Analytical constellation design and link budget computation tool for EO missions

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Abstract

This paper presents the activities carried out in collaboration between SITAEL SpA and the University of Pisa for the development of a computationally light tool capable of performing a parametric analysis of constellation performance as a function of number of satellites and orbital parameters and of estimating the link budget in a reliable way. Such tool is of fundamental importance in the preliminary phases of constellation design. A selected Earth Observation (EO) mission test case is presented to illustrate the advantages of using this simple, fully-integrated tool for the preliminary mission analysis and design.

1. Introduction

The recent trend in Earth Observation (EO) is to use constellations of small satellites for missions so far made possible only by the use of large platforms, with relevant overall mission cost savings. The availability of a computationally light tool capable of performing a parametric analysis of constellation performance as a function of number of satellites and orbital parameters and of estimating the link budget in a reliable way is of fundamental importance in the preliminary phase of the design of EO constellations. Such a tool was recently developed in collaboration between SITAEL SpA and the University of Pisa.

2. Tool description

The code developed consists of three inter-related modules. The first module is dedicated to the constellation design. Under the assumption to use Sun-Synchronous Repeating Ground Track Orbits (SSRGTO), this tool needs as input only the instrument field of view (FOV) and some characteristic dimensions of the Area of Interest (AOI). For repeat cycles (RC) between 1 and 30 days, the altitudes are iteratively computed along with the number of satellites needed to cover the area of interest. For a constellation in a single plane, the module also provides the satellites phasing to cover the area adjacent to the area covered by the previous satellite; for a multi-plane constellation, the number of orbital planes and their relative phasing is provided. The propellant mass needed for drag compensation is estimated at each altitude, using the NRLMSISE-00 model to compute atmospheric density. The latter feature requires some additional inputs such as the mass of the satellite, its cross-sectional area (to ccompute atmospheric drag), and the onboard propulsion system performance parameters. The constellation robustness, i.e. the variation of area of the ground scenario covered in the case of failure of one or more satellites, is assessed considering a mean value of the ground track length in the area of interest.
The second module performs post-processing of data from NASA's General Mission Analysis Tool (GMAT® - a freely available mission analysis package) to analyze the link budget performance among satellites and ground stations. Variables imported from GMAT include position, velocity and temporal information. Considering user specified ground stations (GS), the link budget is then computed. For specified antenna types, the position of the sub-satellite points are calculated relative to the electric field contour levels around a user-defined area. This approach therefore uses varying GS power output with fixed (maximum) gain, thus giving a range for uplink and downlink margins in terms of Signal-to-Noise Ratio (SNR) and Energy per Bit to Noise ratio (E_b/N_0). Losses due to rain, cloud and atmospheric gases are accounted for from ITU-R models, while transmission losses in cables are calculated based on look-up tables for both the ground and the space segment. For the SNR method, the user specifies the bandwidths of

the receivers or transmitters and the required SNR. For the E_b/N_0 method, several selectable modulation/demodulation schemes are incorporated in the tool.

The third module computes visibility among all members of the satellite constellation, for the computation of inter-satellite link budgets under the assumption that the satellites are pointing towards each other in the direction of maximum gain.

2.1 Constellation design module

The constellation design module is specifically developed to design small satellite constellations in SSRGTO. A SSRGTO is an orbit which provides simultaneously the capabilities of repeating ground track orbit (RGTO) and Sun-synchronous orbit (SSO). SSRGTO orbits are well exploited by many EO missions, e.g. by Landsat, SPOT and RapidEye [1].

Sun-synchronous orbits are characterized by the combination of inclination, eccentricity and semi-major axis that guarantees that the average regression of the line of nodes due to the Earth oblateness (the J_2 term in the spherical harmonics representation of the gravitational field) is equal to the Sun apparent motion around the Earth (1 deg/day).

Repeating ground track orbits are generated by choosing combinations of perturbations on the argument of perigee, mean anomaly and RAAN so to have an integer number of revolutions after a given number of days (accounting also for the Earth natural rotation [2].

Under the assumption to use SSRGTO, the first module needs as input only the instrument field of view (FOV) and four characteristic parameters of the area of interest (AOI): minimum latitude λ, maximum distance l_{max} between two points of the AOI in the direction perpendicular to the groundtracks, average length l_{avg} of the groundtrack in the AOI, and area A_{AOI} of the AOI (Figure 1).

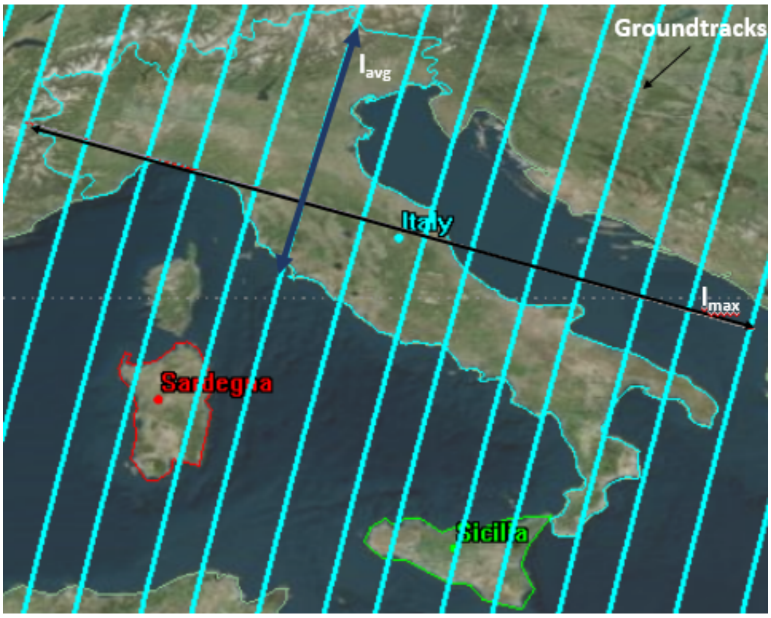

Figure 1: Example of AOI characteristics parameters

For each repeat cycle (RC) between 1 to 30 days, this module provides the spacecraft operative altitude and the number of satellites needed to cover the AOI. For a constellation in a single plane, the module also provides the satellites phasing to cover the area adjacent to the area covered by the previous satellite; for a multi-plane constellation, the number of orbital planes and their relative phasing is provided. As additional features, the module provides the propellant mass needed for drag compensation at each altitude and the constellation robustness, i.e. the area covered in the case of failure of one or more satellites.

