Orbit Updates and Modelling Doppler

Abstract: We are always updating Visualyse Interplanetary with new features. This White Paper discusses a new tool to allow quick and easy definition of systems using Sun synchronous orbits and a new feature to define which reference equatorial plane to use. There is also a description of the improved Doppler modelling and how to use the vector import option to define the type of orbits proposed to be used by the Lunar Gateway.

Introduction

This White Paper addresses new features in Visualyse Interplanetary, namely:

1. Additional tool to define satellites using Sun synchronous orbits
2. Ability to set the equatorial plane to use for orbits defined via classical orbit elements
3. Improvements to the way Doppler is handled
4. How the vector import feature of Visualyse Interplanetary could be used to model halo orbits as proposed to be used by the Lunar Gateway.

What is Visualyse Professional?

Visualyse Professional is a flexible study tool able to model a very wide range of radiocommunication systems, that can be used to analyse system performance including the impact of interference. Visualyse Professional is able to model transmit and receive stations located at fixed positions, mobile stations, aircraft, ships and also satellite systems including Earth stations, geostationary orbit (GSO satellites, non-GSO satellites and highly eccentric orbit (HEO) satellites.

It can be configured to analyse spectrum sharing scenarios using a wide range of methodologies, including static, input parameter variation, area, dynamic, Monte Caro and combinations such as area Monte Carlo.

Visualyse Professional includes a wide range of advanced features to enable it to analyse both co-frequency and non-co-frequency scenarios, the impact of terrain or clutter, the impact of traffic and complex handover strategies between satellites. These features allow it to model anything from a 5G network to a non-GSO mega-constellations such as SpaceX's Starlink or OneWeb. An example screenshot of Visualyse Professional is shown below:

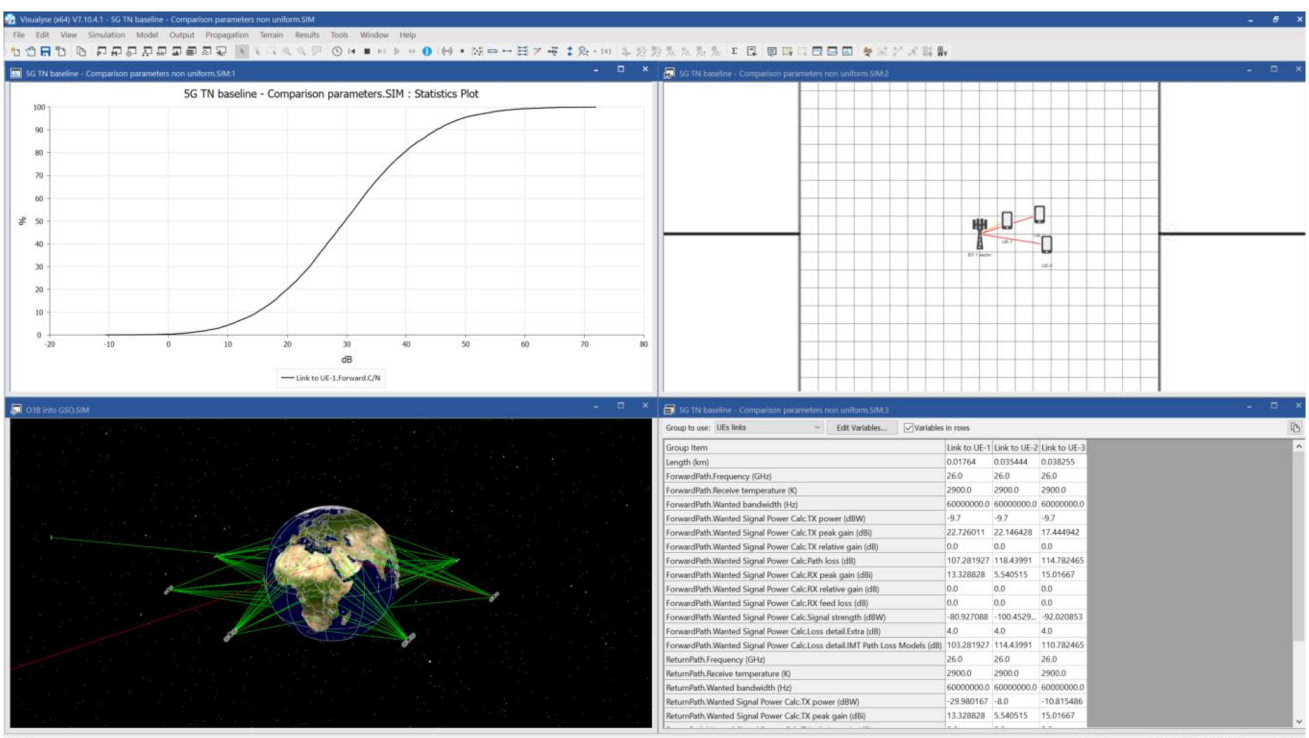


Figure 1: Visualyse Professional Screenshot

Visualyse Interplanetary

The objective of Visualyse Interplanetary is to extend the simulation ability of Visualyse Professional to allow:

1. Modelling of stations around other celestial bodies including the Moon and Mars
2. Enhance the geometric framework with a more detailed description of the Earth's shape and rotation characteristics.

An example screenshot of Visualyse Interplanetary is shown below:

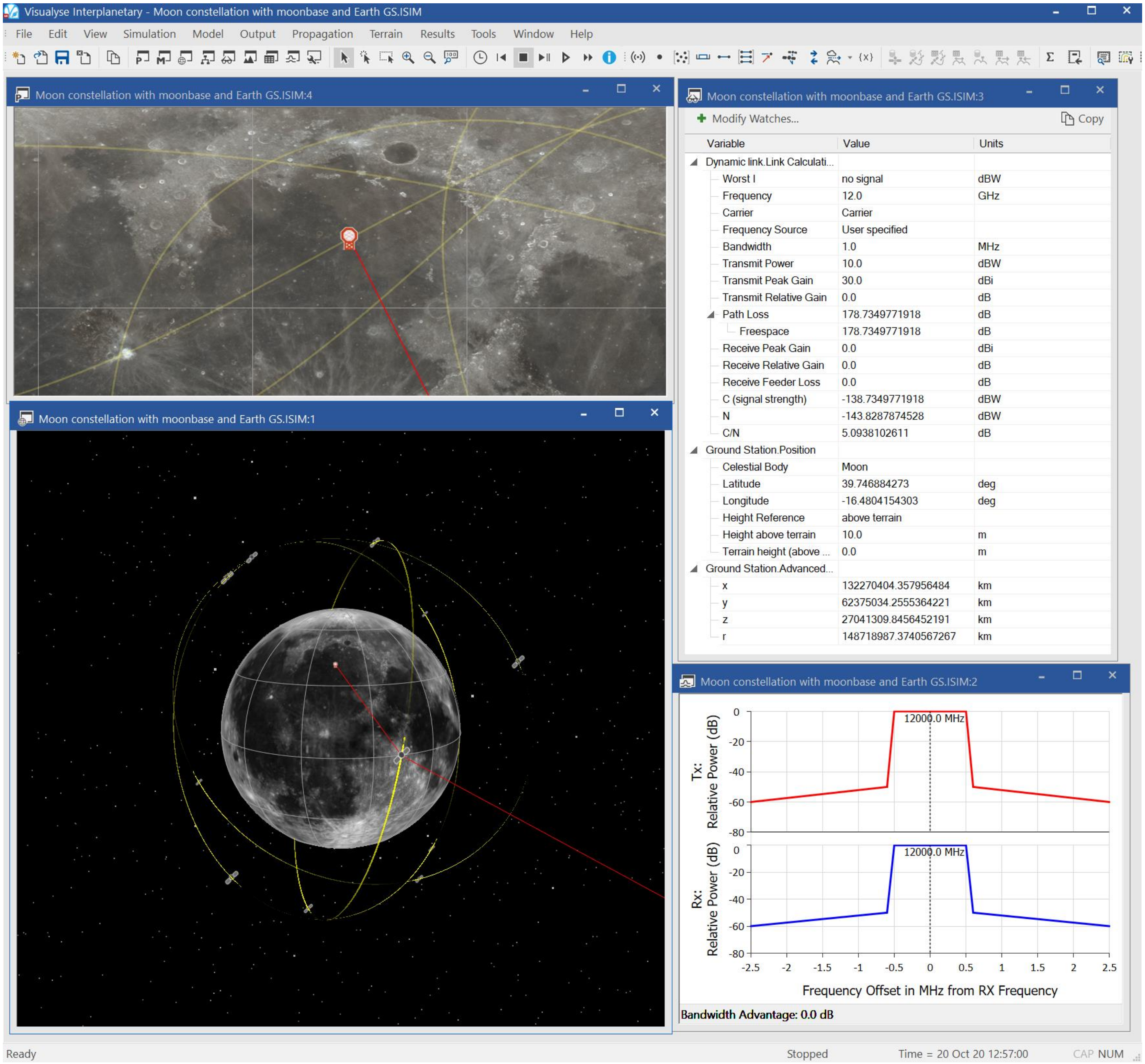


Figure 2: Visualyse Interplanetary Screenshot

Defining Sun Synchronous Orbits

The simplest way to predict the future position of a satellite is using what is called a point mass model. When using this model, the satellite loops within an orbit plane that is fixed in inertial space. Over time, as the Earth orbits the sun, the angle between this fixed plane of the orbit and the line to the sun would then change, as in Figure 3 below (not to scale!):

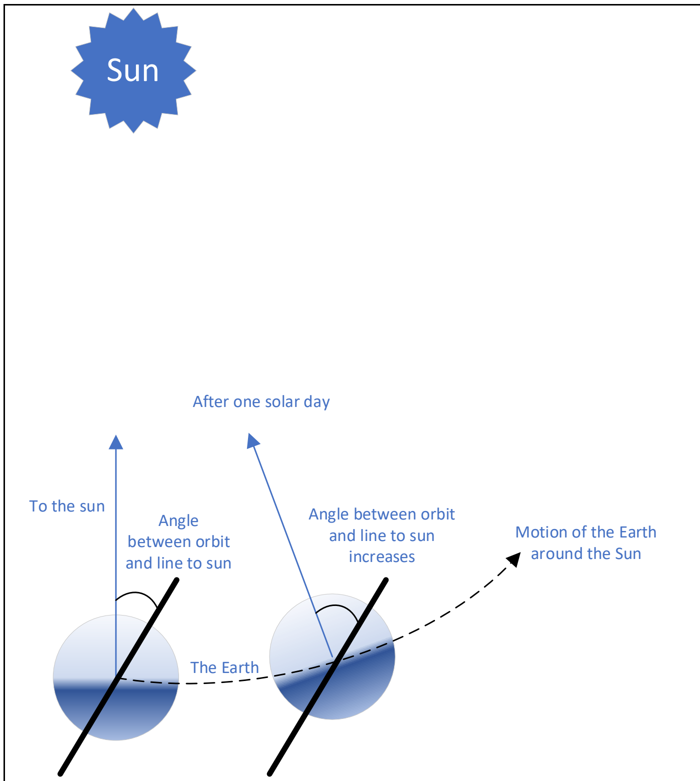


Figure 3: Point Mass Orbit Plane Fixed in Inertial Space

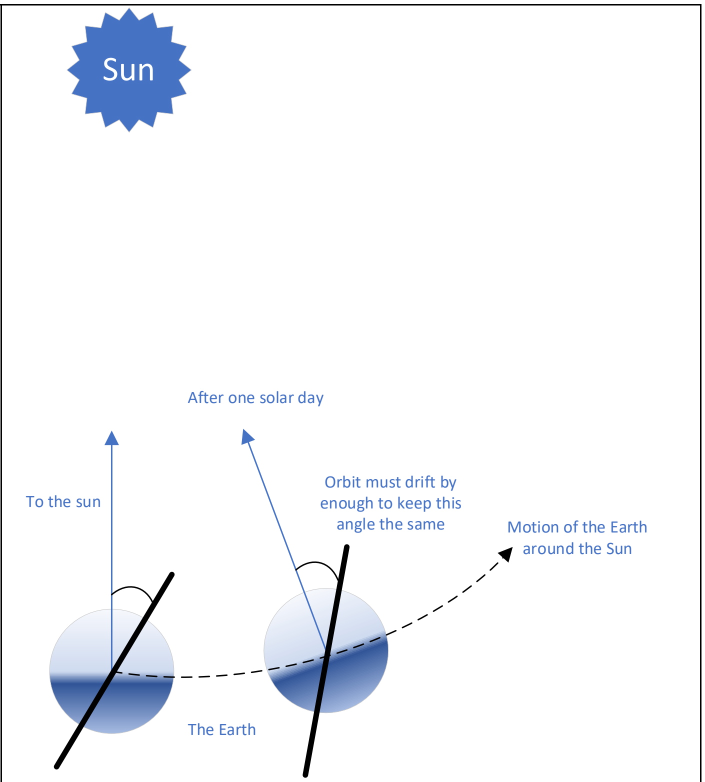


Figure 4: Point Mass and J2 Orbit Plane with Precession

For some systems, such as those that undertake remote sensing, it can be useful if this angle between the vector to the sun and the orbit plane is constant. For example, it could be used so that the same lighting conditions are observed at the same location.

This can be achieved if the orbit were not fixed in inertial space but gradually drifts. Fortunately, this is feasible, as in reality the Earth is a not a uniform density sphere but an oblate spheroid. The impact of this non-spherical Earth is that the orbit will precess slowly, where the rate of angular precession is given by:

$$\Omega_r = -\frac{3}{2}\frac{J_2 R_e^2}{p^2}\bar{n}\cos(i)$$

Here:

- J_2 is a constant related to the oblateness of the Earth
- R_e is the mean radius of the Earth
- p is the semi-latus rectum of the orbit, related to a = semi-major axis and e = eccentricity via $p = a(1-e^2)$. For circular orbits $p = a$.

If the orbit is configured correctly, then the orbit will precess at a rate such that the angle of the orbit's plane to the sun will be constant, as in Figure 4 above. For circular orbit systems, this requires the semi-major axis (a) and inclination angle (i) to be selected appropriately.

An additional factor is whether the satellite would be above the same point on the Earth's surface at the same local time after a fixed set of orbits. These repeating orbits can be configured by fine tuning the (a, i) parameters.

