Universidade do Porto

Faculdade de Engenharia

FEUP

PROTOCOL OF COMMUNICATIONS FOR VORSAT SATELLITE

- Transmission Losses -

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ABBREVIATIONS AND ACRONYMS

AA – Atmospheric Absorption
AML – Antenna Misalignment Losses
CCIR – International Radio Consultative Committee
EIRP – Equivalent Isotropic Radiated Power
FEUP – Faculty of Engineering of University of Porto
FSL – Free Space Loss
GEO – Geosynchronous Earth Orbit
GS – Ground Station
HPA – High Power Amplifier
LEO – Low Earth Orbit
LNA – Low Noise Amplifier
RFL – Receiver Feeder Losses
UHF – Ultra High Frequency
VHF – Very High Frequency
VORSat – VHF Omni Directional Radio Range Satellite
XPD – Cross-Polarization Discrimination

1. TRANSMISSION LOSSES

In any satellite transmission, there are always losses from various sources. Some of those losses may be constant, others are dependent of statistical data and others vary with the weather conditions, especially with rain.

With the following table, it is intended to provide a clear view of the major impairments this kind of communication may suffer, as well as their origin. A detailed explanation will be given below, in order to determine and justify all the values achieved for the calculations for VORSat.

Table 1.1 – Major losses in satellite communications.

TRANSMISSION LOSSES	PROPAGATION LOSSES	FREE SPACE LOSSES		
		ATMOSPHERIC LOSSES	Ionospheric effects	Faraday rotation
				Scintillation effects
			Tropospheric effects	Attenuation
				Rain attenuation
				Gas absorption
				Depolarization
				Sky noise
			Local effects	
		POINTING LOSSES		
	LOCAL LOSSES	EQUIPMENT LOSSES	Feeder losses	
			?????	
		ENVIRONMENT LOSSES		

Losses in the received signal may have their origin in its propagation from the satellite to the ground station or the opposite, although the uplink will not be studied in this case once VORSat will only have downlink signal. They also may appear in the ground station itself or in the satellite.

1.1 PROPAGATION LOSSES

There are three major issues to take into account as far as propagation losses concern.

- Free space losses
- Atmospheric losses
- Pointing losses

1.1.1 FREE SPACE LOSSES

Free space loss is the dominant component in the loss of the strength of the signal. It doesn't refer to attenuation of signal, but to its spreading through space.

In order to perform all the mandatory calculations on the link power budget for any satellite, a key component must be taken into account, the Equivalent Isotropic Radiated

Power (EIRP), which may be considered the input power in one end of the link. EIRP is also introduced precisely at the beginning of all calculations so it can be understood the source of each component and to allow the correct comprehension of all the deductions presented.

The maximum power flux density at a distance r is given by:

$$\psi_M = \frac{G.P_S}{4\pi r^2}$$

where:

ψ_M → maximum power flux density
G → transmission antenna gain
P_S → radiated power from the antenna
r → distance between the satellite and the receiving station

Considering an isotropic radiator with an input power equal to $G.P_S$ the same flux density would be produced.

$$EIRP = G.P_S$$

Once EIRP is usually expressed in dBW, it is possible to write:

$$EIRP\ (dBW) = P_S\ (dBW) + G\ (dB)$$

The first step in the calculations for free space loss (FSL) is to determine the losses in clear-sky conditions. These are the losses that remain constant with time. As said before, FSL derive from the spreading of signal in space.

The received power is given by:

$$P_R = \psi_M.A_{eff}$$

where:

P_R → received power
A_{eff} → effective aperture of the receiving antenna

From the equations above, it is possible to write:

$$\psi_M = \frac{EIRP}{4\pi r^2}$$

The effective aperture of the antenna is provided by:

$$A_{eff} = \frac{\lambda^2 G_R}{4\pi}$$

So, the received power may also be calculated by:

$$P_R = \frac{EIRP}{4\pi r^2} \cdot \frac{\lambda^2 G_R}{4\pi}$$

$$P_R = EIRP.G_R.\left(\frac{\lambda}{4\pi r}\right)^2$$

In dB, this equation can be rewritten as:

$$P_R = EIRP + G_R - 10\log\left(\left(\frac{4\pi r}{4\lambda}\right)^2\right)$$

In this equation, EIRP refers to the transmitter, G_R to the receiver and the last term of the second member of the equation to the free space spreading losses.