The number of satellites is a driving factor for the overall system cost. The number of satellites can be optimised by trading off the achievable figures of merit (revisit time, coverage, constellation robustness) vs. the system cost and complexity (number of launches, satellites cost, propellant mass).

The constellation design workflow (Figure 2) starts with the computation for each RC of the number of orbits per day, z (daily orbital frequency), and the number of revolutions to repeat, j [3].

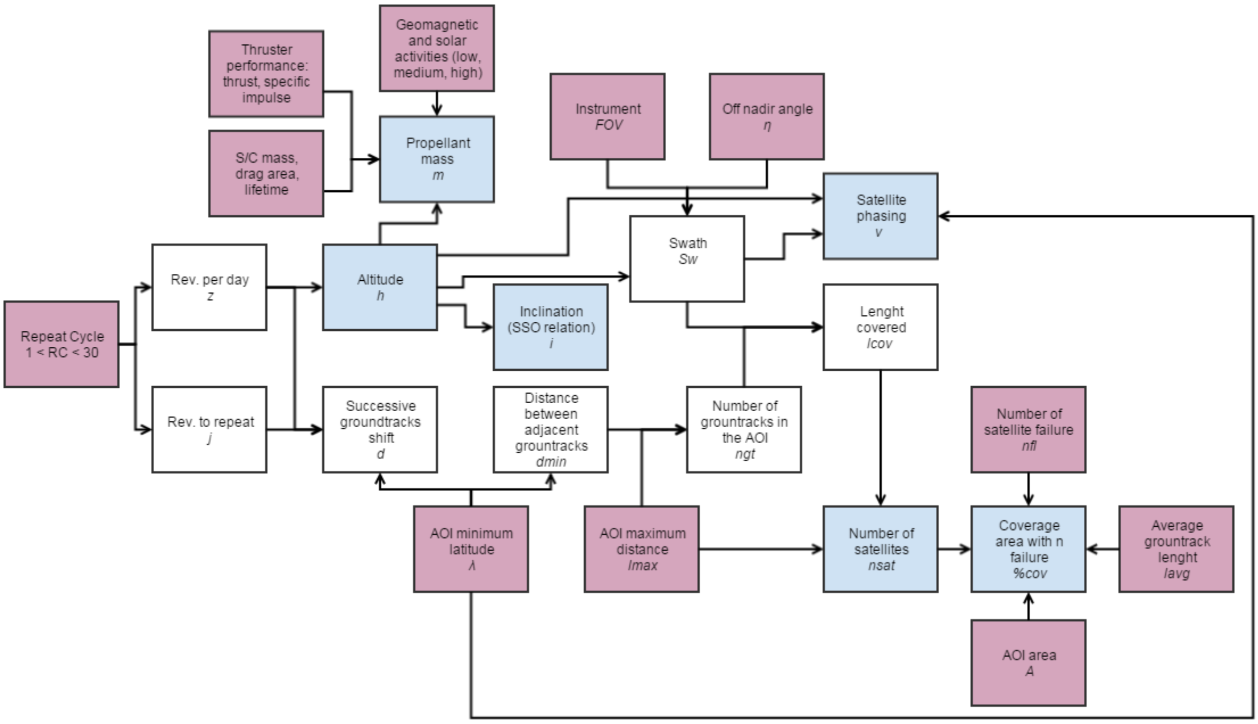

Figure 2: Coverage module block diagram

From these, both the altitude h and equatorial distance d between two successive satellite tracks are computed [3]. The daily orbital frequency z gives the mean motion and draconitic period and as consequence the altitude h. In a SSRGTO, the spacecraft returns after a given number of days on the same Earth location, thus the ground trace of the spacecraft repeats itself. The design of such an orbit requires a fixed orbital period; perturbations, however, cause the orbit itself to rotate with an associated variation of the orbital period. In particular, the rotation of the orbit due to Earth oblateness has to be considered. This results in an iterative process for the design of a SSRGTO due to the fact that the Earth oblateness effects are a function of altitude. As consequence, the altitude h is computed by an iterative process [2]. In a SSO the altitude and inclination are directly related, therefore for each altitude h the relative inclination i is computed by means of the SSO equations [2]. Moreover, taking into account the instrument field of view (FOV), the instrument swath (nadir-pointing) is calculated for each altitude h [2].

The equatorial shift d represents the distance between two successive ground tracks (of the same kind, ascending or descending) at the equator. It is thus very simply related to the daily orbital frequency z. The equatorial shift between ground tracks day by day d_{min} is calculated dividing the equatorial shift d by the repeat cycle RC [4]. This shift represents the minimum distance between two adjacent groundtracks in the entire RC. Introducing the minimum latitude λ of AOI, the latter both distances are calculated at this latitude multiplying for the cosine of λ [2]. Dividing the shift between groundtracks day per day d_{min} at the latitude of interest by the characteristic length l_{max} of the AOI, the number n_{gt} of ground tracks that cross the AOI during the RC is determined. At this point, combining the information related to the altitude (e.g., swath) and to the ground track distance (e.g., number of ground tracks), it is possible to compute the number of satellite needed to cover the AOI. Indeed, the total length covered l_{cov} by one satellite at the RC end is simply obtained by multiplying the swath by the number n_{gt} of groundtacks. Therefore, dividing the characteristics length l_{max} of the AOI by the total length covered by one satellite, the number of satellites n_{sat} needed to sweep 100% of the characteristic length l_{max} of AOI after RC days is calculated. This number corresponds to the number of satellites needed to cover 100% of the AOI. Moreover, the tool provides the true anomaly spacing $\Delta\varphi_{rel}$ of the satellites in a "train" configuration to cover the area adjacent to the area covered by the previous satellite, according to [2]. Introducing the average length l_{avg} of the groundtrack in the AOI and the area A_{AOI} of the AOI, the module provides a preliminary estimation of the constellation robustness, i.e. the area A_{fail} covered in the case of failure of one or more satellites. This area is simply assessed by subtracting the area obtained by multiplying the average groundtrack length l_{avg} by the swath Sw, by the number n_{gt} of groundtracks and by the number n_{fail} of satellite failures, from the AOI area A_{AOI}. Finally the module computes the previous quantities taking into account the instrument off-nadir angle and the corresponding swath length.