A new tool in Visualyse Interplanetary can be used to configure these types of orbits, undertaking the necessary calculations to ensure the (a, i) have been selected as required.

Email us at info@transfinite.com for further information or to give your views on this White Paper

If the orbit doesn't repeat (i.e. it slowly drifts) then the Sun Synchronous tool calculates the required *i* = inclination angle for a given *a* = semi-major axis.

If the orbit does have a repeating ground track, then the (*a*, *i*) are calculated from:

- The number of days over which the orbit will repeat
- The number of orbits over the given number of days.

In both cases it is also necessary to define the longitude of the ascending node (LAN) and time at which the satellite is crossing equator. Having done that, the tool configures the rest of the orbit parameters as requested.

Note this option is only available when the orbit prediction model is point mass plus J_2 and in Visualyse Interplanetary only for Earth orbits. The figure below shows how the tool can be activated on the satellite dialog:

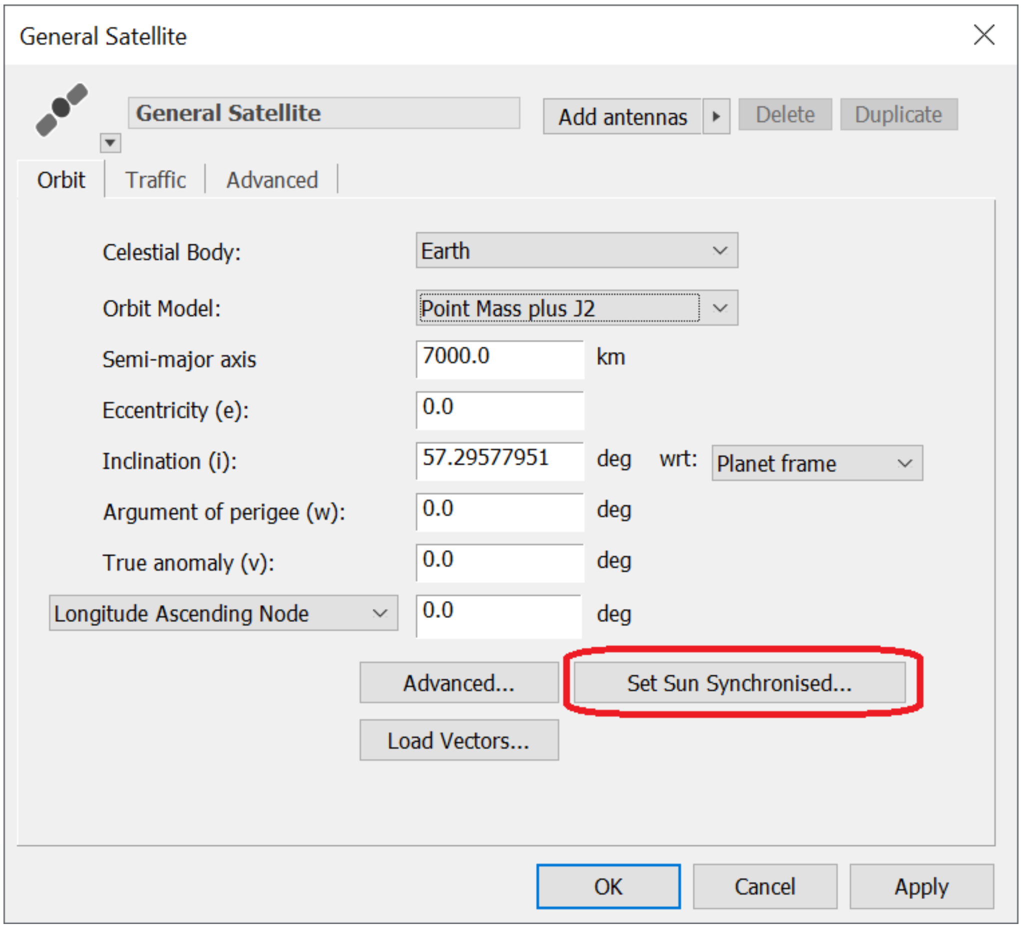


Figure 5: Option to Set Sun Synchronised

The figure below shows the Sun Synchronous tool dialog:

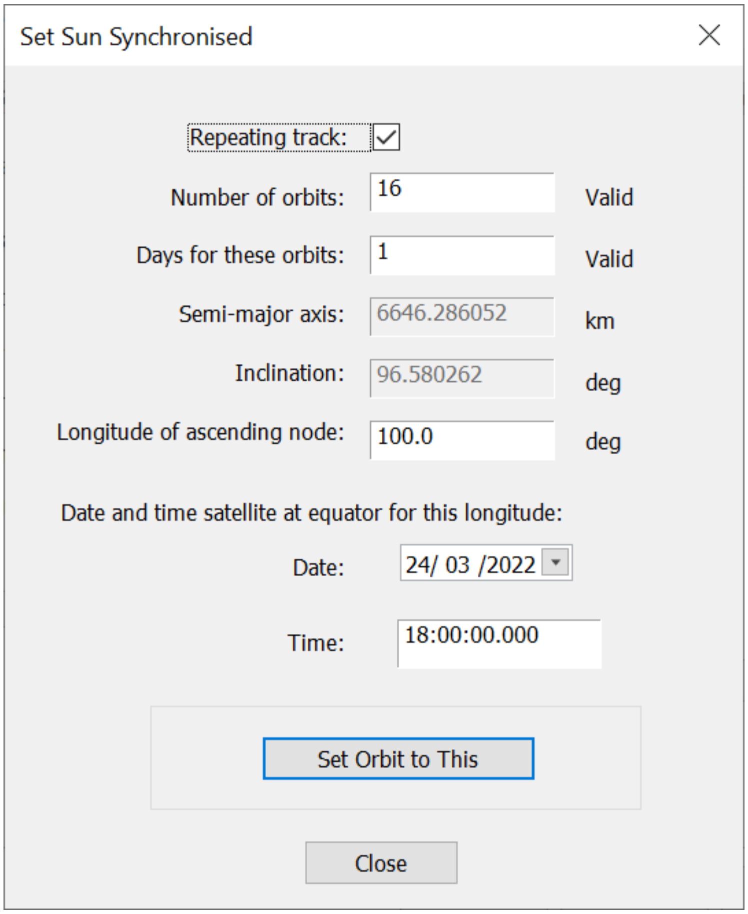


Figure 6: Set Sun Synchronised Dialog

If the parameters above are selected, then the ground track will repeat after 1 day with 16 orbits:

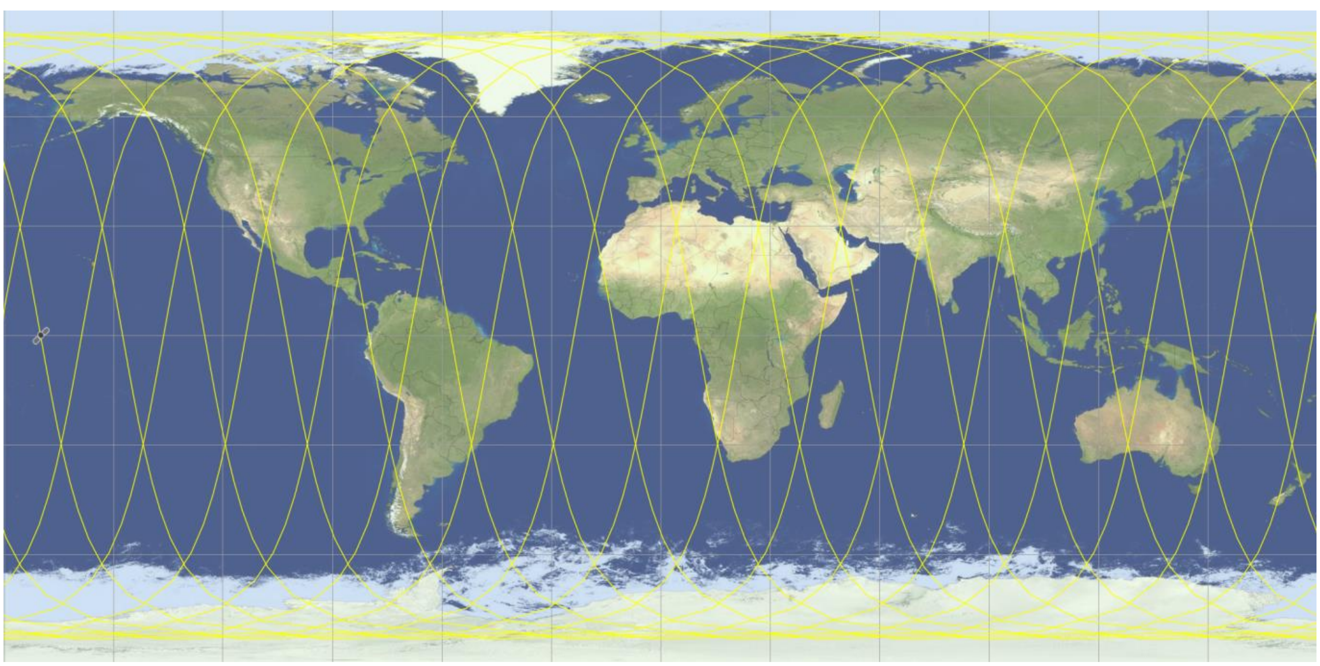


Figure 7: Repeating Ground Sun Synchronised Orbit Track Example

The orbit in space will drift very slightly, just visible in the 3D view:

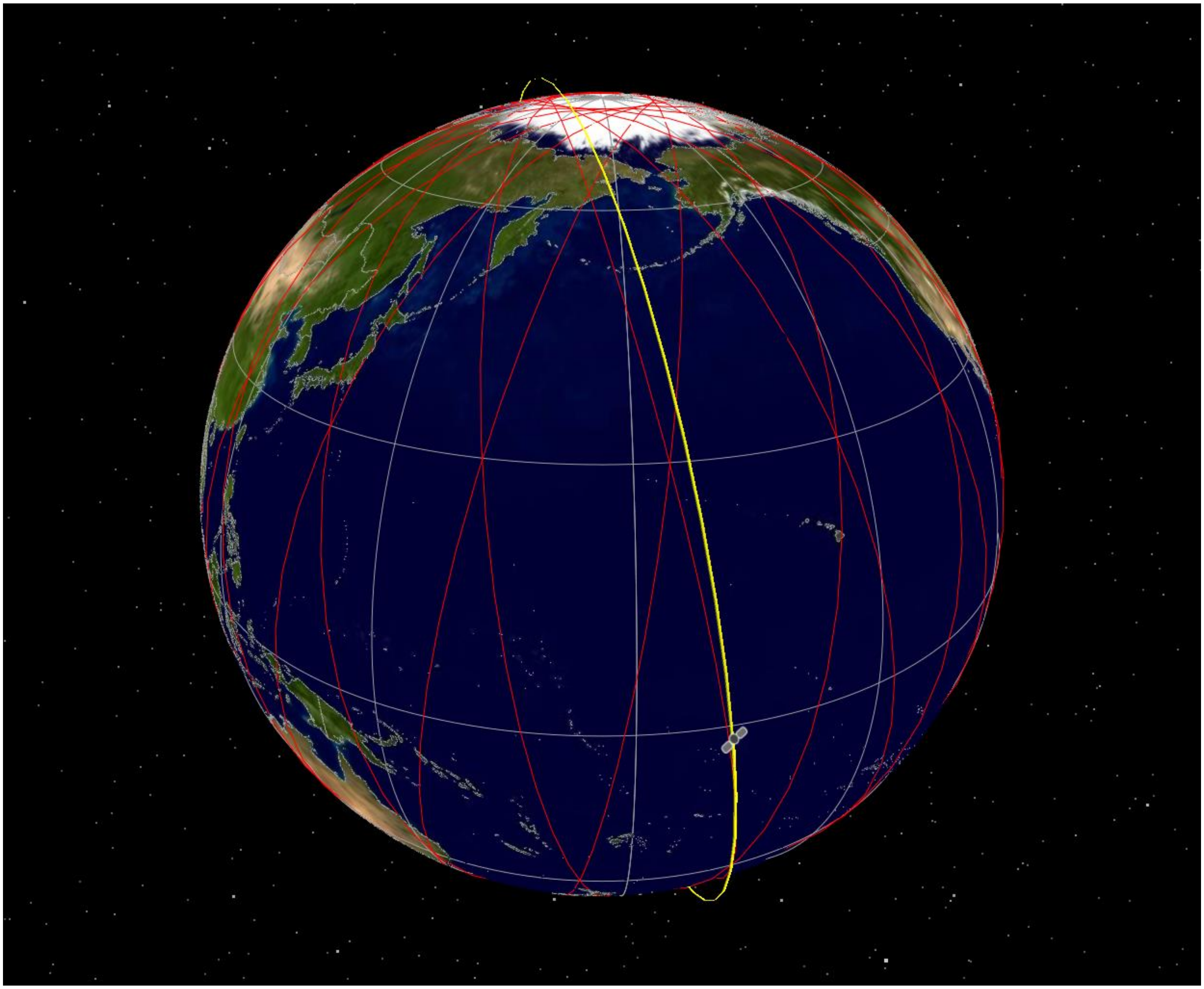


Figure 8: Repeating Ground Sun Synchronised Orbit Track Example 3D View

Specifying the Orbit's Equatorial Plane

One of the classical orbital elements is the inclination angle, which defines the angle between the equatorial plane and the plane of the orbit. There are a number of options, but the most common two are:

1) Use the equator defined in the J2000 reference system, which is fixed in inertial space
2) Use the current equator of the planet i.e. Earth

The Earth axis moves slightly, processes called nutation and precession, so that the planet's equatorial plane varies in inertial space.

If the orbit inclination angle is defined relative to planet's reference frame, then when a satellite has a longitude of ascending node (LAN) = 0, argument of perigee (ω) = 0 and a true anomaly (ν) = 0, it will have a (latitude, longitude) = (0°N, 0°E).

However, if the orbit inclination angle is defined relative to the J2000 reference plane, then when a satellite has a LAN = 0, ω=0 and a ν = 0, it will be slightly offset from the equator and not be exactly at a longitude of 0°E.

In order to make the sun synchronous orbit cross the equator at the required time and longitude, the tool sets the orbit plane to be that of the planet's, rather than the J2000 reference frame.

