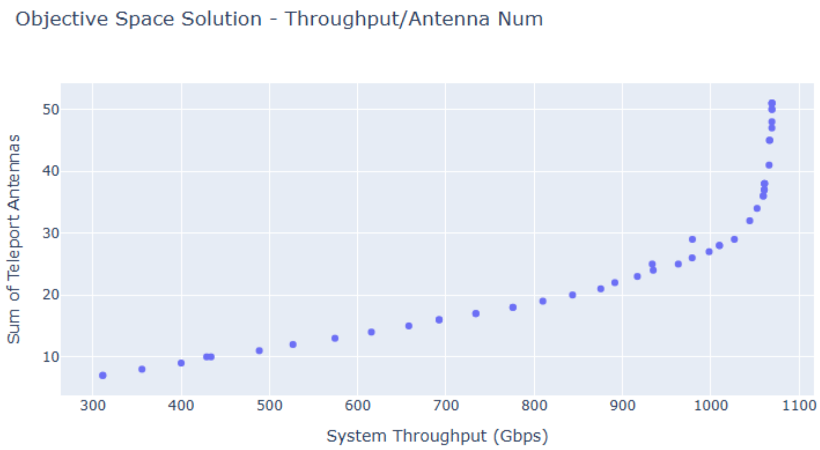

Figure 9 - Number of antennas over system throughput

8. Conclusions

The objective of the GND Tool is to apply and test methodologies and algorithms of ground network dimensioning for NGSO constellations with the target of enabling the combined optimisation of system architecture for secure constellations and evaluate the performance of different concepts of operation for NGSO constellation ground networks.

The Atheras Analytics GDN Tool offers several advantages that make it a powerful and scalable solution for NGSO ground segment dimensioning. The tool includes parallel computation and quantization for large-scale simulations and leverages parallel computing techniques to distribute computational loads across multiple processing cores. This allows for faster execution of large-scale simulations, ensuring that even constellations with hundreds of satellites and multiple gateways can be modelled efficiently.

Moreover, as the tool was designed with modular architecture, GND Tool can scale vertically by increasing the computational resources allocated per simulation. This enables the tool to handle larger datasets, higher-resolution simulations, and more complex network configurations as NGSO systems evolve.

Another advantage of the tool is the flexibility across different network configurations. Unlike rigid modelling tools that assume fixed architectures, GND Tool is adaptable to various NGSO system configurations, including: a) Different satellite orbits (LEO, MEO) and the hybrid case is under development, b) Inter-satellite links (ISL), c) Teleport clustering, d) Single and Dual frequency band gateways, e) Optimisation vs simulation, f) Geopolitical constraints on gateway placement and g) Service coverage area.

This flexibility makes the tool a versatile solution for a broad range of satellite operators, government agencies, and private sector stakeholders.

In terms of commercial advantages of the tool, the most important one is its ability to reduce infrastructure costs by optimising: a) The number and placement of ground stations, b) The utilisation of inter-satellite links (ISL) to reduce the reliance on expensive terrestrial networks and c) Network routing strategies to minimise operational overhead.

By leveraging advanced optimisation techniques, satellite operators can achieve higher performance at lower operational costs, improving the overall return on investment (ROI).

Acknowledgement

The work in this paper was carried out under the ESA Programme Related to EU Secure Connectivity and funded by the European Space Agency. The paper reflects the views of the authors and can in no way be taken to reflect the official opinion of the European Space Agency.

References

[1] A. D. Panagopoulos, et al., "Satellite communications at KU, KA, and V bands: Propagation impairments and mitigation techniques,", IEEE Communications Surveys & Tutorials, vol. 6, no. 3, pp. 2-14, Third Quarter 2004
[2] T. Cooklev et al., "The VITA 49 Analog RF-Digital Interface," in IEEE Circuits and Systems Magazine, vol. 12, no. 4, pp. 21-32, Fourthquarter 2012
[3] P. Martinez de Tejada et al., “On The Extension Of Outage Prediction Algorithm For NGSO Applications: Calculation Of Link Availability For Different Azimuth And Elevation Angles”, 28th KaBSC, Bradford, 2023.
[4] ITU-R. P. 618-13, “Propagation data and prediction methods required for the design of Earth-space telecommunication systems,” 2017.
[5] C. Kourogiorgas et al., “Design and operation of a smart gateway diversity network using outage prediction algorithm,” in 27th Ka and Broadband Communications Conference, Stresa, Italy, 2022.
[6] S. Ventouras et al. , “Assessment of spatial and temporal properties of Ka/Q band earth-space radio channel across Europe using Alphasat Aldo Paraboni payload,” International Journal of Satellite Communications and Networking, vol. 37, pp. 477-501, 2019.
[7] C. I. Kourogiorgas et al., “Capacity Statistics Evaluation for Next Generation Broadband MEO Satellite Systems,” IEEE Transactions on Aerospace and Electronic Systems, vol. 53, no. 5, pp. 2344-2358, 2021.