The relations used in the coverage module to compute the constellation satellite numbers and relative phasing are reported below, where R_e is the Earth radius, τ is the keplerian orbit period and τ_E is the Earth's rotation period. This first module has been validated using results form the commercial AGI-STK software package as a reference.

$$d = \frac{2\pi}{z\,R_e} cos\lambda \tag{1}$$

$$d_{min} = \frac{d}{RC} \tag{2}$$

$$n_{gt} = \frac{l_{max}}{d_{min}} \tag{3}$$

$$l_{cov} = S_w\, n_{gt} \tag{4}$$

$$n_{sat} = \frac{l_{max}}{l_{cov}} \tag{5}$$

$$A_{fail} = A_{AOI} - l_{cov}\, S_w\, n_{gt}\, n_{fail} \tag{6}$$

$$\Delta\varphi_{rel} = \left\lceil \left(\frac{\tau_E S_w}{2\pi R_e \cos\lambda}\right)\frac{360}{\tau} \right\rceil \tag{7}$$

As an additional feature, the first module provides an estimation of propellant mass needed to counteract the drag at each altitude. The drag coefficient is assumed to be equal to 2.2. The NRLMSISE-00 atmospheric model is adopted to define the atmospheric density at each altitude, while the solar flux and magnetic indices are set according to the level of solar and geomagnetic activities selected by the user. Moreover the model requires other inputs, such as thruster performance (thrust, specific impulse), spacecraft mass and drag area. For circular orbits, the loss of velocity ΔV per revolution due to the atmospheric drag is computed according to [2]:

$$\Delta V_{rev} = \pi\, \frac{C_D A_D}{m} \rho a V \tag{8}$$

where ρ is the atmospheric density, C_D is the dimensionless drag coefficient of the satellite, A_D is the cross-section area, m is the satellite mass, V is its velocity and a is the semi-major axis.

2.2 Link budget module

After designing the constellation by the analytical method described previously, all the satellite trajectories can be propagated in GMAT. The successive modules involve post-processing of the variables from a GMAT report file, which contains position, velocity and temporal information. These report files (corresponding to the number of satellites of the constellation) are read by the program, and a routine extracts the orbital elements of every satellite in the constellation. The post-processing techniques implemented in the tool will then compute the link budget between satellites of the constellation and multiple user-defined ground stations, as well as among different satellites of the constellation.

A brief introduction to the link budget formulation is given below for computation of the uplink margin (ground station to spacecraft). Losses are denoted by L, the letters followed by the underscore determine which segment we are dealing with: *L_SC* refers to spacecraft (SC) losses whereas *L_GS* refers to ground station (GS) losses. If a loss is not followed by an underscore, it indicates a path loss. The subscripts which follow indicate which particular loss we are dealing with: tl = transmission losses; pt = pointing; pol = polarization losses; $fspl$ = free space path loss; atm = atmospheric gas losses; $rain$ = rain losses; $cloud$ = cloud losses. Ga refers to gain, and the subscript which follows indicates which segment (GS or SC) we are referring to.

The Effective Isotropic Radiated Power of the ground station antenna is given by:

$$EIRP_{GS} = P_o + L\_GS_{tl} + Ga_{GS} \tag{9}$$

where P_0 is the ground station transmitter power output.

The Isotropic Signal level at the SC is given by (see equation (1)):

$$ISL_{SC} = EIRP_{GS} - (\mathrm{L\_GS}_{\mathrm{pt}} + \mathrm{L\_GS}_{\mathrm{pol}} + \mathrm{L}_{\mathrm{fspl}} + \mathrm{L}_{\mathrm{atm}} + \mathrm{L}_{\mathrm{rain}} + \mathrm{L}_{\mathrm{cloud}}) \quad \textbf{(10)}$$

The user can choose to evaluate the link performance by selecting one of two methods: SNR method or the E_b/N_0 method. The above computations are common for both methods, and from this point, the tool will take different paths, depending on the user selected method, to evaluate the link margin.

2.2.1 SNR method

The signal power at the spacecraft Low Noise Amplifier (LNA) input is given by:

$$Signal\ power\ at\ SC\ LNA\ input = ISL_{SC} + Ga_{SC} - (L\_SC_{pt} + L\_SC_{tl}) \quad \textbf{(11)}$$

The spacecraft noise power Pn is given by:

$$Pn = K + 10log(Ts) + 10log(B) \quad \textbf{(12)}$$

where T_S= antenna/ sky temperature and B=Receiver bandwidth (user input).

The Signal-to-Noise Power Ratio at the GS receiver, from (3) and (4), is given by:

$$SNR = Signal\ power\ at\ SC\ LNA\ input - Pn \quad \textbf{(13)}$$

$$Margin = SNR - S/N \quad \textbf{(14)}$$

where the required S/N is an input.

2.2.2 E_b/N_0 method

The S/C Signal-to-Noise ratio is given by:

$$(S/N0) = ISL_{SC} - L\_SC_{pt} - K + G/T \quad \textbf{(15)}$$

This value is used in (9), and the figure of merit G/T is:

$$G/T = Ga - L\_SC_{tl} - 10log(Ts) \quad \textbf{(16)}$$

$$Command\ system\ Eb/N0 = 10log(R) - (S/N0) \quad \textbf{(17)}$$

where the desired data rate R is a user input. From (9),

$$Margin = Command\ system\ Eb/N0 - Eb/N0 \quad \textbf{(18)}$$

where $Eb/N0$ is a function of the desired modulation/ demodulation scheme.

A similar approach is used to compute the downlink margin. These computations are also extended to inter-satellite link budget performance evaluation, as will be explained in the following sections. For the computation of the losses in the uplink/downlink path and at the receiving/ transmitting end, efforts were made to reduce user inputs and carry out computation of these losses within the code. In the following sections, the inputs required, the computations carried out, and the outputs are analyzed in detail for link performance evaluation for both a ground station-satellite link as well for inter-satellite links.

2.2.3 GS-Satellite Link Budget

This module computes the link budgets between satellites of the constellation and user-specified points, which correspond to the ground stations. For specified spacecraft and ground station antenna types, the position of the sub-

satellite points are calculated relative to the electric field contour levels of the ground station antenna around a user-defined area. This approach therefore uses varying ground station antenna power output with fixed (maximum) gain, thus giving a range for uplink and downlink margins in terms of SNR or E_b/N_0, depending on the user's choice.
For the ground segment, the user inputs the number of ground stations, and correspondingly, their latitude, longitude, height, azimuth and elevation. Then, the type of antenna can be selected for each ground station and satellite. Ten antenna types from MATLAB®'s parametrized antenna library are made available for selection. The antenna parameters to be input by the user are specified in Table 1.