This option can be selected for any orbit defined using classical orbit elements using the field shown in the figure below:

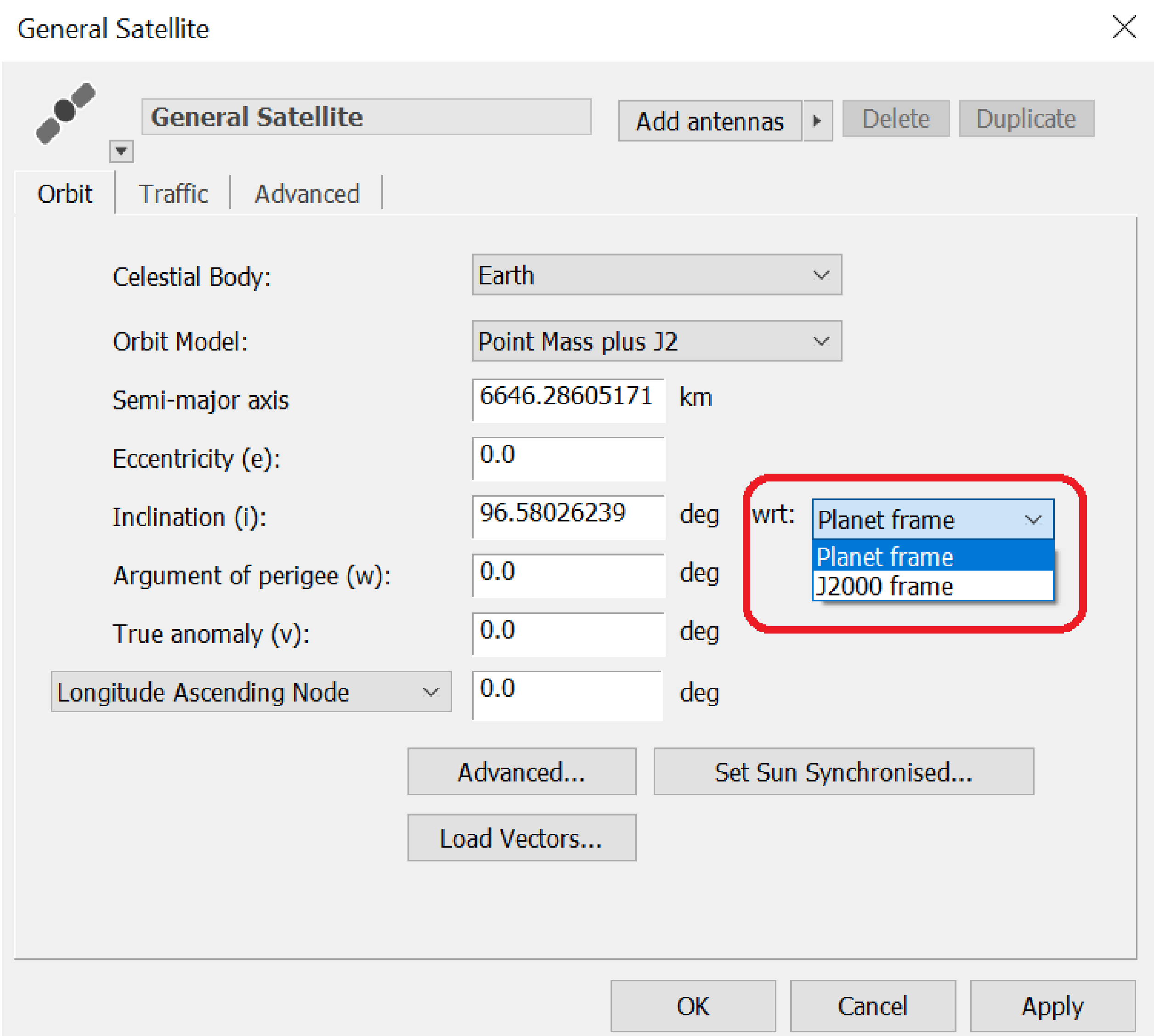


Figure 9: Specifying an Orbit's Equatorial Plane

Modelling Doppler

What is Doppler?

The Doppler effect[1] is how the observed frequency of a signal changes depending upon the relative velocity of the transmitter towards or away from the receiver. In particular:

- If the transmitter is moving towards the receiver, the detected frequency is higher than if they were stationary with respect to each other.
- If the transmitter is moving away from the receiver, the detected frequency is lower than if they were stationary with respect to each other.

This change in frequency Δf is proportional to the ratio of the difference in velocity to the speed of the signal. In the case of radio waves, this is the speed of light, *c*, where approximately *c* = 3e5 km/s. Hence the change in frequency f_0 is:

$$\Delta f = \frac{\Delta v}{c} f_0$$

When modelling most terrestrial systems, the relative velocities of the transmit and receive stations are relatively small, and hence this effect can be ignored. However, for satellite systems, this can be a significant effect.

Consider the scenario below, where a satellite at a height of 400 km is flying directly overhead an ES transmitting at a frequency *f* = 2,100 MHz.

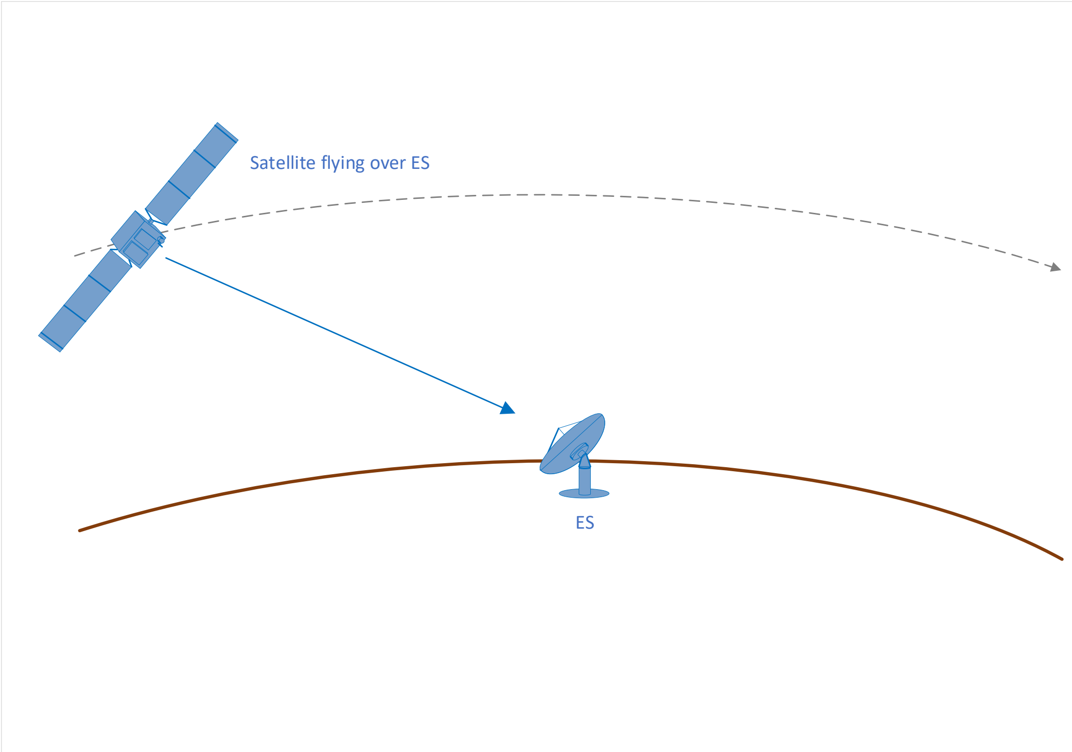


Figure 10: Doppler Example with Satellite Flying Over Earth Station

A satellite at this altitude will have an orbital velocity of around 7.6 km/s. Assuming that is entirely in the direction of the ES, then the change in frequency would be:

$$\Delta f = \frac{7.6}{3e5} 2100 \sim 0.053\ MHz = 53\ kHz$$

[1] https://en.wikipedia.org/wiki/Doppler_effect

The difference in relative velocity would decrease until the satellite is overhead, at which the satellite is neither moving towards or away from the ES, so the Doppler shift would be zero. Then as the satellite flew away from the ES the Doppler shift would become negative, as in the plot below:

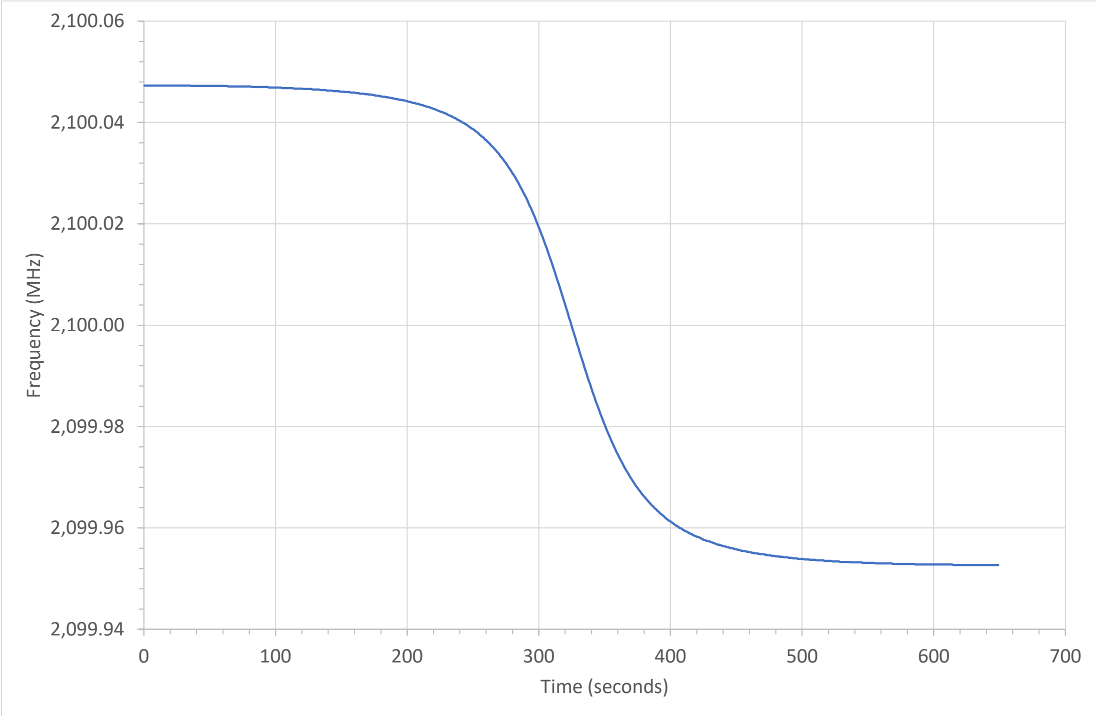


Figure 11: Change in Frequency for Satellite Flying Over Earth Station

Including Doppler in Visualyse Interplanetary

Recent features have been added to Visualyse Interplanetary to model this type of behaviour.

By default, the calculations are all undertaken using the frequencies as entered directly in the links. As noted above, in many scenarios, this is a reasonable assumption, and many studies of terrestrial and satellite systems have been undertaken without considering the impact of Doppler.

If, however, it would be useful to consider the impact of Doppler, it can be enabled using the field on the Simulation Settings dialog:

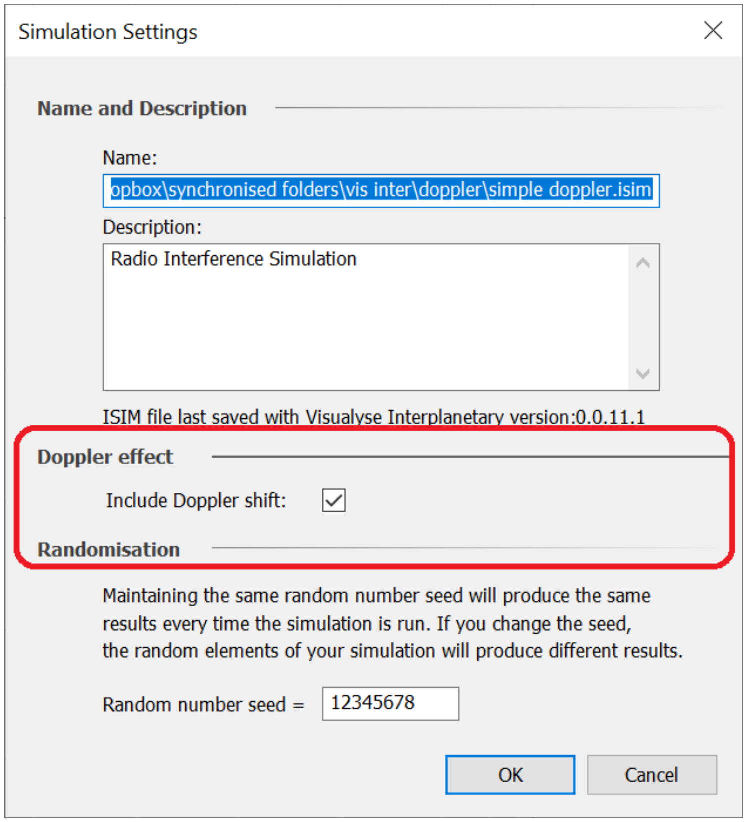
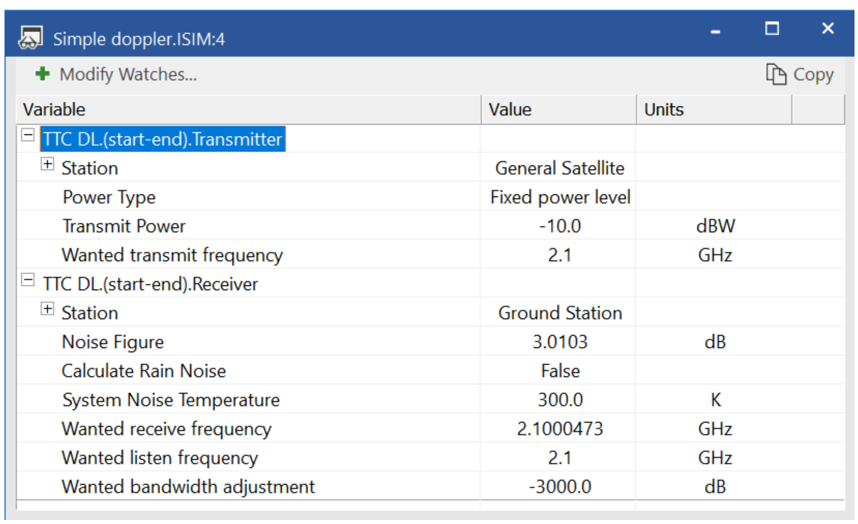


Figure 12: Enabling Doppler in Visualyse Interplanetary

There are additional fields visible in the watch window that show how the various frequencies involved available in the Link Transmitter and Receiver objects:


Simple doppler.ISIM:4
Modify Watches...
Copy

Variable	Value	Units
TTC DL.(start-end).Transmitter		
Station	General Satellite	
Power Type	Fixed power level	
Transmit Power	-10.0	dBW
Wanted transmit frequency	2.1	GHz
TTC DL.(start-end).Receiver		
Station	Ground Station	
Noise Figure	3.0103	dB
Calculate Rain Noise	False	
System Noise Temperature	300.0	K
Wanted receive frequency	2.1000473	GHz
Wanted listen frequency	2.1	GHz
Wanted bandwidth adjustment	-3000.0	dB

Figure 13: Showing the Transmit, Receive and Listen Frequencies in a Watch Window

The frequency view can also show how the frequency varies, as can be seen in the three snapshots below using the Frequency View, assuming the satellite is transmitting a narrowband 10 kHz carrier:

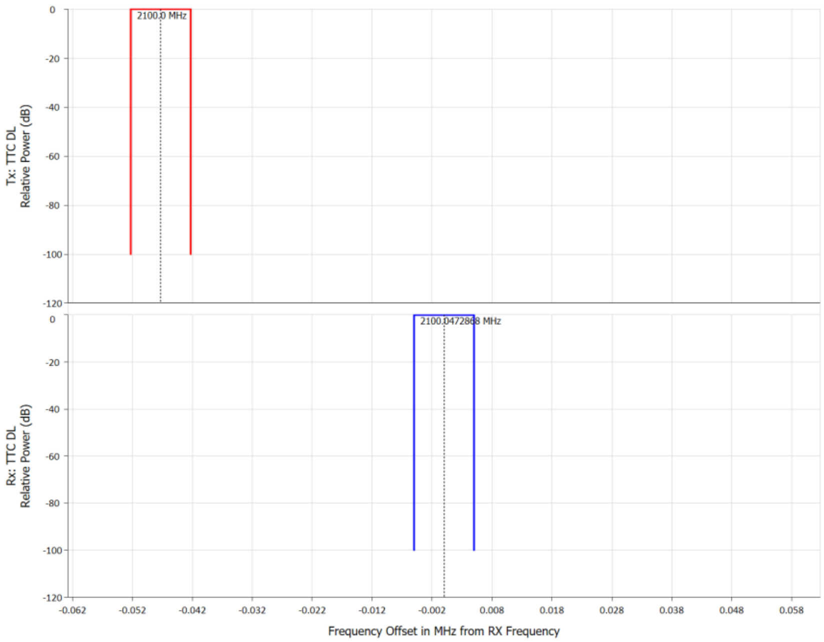


Figure 14: Frequency Change with Satellite Moving Towards the ES

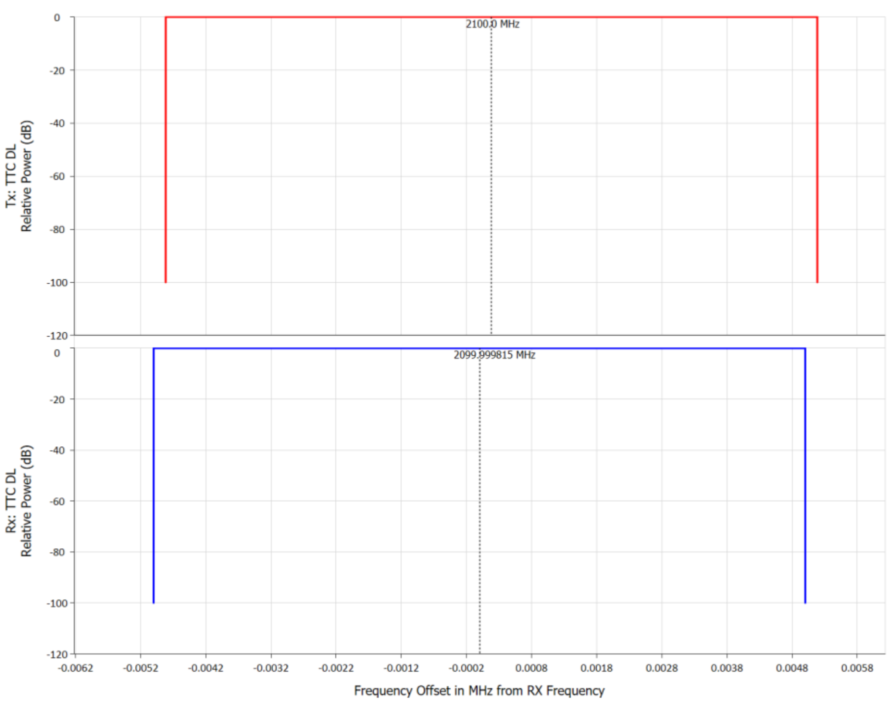


Figure 15: No Frequency Change when Satellite Over the ES

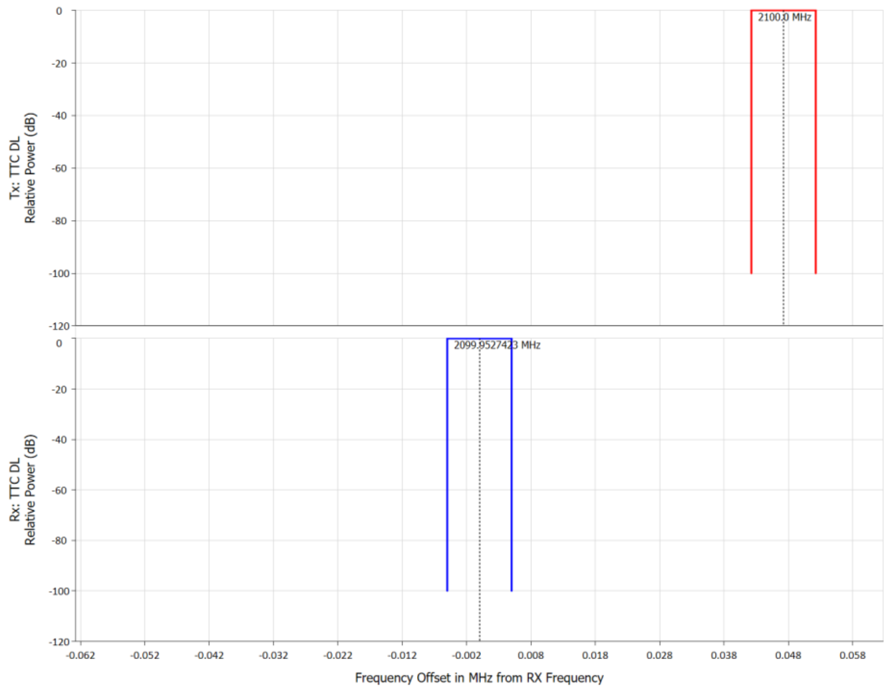


Figure 16: Frequency Change with Satellite Moving Away From the ES

As can be seen with the figures above, the Doppler shift can result in a change in the frequencies that is greater than the bandwidth of the carrier, and hence the receiver would not detect the wanted signal.

Visualyse Interplanetary can model this by including a bandwidth adjustment factor into the calculation of the wanted signal:

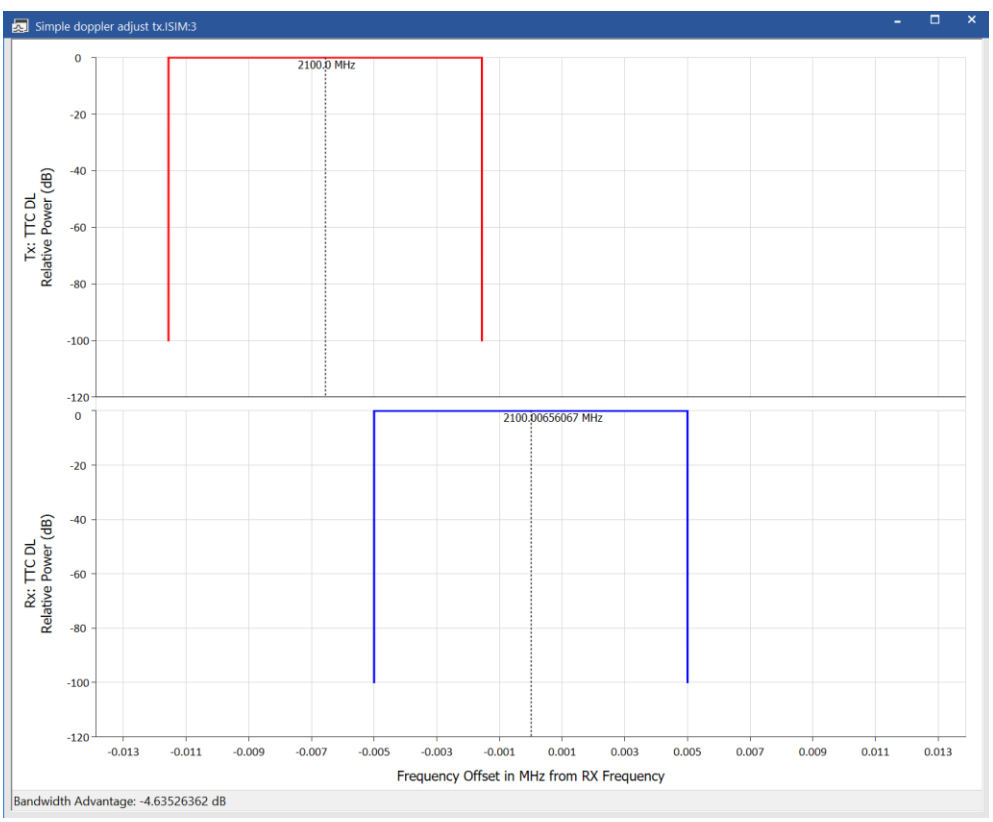


Figure 17: Bandwidth Overlap of Doppler Shifted Wanted Signal

Adjusting Wanted System's Transmit and Receive Frequencies

With such narrowband carriers, this could result in significant reductions in link availability and signal strength. Hence it would be preferable if either the frequency of the transmitter or the receiver were to be adjusted to take account of this Doppler shift.

In Visualyse Interplanetary, this can be modelled by using one of the following two options:

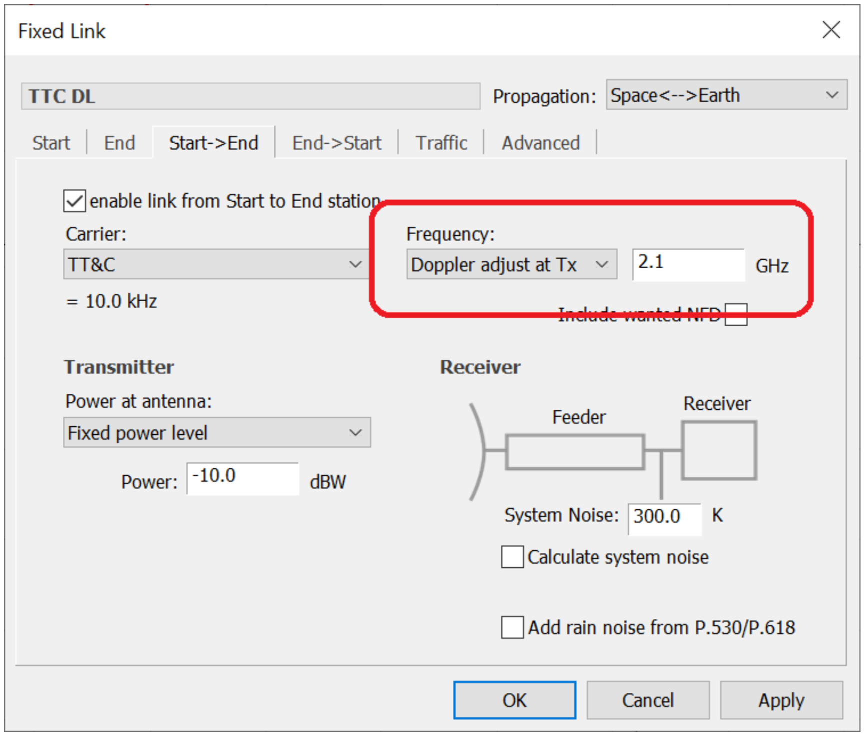


Figure 18: Modifying Transmit Frequency of Wanted Link to Adjust for Doppler

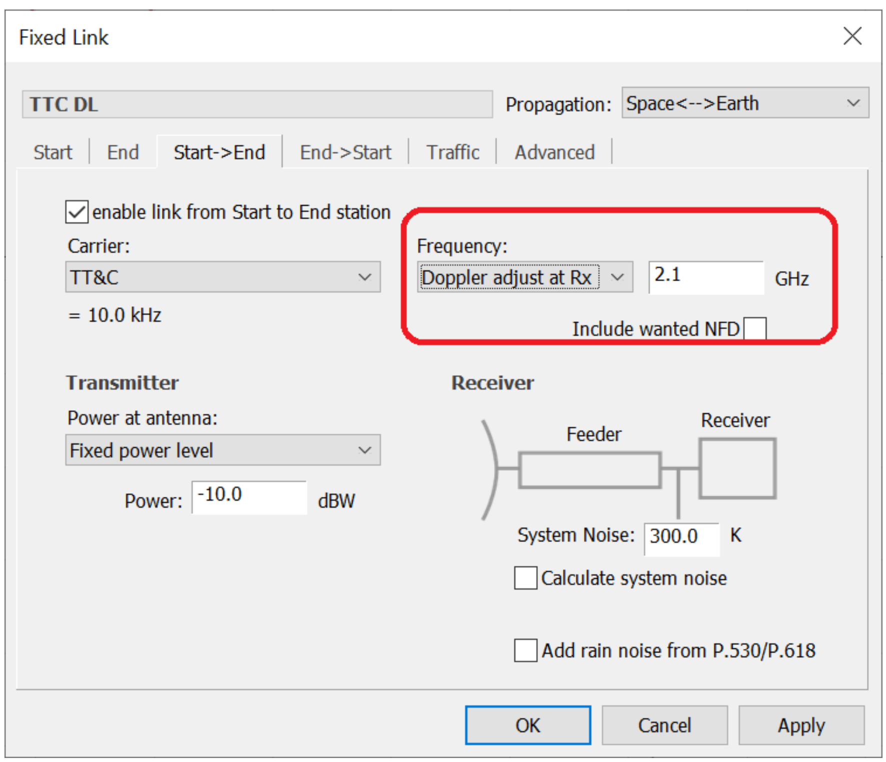


Figure 19: Modifying Receive Frequency of Wanted Link to Adjust for Doppler

If one of these is enabled, such as, for example, adjust the frequency at the transmitter, then the receiver always sees the wanted signal as being co-frequency:

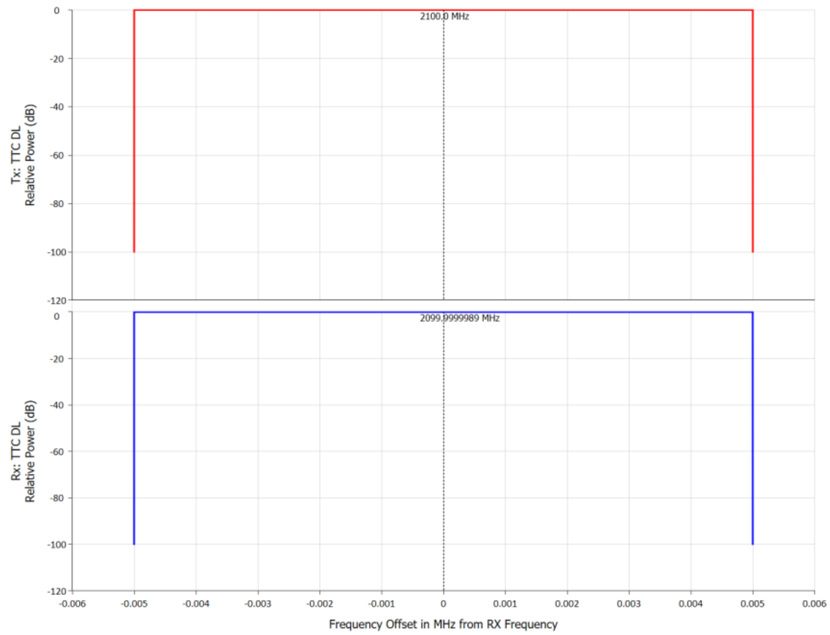


Figure 20: Wanted Signal Co-frequency After Adjusting for Doppler

Calculated Wanted Signal using Spectrum and Filter Mask Integration

The wanted bandwidth adjustment is by default calculated using rectangular blocks of spectrum. However, it can be calculated using shaped transmit spectrum masks and receive spectrum masks (e.g. due to receive filters). This can be enabled using the option highlighted below:

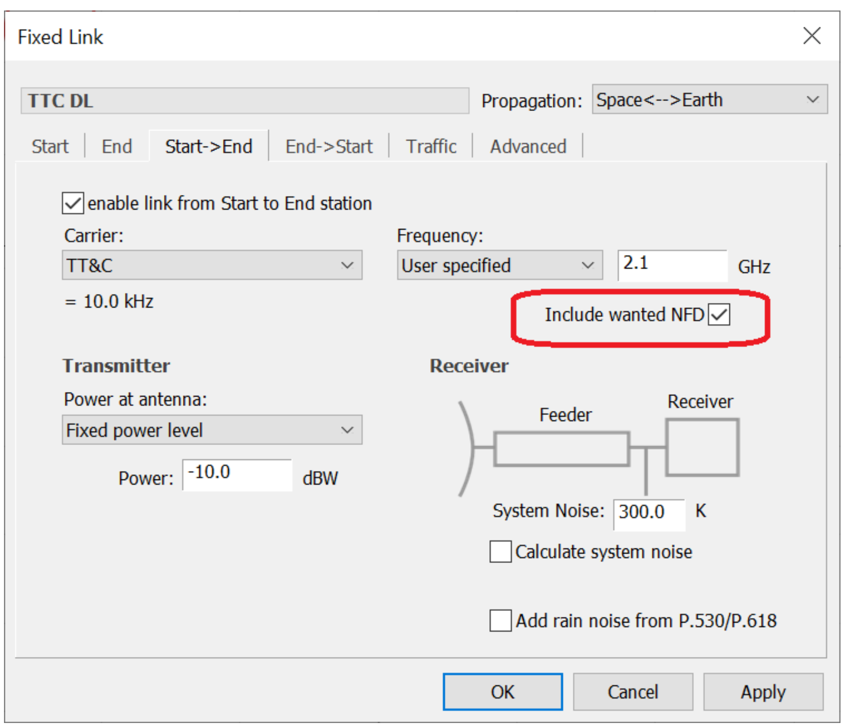


Figure 21: Calculating Wanted Signal by Integrating Wanted Carrier Transmit and Receive Spectrum Masks

The resulting net filter discrimination (NFD) is shown on the frequency view by selecting the transmit and receive masks to both come from the same link, as shown in the figure below:

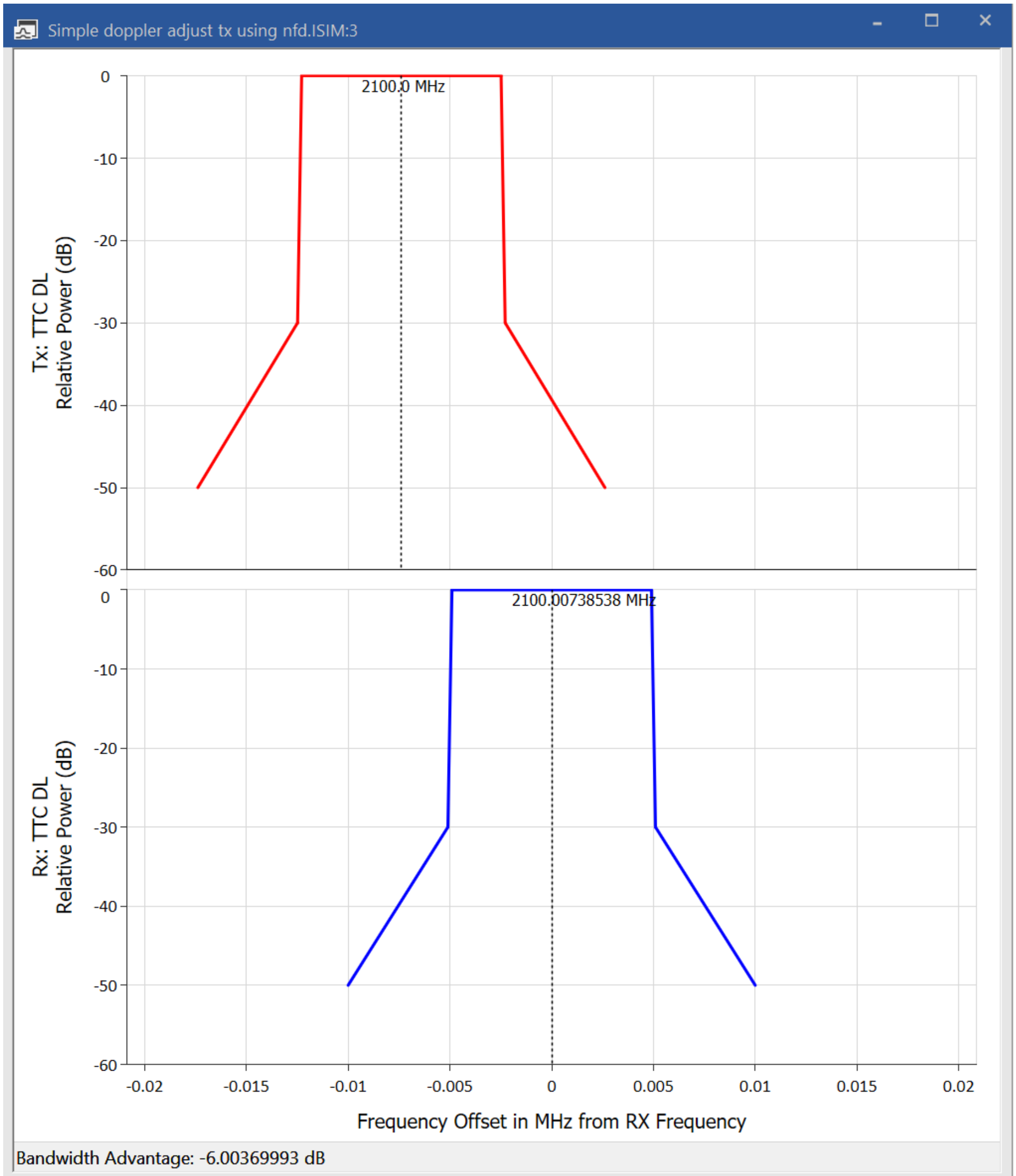


Figure 22: Wanted Signal Bandwidth Adjustment Calculated using NFD

Impact of Doppler on Interference Calculations

As well as being used for the wanted link budget calculation, Doppler can also be included in the interfering link budget calculations.

Consider if the satellite in the example above was suffering interference from another satellite in the same orbit but slightly behind, as in the figure below:

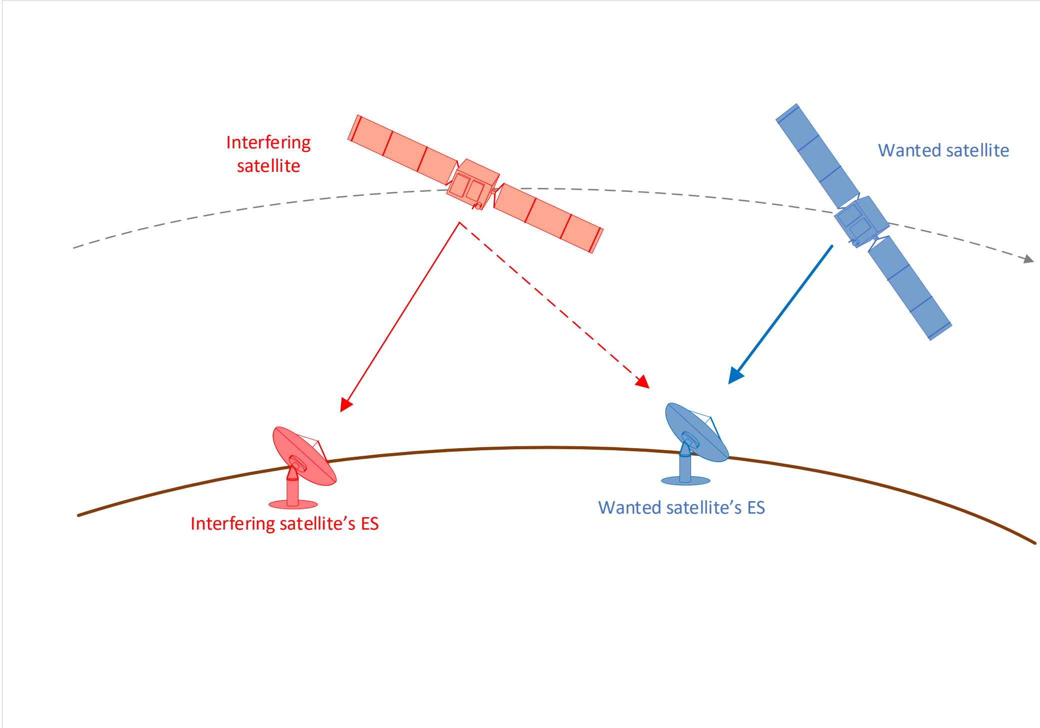


Figure 23: Doppler Example with Wanted and Interfering Satellites Flying Over Earth Stations

Each satellite, offset by 10 degrees of longitude, is communicating with its own ES which are also separated by 10 degrees of longitude.

In both cases the satellites adjust their transmit frequencies so that the receive frequency is 2.1 GHz. The satellite is modelled as using a low gain isotropic antenna while the ES antenna is assumed to be directional with gain pattern from Recommendation ITU-R S.580.