Table 1: List of antenna types available and modifiable design parameters

TYPE	**DIMENSIONS**
Dipole	Length, Width
Monopole	Height, Width, Ground Plane Length, Ground Plane Width
Helix	Radius, Width, Turns, Spacing ,Ground Plane Radius
Patch Microstrip	Length, Width ,Height, Ground Plane Length, Ground Plane Width
Reflector	Ground Plane Length, Ground Plane Width, Spacing
Yagi Uda	Number of detectors, Director Length, Director Spacing, Reflector Length, Reflector Spacing
Slot	Length, Width, Ground Plane Length, Ground Plane Width
Horn	Flare length, Flare width, Flare height, Length, Width, height
Dipole Helix	Radius, Width, Turns ,Spacing
Waveguide	Length, Width, Height

MATLAB's Antenna Toolbox is used to model the antennas. For each ground station antenna, gain, beamwidth and power is calculated within the program, using in-built MATLAB functions. The frequency is used, in addition to the range, to compute the free space path loss L_{fspl} using the function *fspl* available in MATLAB. The range corresponding to having the sub-satellite point (SSP) inside any of the electric field contours of the ground station antenna is calculated within the program and is used to calculate the free space path loss. The frequency and cable type dependent transmission losses (in dB/meter) are listed in two look-up tables for typical cables used in spacecraft [7] and ground stations [5]. These tables can be updated to include new cable types. The cable types currently listed are shown in Table 2 and Table 3 for the ground and space segment, respectively. To calculate transmission losses L_GS_{tl} and L $\_SC_{tl}$, the user input required is the type of cable for each satellite and ground station and the total transmission cable length.

Table 2: List of selectable spacecraft cable types

Cable specification	**Material**	**Diameter [mm]**	**Loss/ unit length**	**Shielding**	**Ideal for**
RG-188 A/U	PTFE (Teflon)-wrapped	2.49	High	Silver plated Copper, 19 strands, each #33 AWG	Short coax runs in small spacecraft, SMA or SMC connectors
RG-142 A/U	FEP (Teflon) solid covered	4.95	Moderate	double shielded with two silver coated copper braids	SMA or TNC connectors
RG-303 /U	PTFE (Teflon) solid covered	4.32	Moderate	single shielded with a silver coated copper braid	SMA or TNC, long spacecraft runs
50 ohm Semi-Rigid Cable (0.085" dia.)	Solid copper outer conductor	2.18	Low	-	SMA,SNC ,TNC connectors
50 ohm Semi-Rigid Cable (0.141" dia.)	Solid copper outer conductor	3.58	Very low	-	SMA,SNC ,TNC connectors
RG 178	Silver coated copper clad steel	0.86	Very high	Silver-coated copper	-

Table 3: List of selectable ground station cable types

Cable specification	Material	Diameter [mm]	Loss/ unit length	Shielding	Ideal for
RG-174	PTFE (Teflon)-wrapped	2.49	High	Silver plated Copper, 19 strands, each #33 AWG	Short coax runs in small spacecraft, SMA or SMC connectors
RG-58	FEP (Teflon) solid covered	4.95	Moderate	double shielded with two silver coated copper braids	SMA or TNC connectors
RG-8X	PTFE (Teflon) solid covered	4.32	Moderate	single shielded with a silver coated copper braid	SMA or TNC, long spacecraft runs
RG-213	Solid copper outer conductor	2.18	Low	-	SMA,SNC ,TNC connectors
RG-6	Solid copper outer conductor	3.58	Very low	-	SMA,SNC ,TNC connectors
RG-11	Silver coated copper clad steel	0.86	Very high	Silver-coated copper	-
BFLEX	-	-	-	-	-
RF-9913	-	-	-	-	-

For the calculation of the effective noise temperature, the Low Noise Amplifier (LNA) temperature and LNA gain are left as user input, as well as the temperature of the second stage of the LNA. In addition, this computation also uses the transmission losses. For the antenna or sky temperature, a few simple assumptions were made: for the satellite antenna, we can assume that 25 % of the earth (at 290 K) is in the FOV, while the remaining 75% sees cold space (2.7 K); for the ground station antenna, we can assume that it sees cold space, thus having an antenna temperature of 2.7 K. The antenna pointing loss depends on the beamwidth of the antenna, which is calculated within the program using the MATLAB function *beamwidth* from the type and dimensions of the antenna [6]. An additional constant pointing error provided as an user input is also considered. The polarization loss depends upon the polarization angle mismatch between the two antennae at the opposite ends of the link and on the axial ratio of the antennae ([7]). The polarization angle between the antennae is input buy the user, whereas the axial ratio is computed in the code using the MATLAB function *axialRatio*.

- SNR Method: the user specifies bandwidth B of the receivers or transmitters (data filter through which signal spectrum must pass). An additional input required is the analog or digital system required S/N for uplink and downlink. For digital systems, this is the equivalent of E_b/N_0, and is based on the type of modulation and demodulation scheme implemented. For analog systems, this depends on the user input.

2) E_b/N_0 method: the user inputs the system desired data rate in bps for uplink and downlink. The S/N_0 ratio is then computed and a command system E_b/N_0 threshold is then selected, which depends on the type of modulation and demodulation scheme implemented. A constant coding implementation loss of 1 dB is added. The required E_b/N_0 threshold based on type of modulation or demodulation scheme is shown in Table 4.

Table 4: List of available modulation/ demodulation schemes [7]

SCHEME	BER	E_b/N_0 threshold
AFSK/FM	1e-4	21
G3RUH FSK	1e-4	16.7
Non-Coherent FSK	1e-4	13.4
Coherent FSK	1e-4	10.5
GMSK	1e-4	8.4
BPSK	1e-5	9.6
QPSK	1e-6	10.5
BPSK(Convolutional R=1/2, K=7)	1e-6	2.5
BPSK(Convolutional R=1/6, K=15)	1e-6	0.8

Some suggestions for typical data rates for three different mission modes (Command, Housekeeping and Mission mode) are suggested in the program to the user. The losses calculated are described below.