The initial state is shown in the following Visualyse Interplanetary map view:

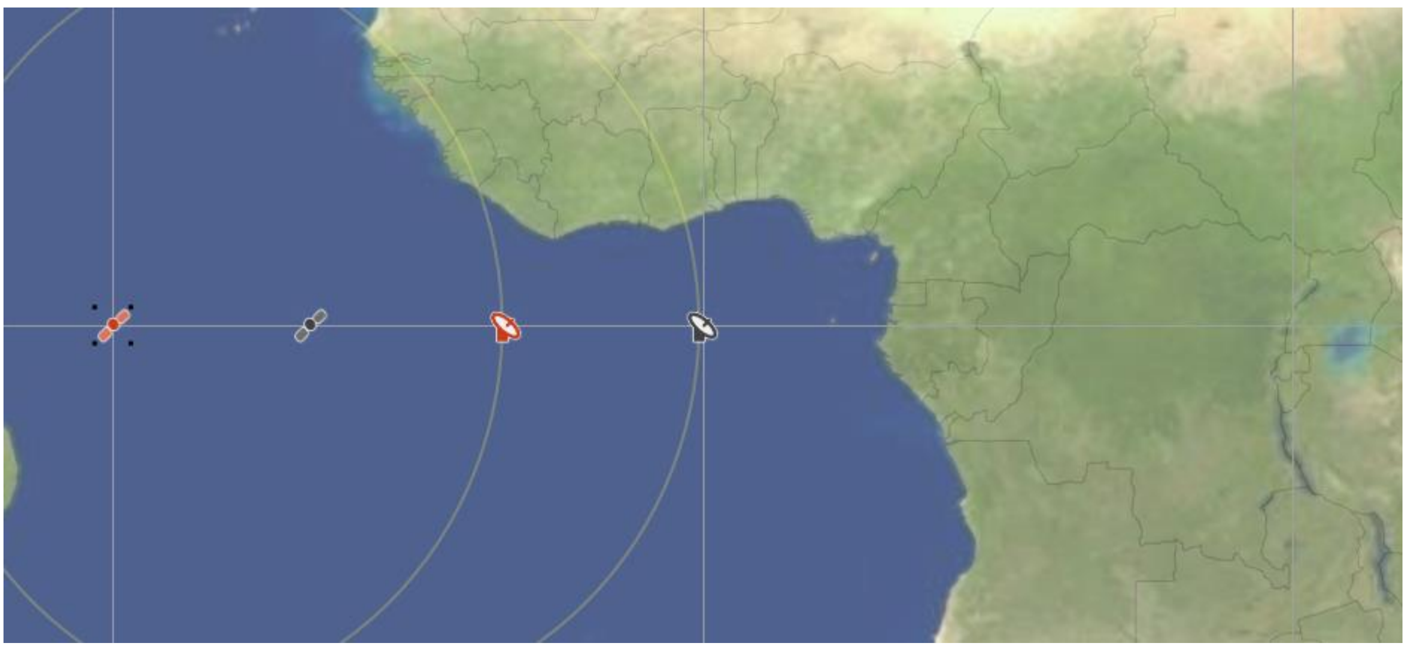


Figure 24: Screenshot of Doppler Example with Wanted and Interfering Satellites Flying Over Earth Stations

The frequency is adjusted as follows:

- As the satellite heads towards the ES, the frequency it transmits on is reduced to ensure the receive frequency is 2.1 GHz
- As the satellite heads away from ES, the frequency it transmits on is increased to ensure the receive frequency is 2.1 GHz

This can be seen in the following plots that show for the {wanted, interfering} systems:

- The satellite transmit frequency
- The frequency of the link at the ES
- The frequency of the receiver at the ES

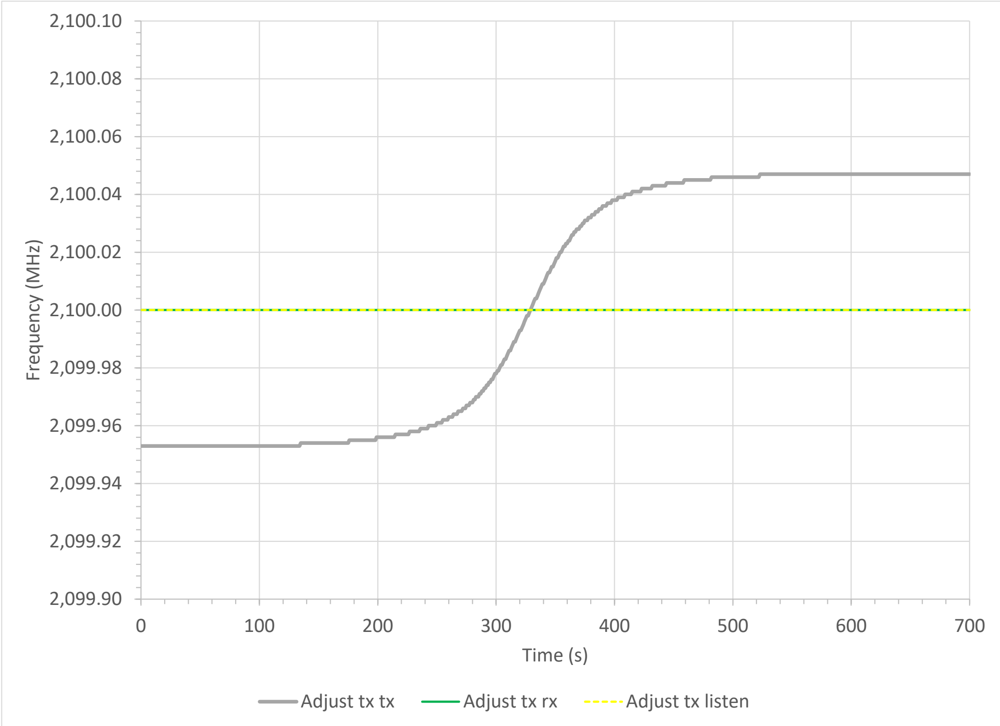


Figure 25: Wanted Link's Frequencies against Time

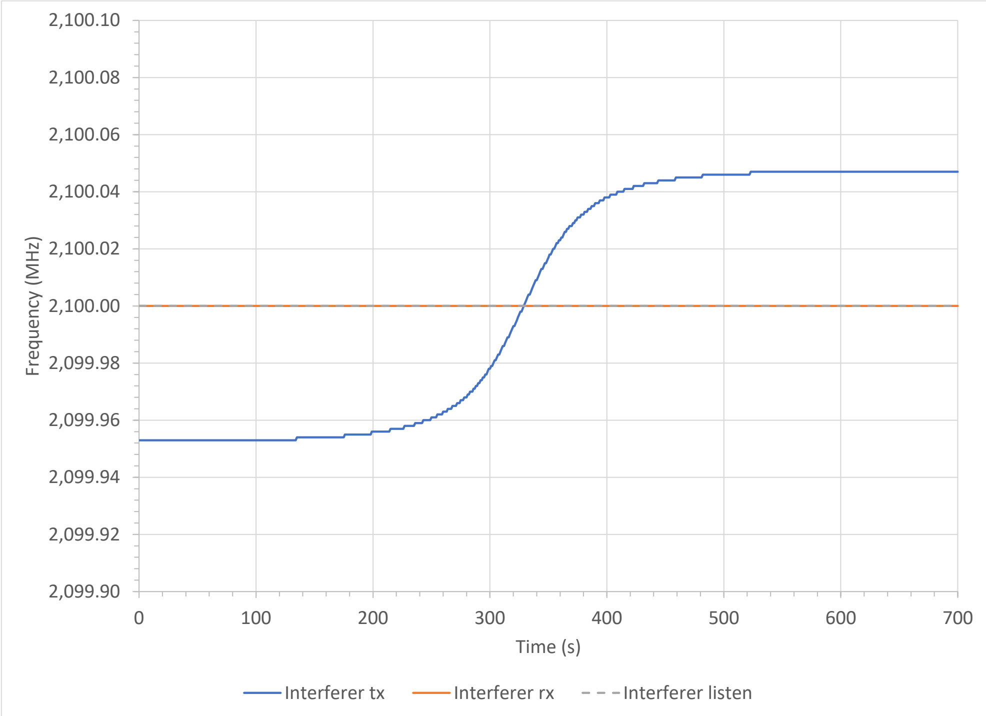


Figure 26: Interfering Link's Frequencies against Time

It can be seen that the plots are identical.

However, the frequency received at the victim ES will vary significantly due to Doppler. Consider the moment that the interfering satellite is between the victim and interfering system's ES, as in the screen shot below:

Figure 27: Screenshot of Doppler Example with Interfering Satellite between Two ES

At this point both satellites are moving away from their respective ES, so to keep a constant frequency at the receivers, they must have adjusted their transmit frequency to be higher.

But, while the interfering satellite is moving away from its ES, it is moving *towards* the victim ES. Hence its frequency, already selected to be higher, appears to be even greater at the victim ES receiver. This can be seen in the plot below of the frequencies against time:

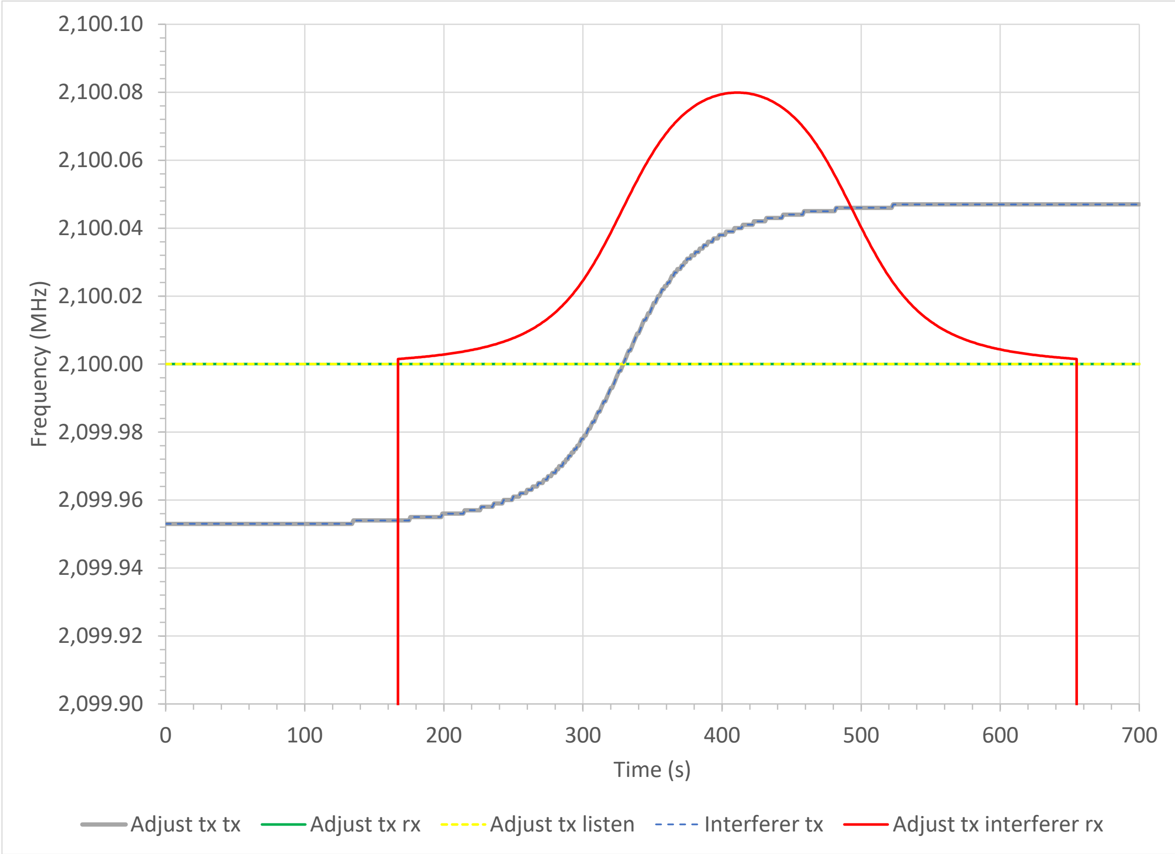


Figure 28: Frequency at Victim ES of Interfering Satellite Taking into Account Doppler

When undertaking interference analysis, considering factors such as Doppler and how satellite systems adjust for changes in frequency can compound together to create significant differences.

The figure below shows the I/N at the receiver when either including or excluding the Doppler effect.

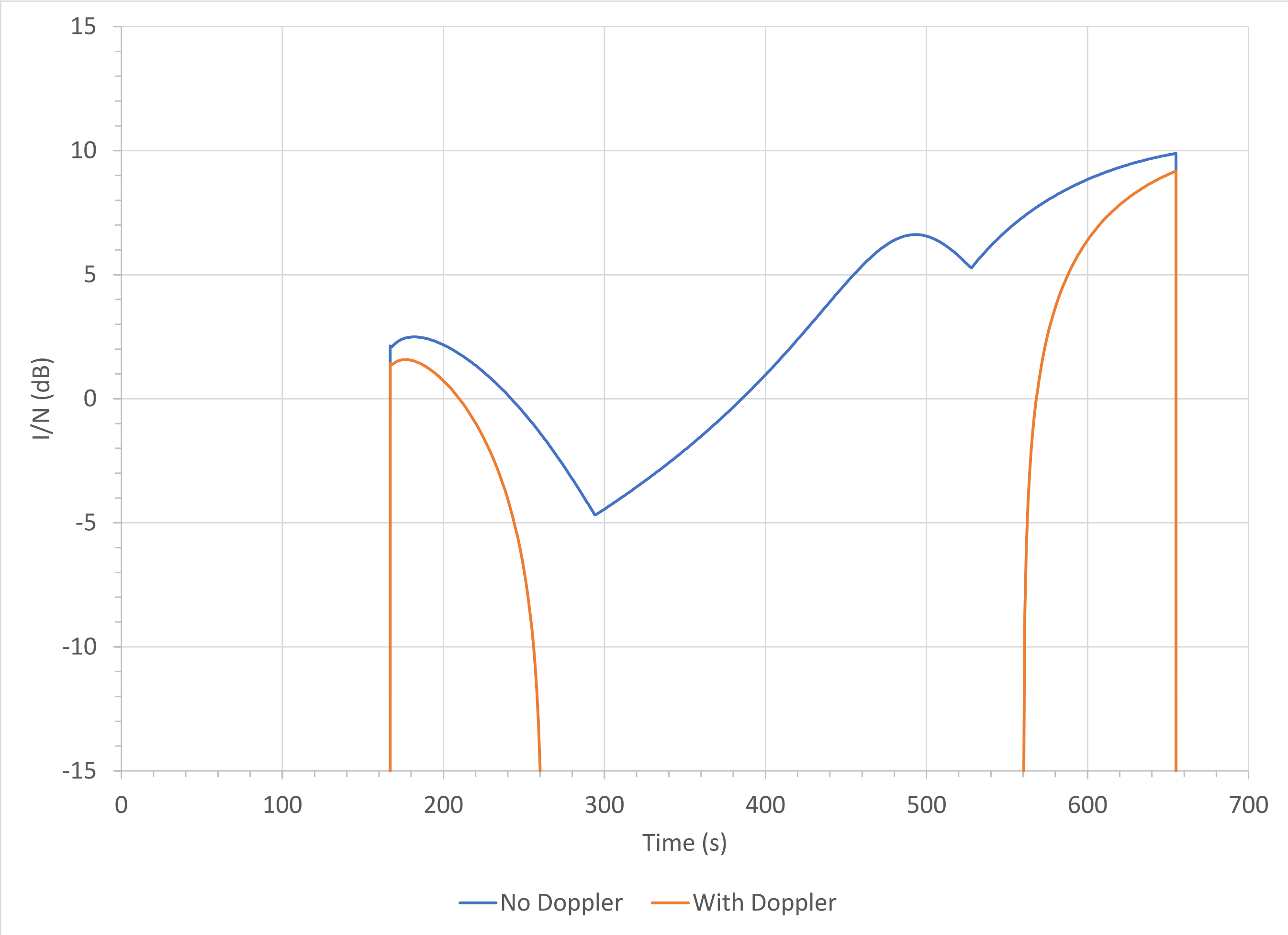


Figure 29: I/N at Victim ES Modelled without Doppler and with effect of Doppler

It can be seen that the results change significantly due to the impact of Doppler, by changing the degree of frequency overlap, at times making the interferer non-co-frequency.

Modelling Lunar Gateway Orbits

One of the key objectives of developing Visualyse Interplanetary was the ability to model systems operating on or around other celestial bodies. An additional field was added to each of the station dynamic's tabs to select the relevant celestial body, as in this example below:

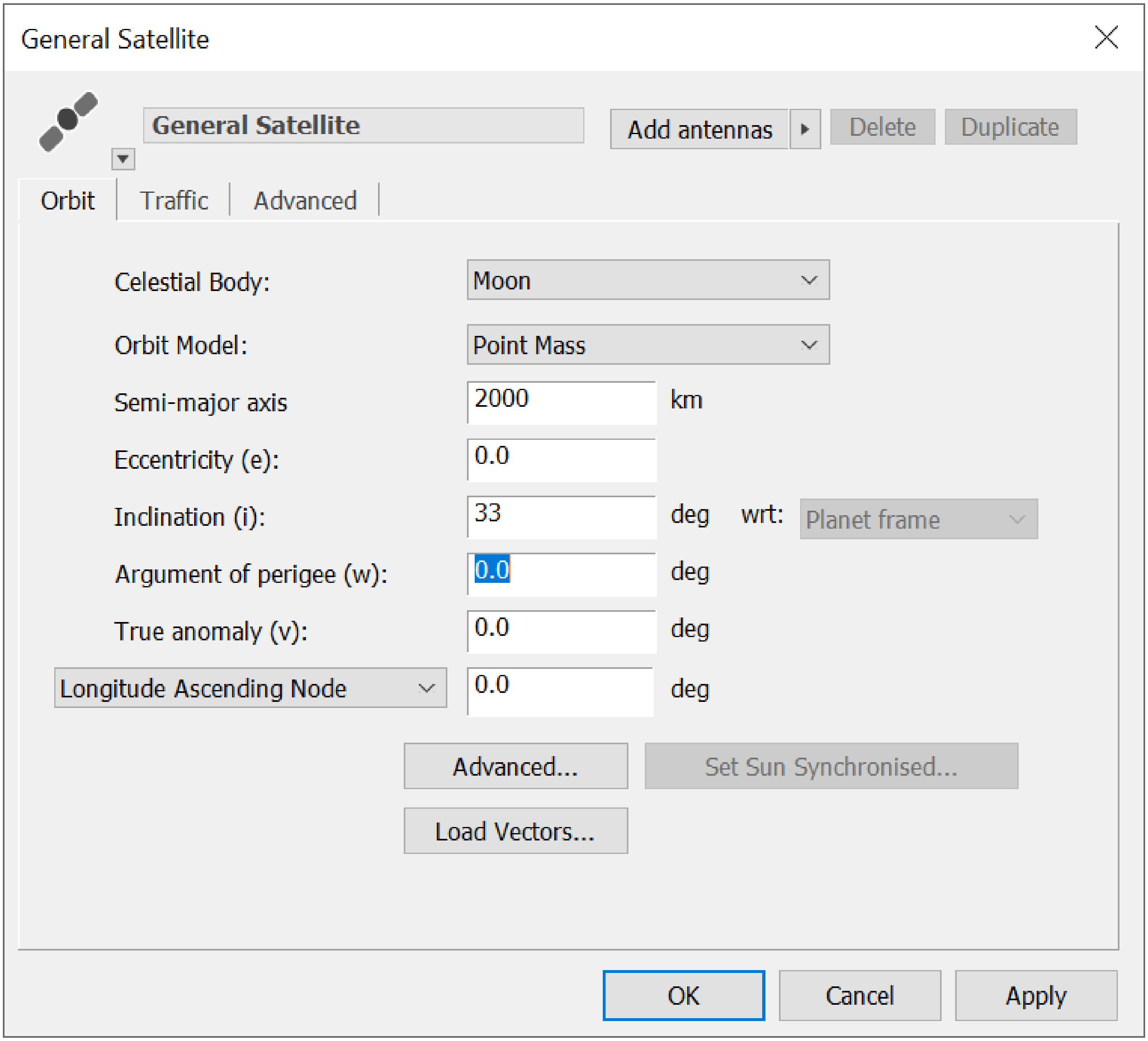


Figure 30: Selecting Celestial Body and Orbit Parameters in Visualyse Interplanetary

This shows an example of a satellite in orbit around the Moon. For the Earth – Moon system, there can be significant perturbations from Keplerian orbits, and it can be necessary to consider motion within a three-body gravitational field.

Examples of this including modelling the Lagrange points, orbits around the Lagrange points and variations such as halo orbits. The Lagrange points are equilibrium points within the gravitational forces of two primary masses, and there are five, as shown in the figure below for the Earth-Moon system:

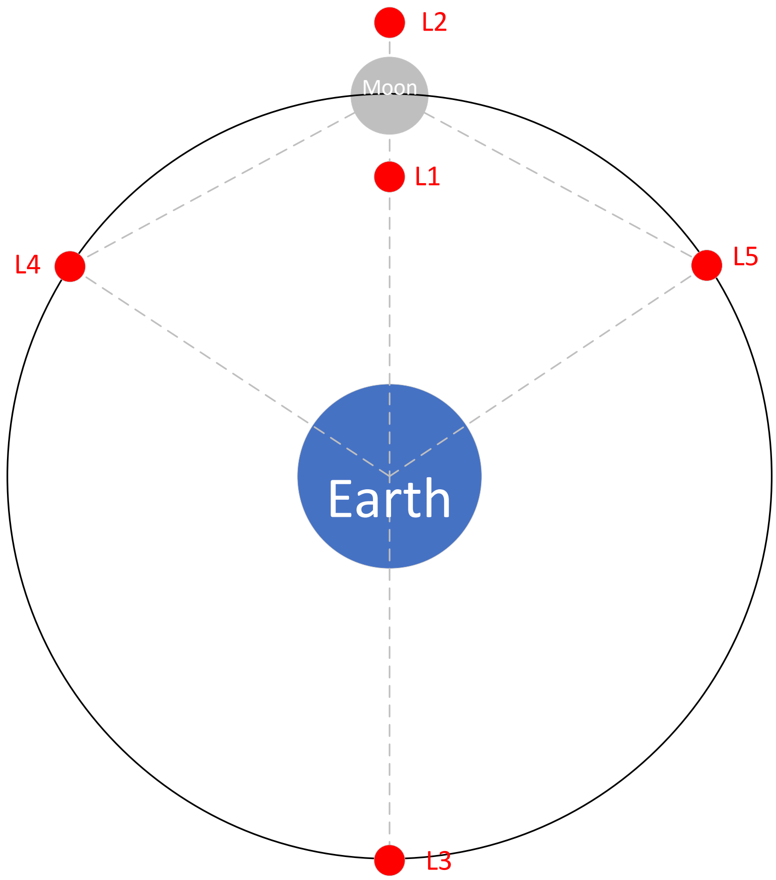


Figure 31: Location of Earth-Moon Lagrange Points

How could these sorts of dynamics be modelled in Visualyse Interplanetary? The answer is via the ability to define a station's location via the J2000.0 reference frame vectors, as shown below:

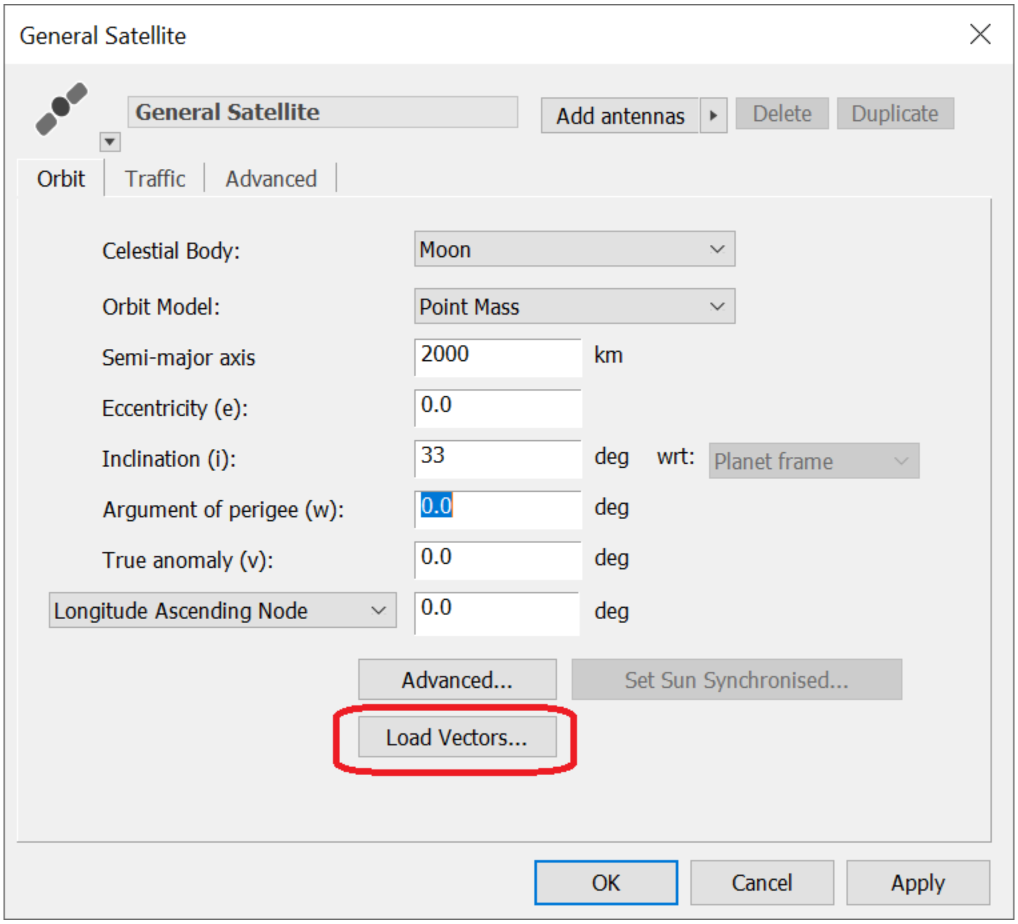


Figure 32: Loading Vectors to Define Satellite Location

This option allows the position and velocity vectors at given Julian date and times to be loaded from a comma separated value (CSV) file. The FreeFlyer astrodynamical software tool[2] was used to generate a text file containing the position and velocity vectors of the proposed Lunar Gateway mission in halo orbit around the Moon.

This was converted into the Visualyse Interplanetary CSV file format and then loaded into a simulation file. This could then be used to model communications to / from the Lunar Gateway station, as shown in the figure below.

[2] For more information, see https://ai-solutions.com/freeflyer-astrodynamic-software/

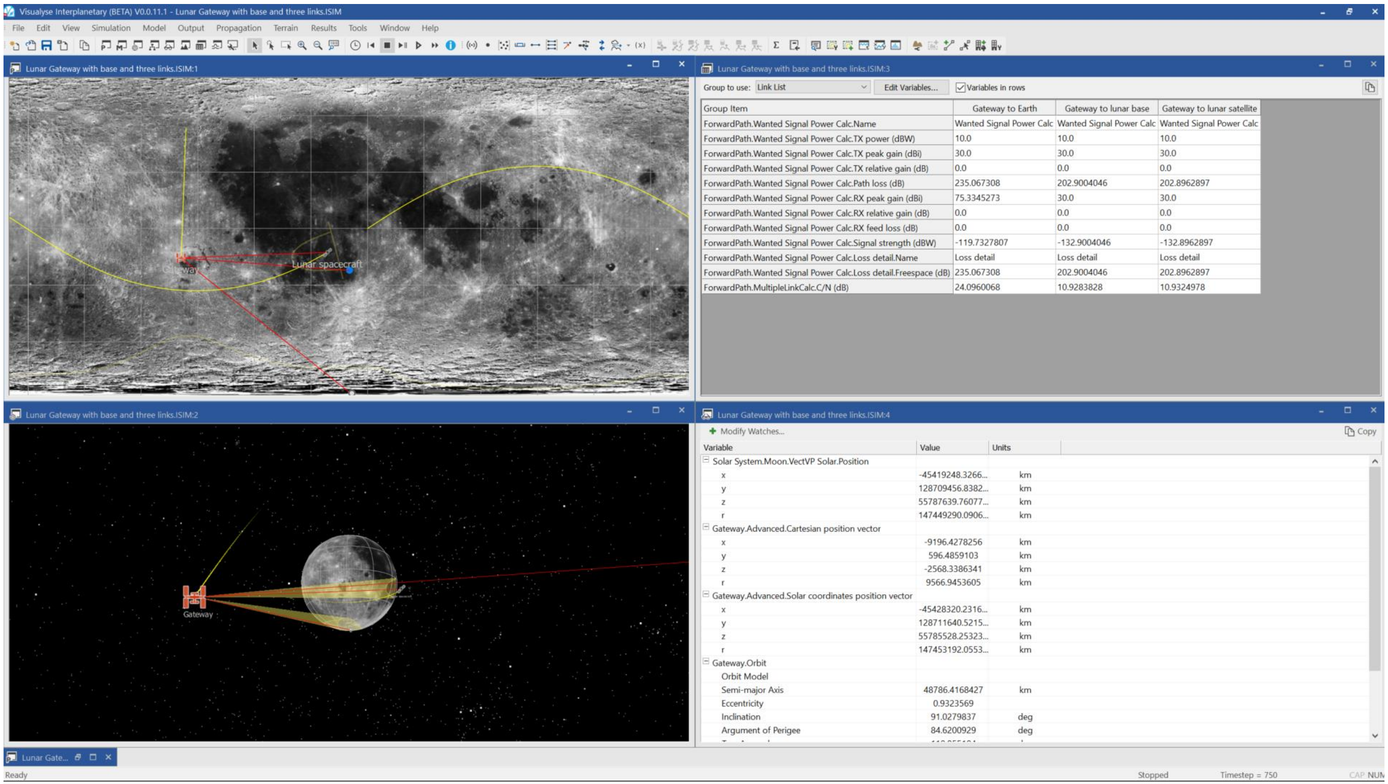


Figure 33: Lunar Gateway Visualyse Interplanetary Simulation File

This screenshot shows three links:

- From the Gateway to the ground network on Earth
- From the Gateway to a base at the Lunar south pole
- From the Gateway to a spacecraft in Lunar orbit.