Rain attenuation L_{rain}: Frequency dependent rain attenuation empirical values are taken from [8].Calculation of rain specific coefficients are then carried out based on the relations from [9]. Slant path length depends on rain height, which are different heights above sea level depending on a region on the earth, and is a user input. Another parameter which the user can input is the rate of rainfall. In the tool, a medium rate of 10 mm /hour has been considered. The algorithm used to compute the signal attenuation due to rain is shown in Figure 3.

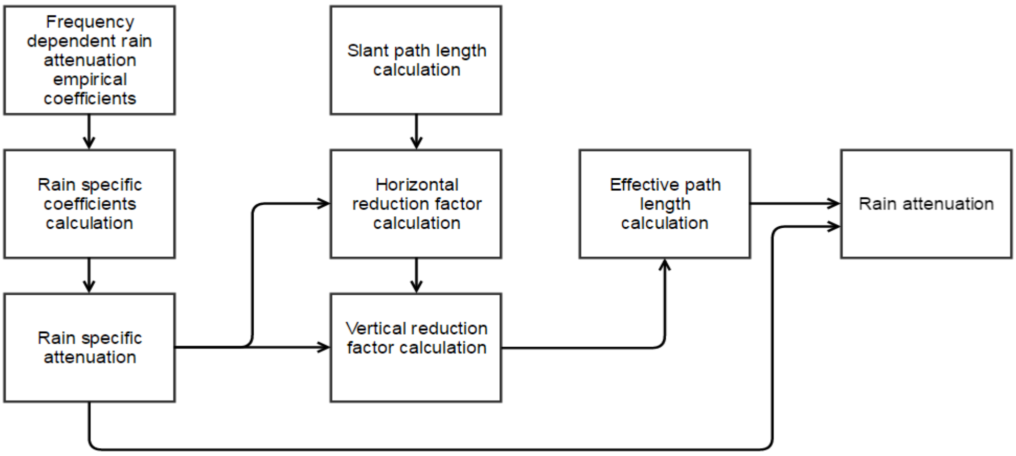

Figure 3: Rain attenuation loss algorithm

Cloud attenuation L_{cloud}: The procedure to compute cloud attenuation is taken from [10]. The Liquid Water Content (LWC), which depends on location, is taken as a fixed 0.2 kg/m^3 based on recommendations from [10]. The algorithm used to compute the signal attenuation due to clouds is shown in Figure 4.

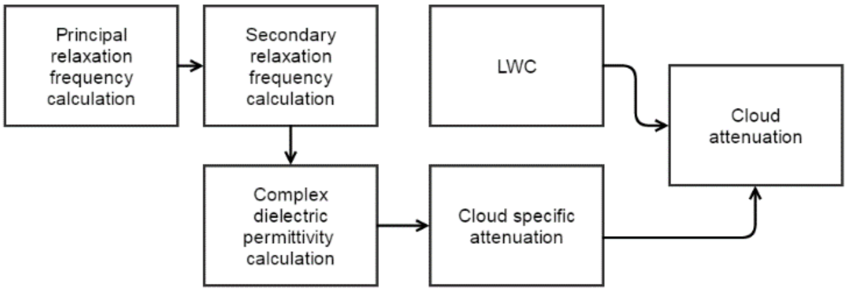

Figure 4: Cloud attenuation loss algorithm

Atmospheric gases attenuation L_{atm}: Specific attenuation due to dry air and water vapour content are calculated based on formulae from [11]. Relative Humidity depends on location, but is taken as 60 % (conservative) in the code. This could be implemented as a user input. The path lengths for oxygen and water vapour content are calculated based on formulae from [9]. For these three losses, the pressure and temperatures at the ground station sites are calculated using MATLAB's *atmosisa* function.

The code will detect the position of the SSPs relative to each electric field contour polygon of every ground station. To optimize the code performance and get obtain reasonable processing times, this process is carried out regardless of the time step used in the GMAT simulation; i.e., when the ground track reaches the edge of the user defined box around each ground station, interpolation of points is implemented. If the sub-satellite points are found not to lie inside the E-field contour polygons of any ground station, the link is not computed. The values of the E-field levels are recorded and the ground stations antenna power is changed according to need, assuming the gain (maximum) to be constant. Thus, a range of system link margins for uplink and downlink is presented in the form of a report for each combination of GS and satellite. To get a better visual on the performance of the links, bar graphs of link margins vs. dwell time of the SSP in each of the corresponding link margin are also available as output. The inputs, computations and outputs are shown in Figure 5.

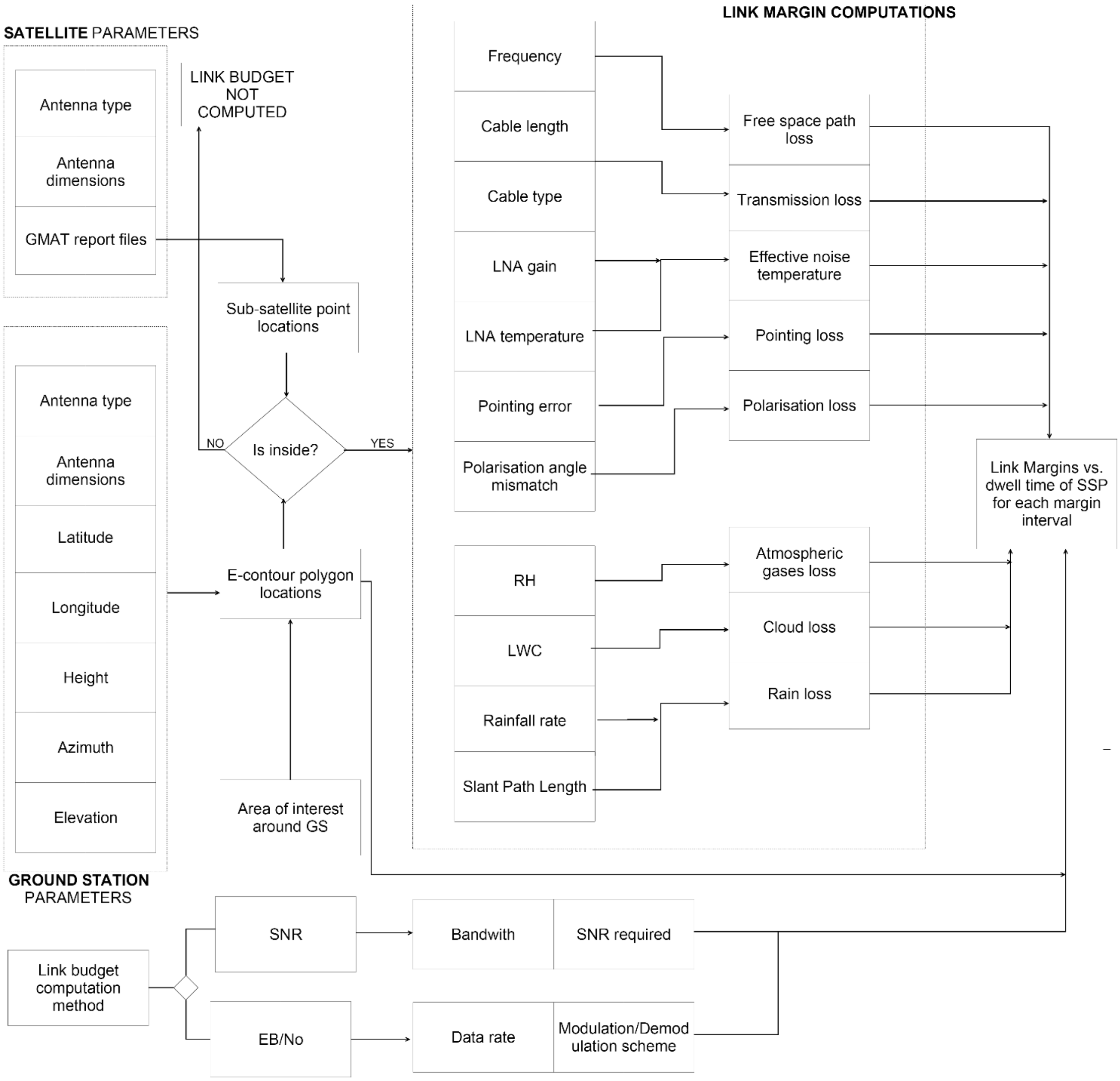

Figure 5: Link budget algorithm

2.2.4 Intersatellite Link Budget

Inter-satellite links are primarily used for data relay purposes. To compute the inter-satellite link budget, mutual visibility between the two satellites is calculated along with uplink and downlink system margins. The procedure is the same as above, except that rain losses, cloud losses and atmospheric losses are obviously neglected. In addition, the gains and power considered are constant. For the antenna sky temperatures, it has been assumed that the satellite at higher altitude will have a sky temperature of 74.5 K, whereas the other will be facing towards cold space and have an antenna temperature of 2.7 K. Given a number of satellite report files, this tool will analyze mutual visibility between all possible combinations of satellites, two at a time. Additionally, if two satellites are mutually visible, the code will compute uplink and downlink system link margins by the same two methods which are described in the previous sections. This visibility information can also be useful for potential data fusion applications. The visibility information will be displayed as a graph, in addition to generation of a report file containing number of visibility arcs, duration of each visibility arc, and time till the next arc.

3. Earth Observation Case Study

In this section, the design process of an Earth Observation mission is described to illustrate the operational capabilities of the tool. The selected Area of Interest (AOI) for this EO case study is Italy. The instrument selected is a hyperspectral imager, typically used for land observation and detailed vegetation classification. A constellation of 200 kg satellites is considered and it is required to maintain each satellite altitude with one propulsive maneuver per revolution. SITAEL's HT100 Hall Effect Thruster is assumed as the onboard propulsion system. The input set for the first module is shown in Table 5.

Table 5: Coverage module inputs

Coverage tool inputs	
Area of Interest (Italy)	Minimum latitude λ = 36.4 deg
	Maximum distance l_{max} = 900 km
	Average groundtrack length l_{avg} = 500 km
	Area A_{AOI} = 301338 km^2
Instrument	FOV = 2.63 deg
	Off-nadir angle = 0 deg
Number of satellite failures	1
Spacecraft parameters	Mass M_0 = 200 kg
	Drag area A_d = 1 m^2
Solar and geomagnetic activities	Medium (F10.7 = 140 F10.7$_{avg}$ = 140 Ap = 15)
	Mission lifetime: 3 years
Thruster performance (HT100 Sitael)	Thrust T = 10 mN
	Specific impulse I_{sp} = 1100s