This technique could be used to model a wide range of other orbits, including:

- Orbits around Earth-Moon Lagrange points
- Orbits around Earth-Sun Lagrange points, such as used by the James Webb Space Telescope
- Earth fly-by orbits
- Interplanetary transfer orbits
- Etc.

Our thanks to FreeFlyer for providing the information used to generate this simulation file.

About Transfinite

We are one of the leading consultancy and simulation software companies in the field of radio communications. We develop and market the leading Visualyse products:

- Visualyse Professional (as described above)
- Visualyse Interplanetary (as described above)
- Visualyse GSO
- Visualyse EPFD

Visualyse GSO

We have developed Visualyse GSO to support satellite coordination tasks, in particular for GSO satellites. It includes IFIC checking, detailed C/I calculations and integrates with ITU databases such as the SRS/IFIC and GIMS. It can be also used to identify coordination requirements of non-GSO satellites.

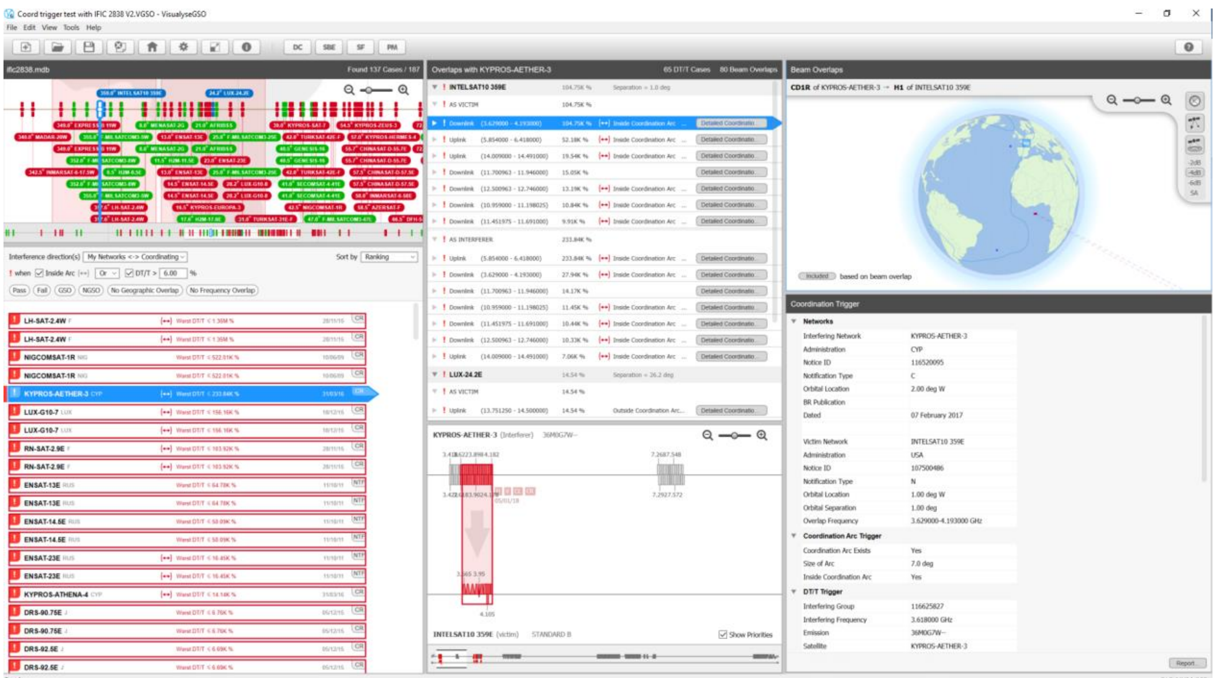


Figure 34: Visualyse GSO Coordination Trigger Tool Screen Shot

The figure above shows the coordination trigger tool while the figure below shows the detailed coordination tool.

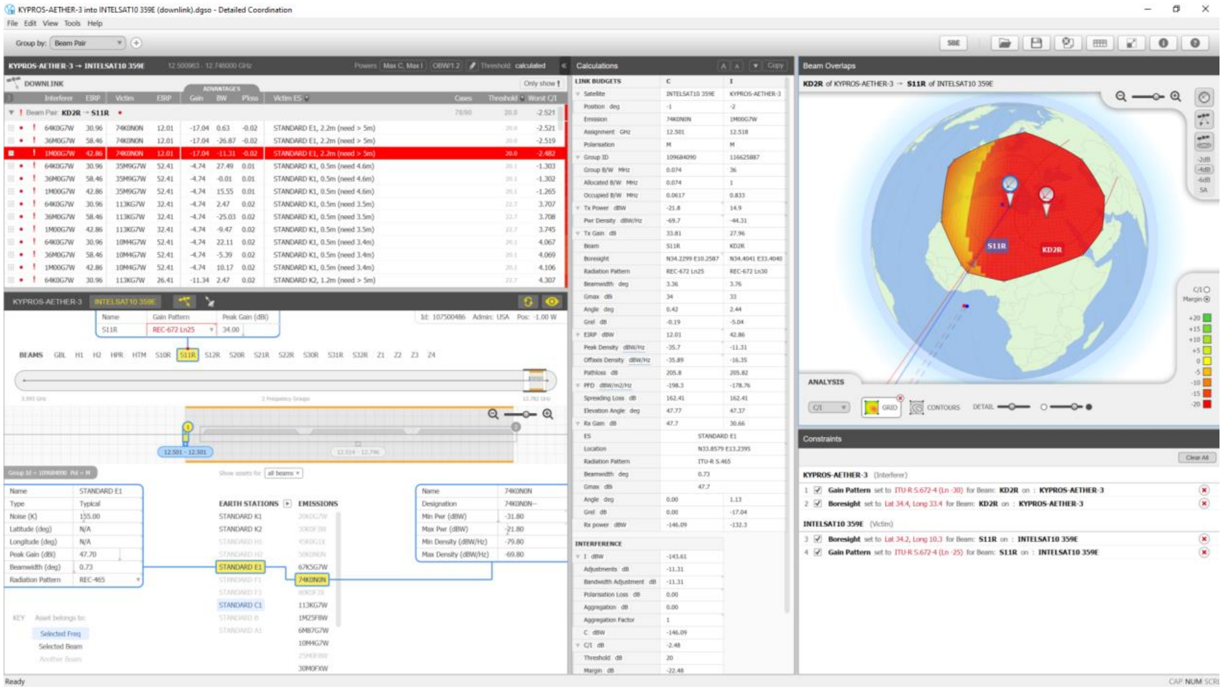


Figure 35: Visualyse GSO Detailed Coordination Tool Screen Shot

Visualyse EPFD

Our Visualyse EPFD software is the leading implementation of the algorithm in Rec. ITU-R S.1503. It has been verified during testing with the ITU BR and can calculate:

- EPFD (up)
- EPFD (down)
- EPFD (IS)

It can also analyse both the Article 22 and Articles 9.7A and 9.7B cases. It is available in two versions, one the ITU's "black-box" for pass/fail decisions and the other a product with graphical user interface that provides feedback on the calculation process and allows additional options to be modified.

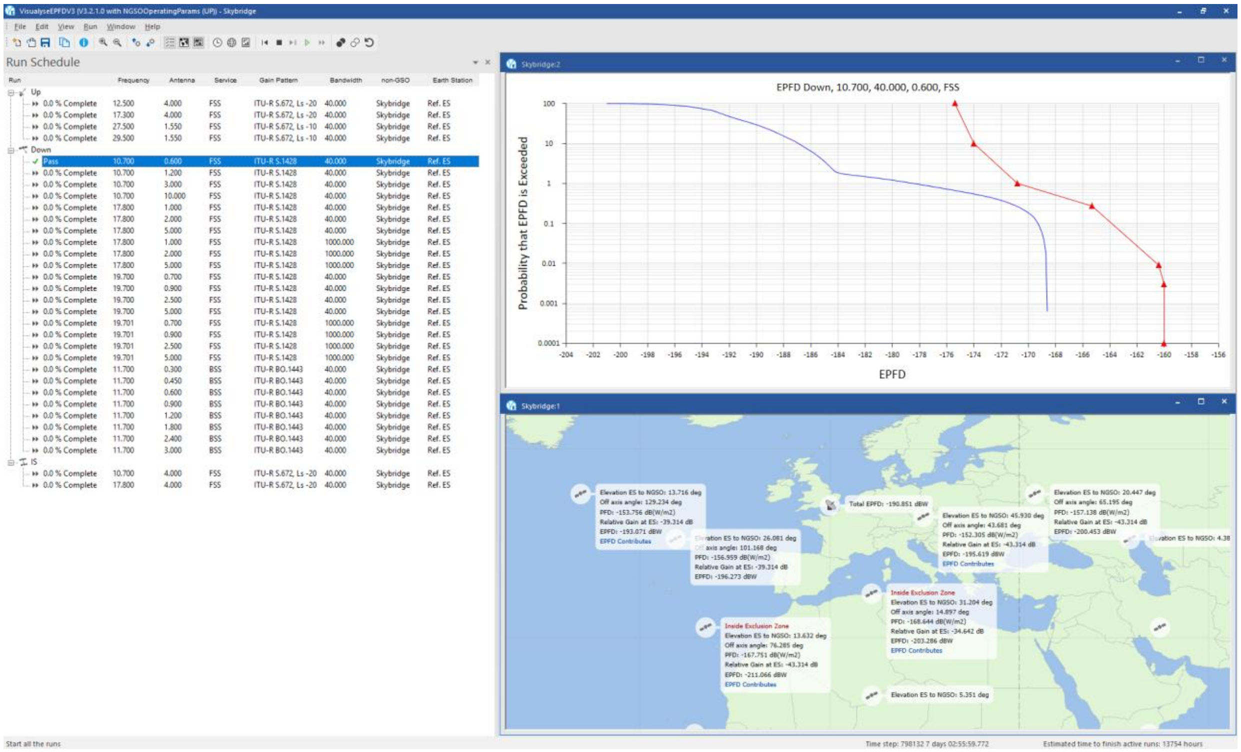


Figure 36: Visualyse EPFD Screen Shot

An additional tool is available to assist in the generation of PFD masks:

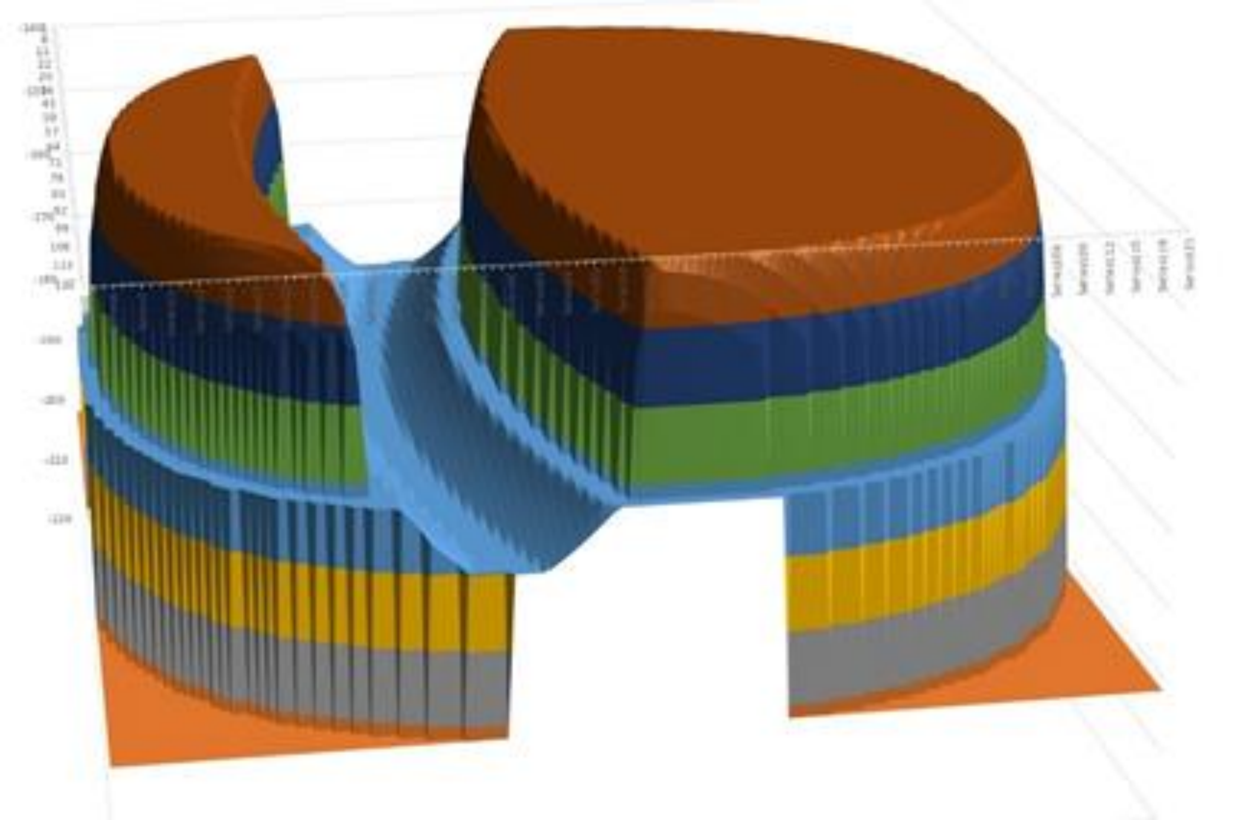


Figure 37: PFD Mask Generated using PMGT

Training Courses

We also provide training courses in the use of our products including advanced training that can cover modelling of specific systems and scenarios.

Consultancy Services

We can provide a wide range of consultancy services using our world-leading experts and software tools to rapidly generate solutions, including:

- Interference analysis and spectrum sharing studies
- Coordination support and meeting representation
- ITU-R and CEPT meeting representation and support
- Strategic consultancy to achieve regulatory goals.

Contact us

More information about these products and services is available at our web site:

http://www.transfinite.com

If you have any questions or comments about this White Paper or would like more information, please do not hesitate to contact us at:

info@transfinite.com