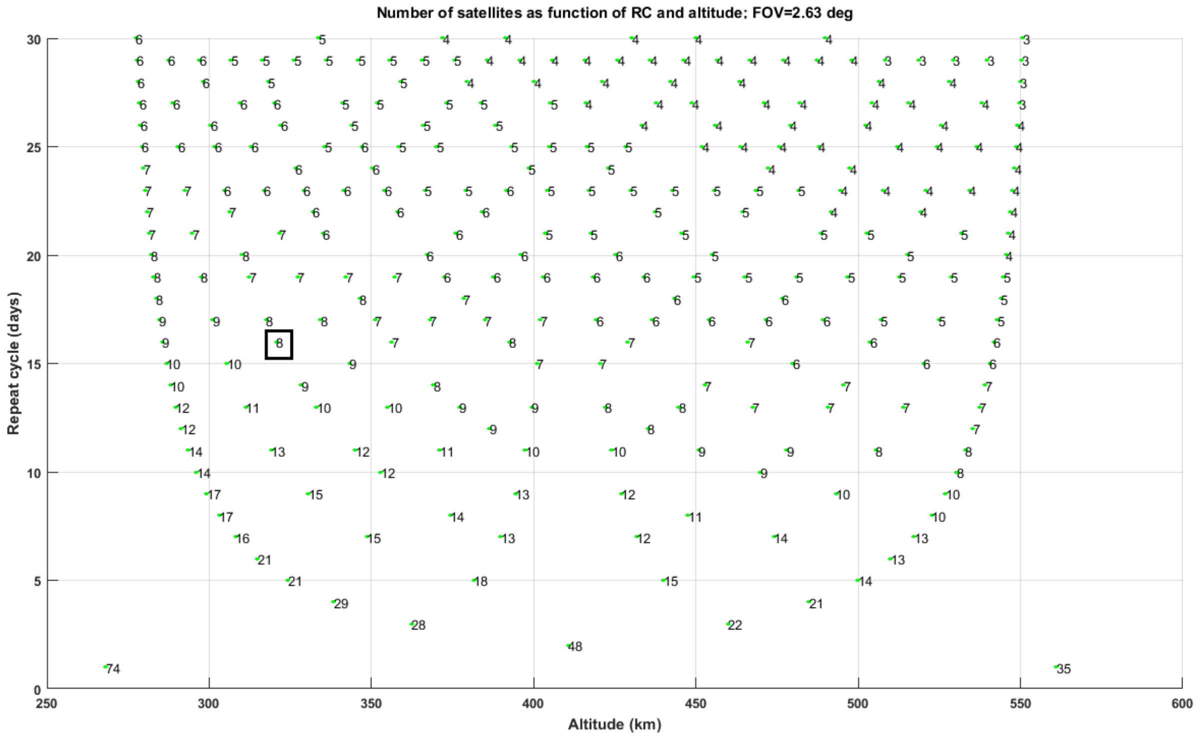

Figure 6: Recurrence Diagram

The first module provides for each RC the whole set of outputs described in Section 2. In detail, Figure 6 shows the recurrence diagram for the case study, i.e. the number of satellites needed to cover the AOI for each combination of RC and altitude. To show the capabilities of the other inter-related modules, the reference mission scenario highlighted in Figure 6 was chosen. This reference scenario was selected considering the minimum altitude for which the number of satellites is lower than 8 and the corresponding RC is at the minimum. Table 6 shows the whole output set.

Table 6 : Coverage module outputs

Coverage tool outputs

Repeat cycle	16 days
Altitude	320.69 km
Inclination	96.745°
Number of satellite	8
Satellite phasing	2.591°
Percentage of AOI covered with 1-sat failure	92%
Propellant mass for drag make-up	5.93 kg

These 8 satellites are then propagated in GMAT for the duration of the RC- 16 days. For the sake of brevity, only results for satellites 1 and 3 of the constellation are presented here. The input parameters for the type of antenna are shown in Table 7.

Table 7 : Select input parameters: Satellite 1 and 3 (of case study)

Satellite	Antenna type	Dimensions [m] (refer to Table 1)	Frequency (Hz)
1	Monopole	[1;0.1;2;2]]	2.4 e9
3	Patch Microstrip	[0.075;0.0375;0.006;0.15;0.075]	2.8 e9

For the second module, the first output is a map showing the contours on flat Earth of the E-field levels of each ground station antenna around a user defined box area around the center of the ground station location. In addition, a zoomed view of these ground station antenna radiation patterns around the user-defined area is presented. This can be seen in Figure 7 and the inputs are shown in Table 8. The locations of the four ground stations have been arbitrarily selected.

Table 8: Ground station parameters input set

GS	Antenna type	Dimensions [m] (refer to Table 1)	Frequency (Hz)	Azimuth (°)	Tilt(°)	Height (m)
1	Reflector	[0.2;0.2;0.075]	2.4 e9	30	10	0
2	Helix	[0.022;1e-3;3; 0.035; 0.075]	2.8 e9	0	10	0
3	Reflector	[0.2;0.2;0.075]	3 e9	10	10	0
4	Dipole	[2;0.1]	3 e9	5	10	0

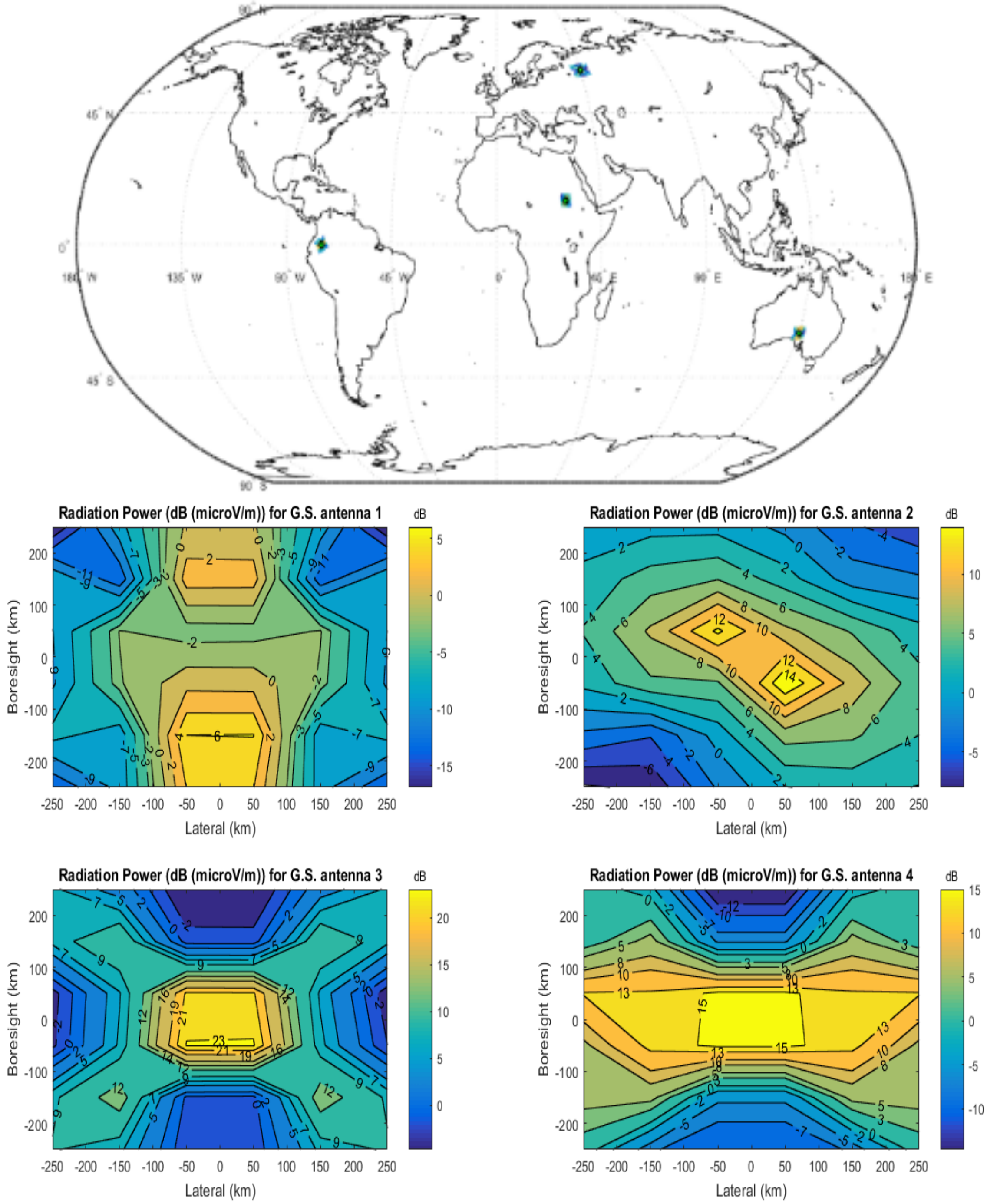

Figure 7: GS antenna E-field contour polygons

The second output is a detailed link report made by combining the results for every satellite-ground station combination. This report provides detailed duration and timestamps of the link margins, and thus proves useful for scheduling communication and data transfer activities.

The third output contains graphical representations of the link report data, allowing for a quick assessment of the effects of the choices of hardware type, dimensions, and other variables on the link performance. As an example, Figure 8 shows the results for the downlink margin of a selected satellite of the constellation.

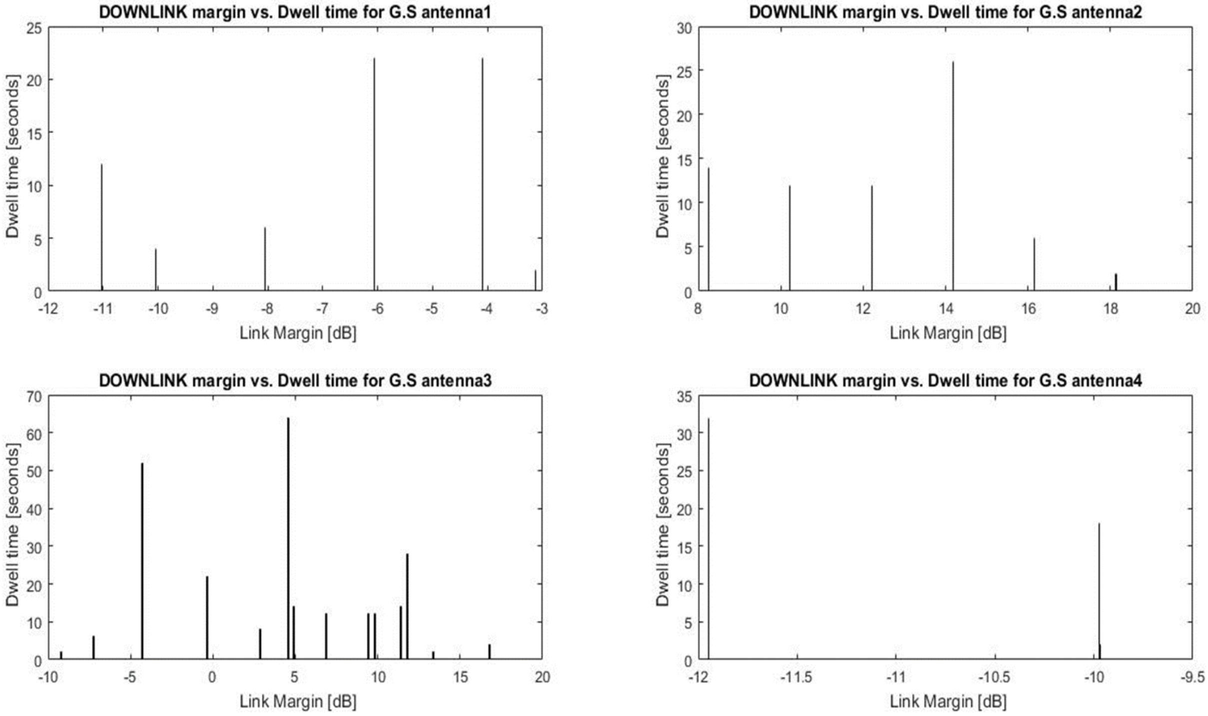

Figure 8: GS-Satellite Link Budget –output bar graph extract

The third module computes the inter-satellite link budget following the same process as the previous module between every possible combination of satellite pairs, if mutual visibility exists. In addition to a visibility status graph, a detailed visibility report is also generated, including the time stamps of visibility start and stop events, as well as the average, maximum and minimum visibility times. Figure 9 shows the results for the uplink and downlink margin for a selected satellite pair.

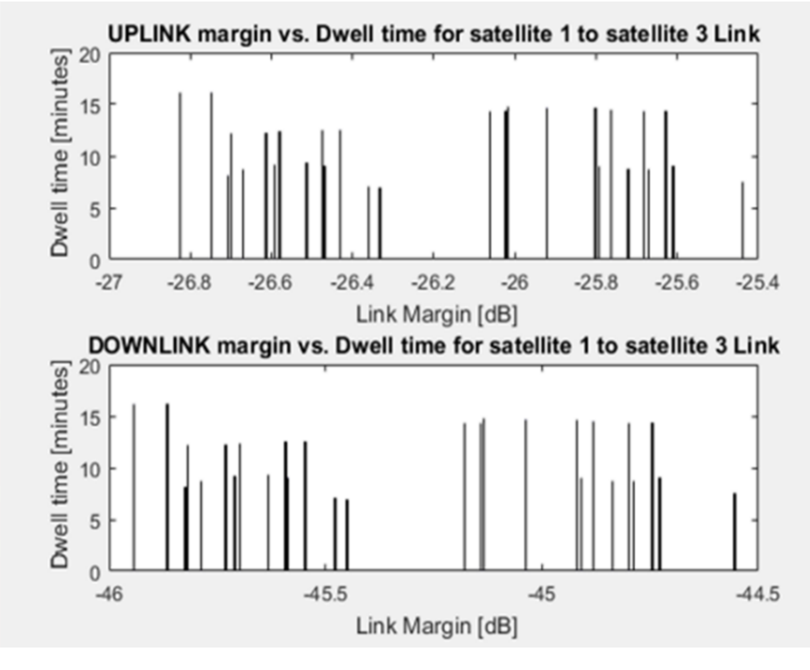

Figure 9: Intersatellite Link Budget –output bar graph extract

4. Conclusion

The SITAEL-University of Pisa integrated software package for analytical constellation design and link margin analysis has proven to be a simple, reliable tool for preliminary design of sun-synchronous, repeating ground track constellations. Relying on the power of the free GMAT programme, the tool allows for quick, accurate evaluation of complex EO constellations, providing an effective support to the designer in performing system trade-offs. The capability to compute drag compensation maneuvers is specially suited to the design of low altitude, extended life constellations.

Future additons to the software tool will include a wider range of propulsion system models and more sophsticated drag compensation strategy allowing for pre-defined altitude decay margins.

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