Once

$$\lambda = \frac{c}{f}$$

FSL are given by the following expression:

$$FSL = 10\log\left(\left(\frac{4\pi rf}{c}\right)^2\right)$$

When the frequency f is represented in MHz and the distance r in km, the above expression for free space loss comes as:

$$FSL = 32,4 + 20\log(r) + 20\log(f)$$

VORSat will operate at a frequency of 2.45 GHz and its signals will be received from very different distances, as a result of its LEO. So, the following graphic can be made.
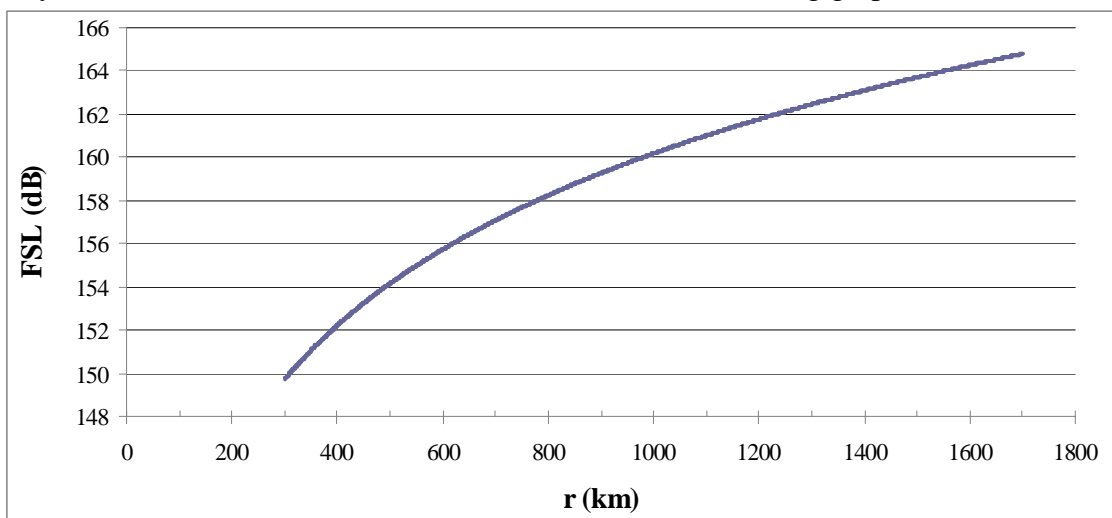

Figure 1.1 – Variation of the FSL with the distance, considering f = 2.45 GHz.

For VORSat link budget calculations, a value of 161.47 dB will be used.

1.1.2 ATMOSPHERIC LOSSES

This kind of losses derives from the absorption of energy by atmospheric gases. They can assume two different types:

- Atmospheric attenuation;
- Atmospheric absorption.

The major distinguishing factor between them is their origin. Attenuation is weather-related, while absorption comes in clear-sky conditions.

Likewise, these losses can be due to ionospheric, tropospheric and other local effects.

1.1.2.1 IONOSPHERIC EFFECTS

All radio waves transmitted by satellites to the Earth or vice versa must pass through the ionosphere, the highest layer of the atmosphere, which contains ionized particles, especially due to the action of sun's radiation. Free electrons are distributed in layers and clouds of electrons may be formed, originating what is known as travelling ionospheric disturbances, what provoke signal fluctuations that are only treated as statistical data. The effects are:

- Polarization rotation;
- Scintillation effects;
- Absorption;
- Variation in the direction of arrival;
- Propagation delay;
- Dispersion;
- Frequency change.

These effects decrease usually with the increase of the square of the frequency and most serious ones in satellite communications are the polarization rotation and the scintillation effects, and those are the ones that will be treated in this dissertation.

Polarization rotation

When a radio wave passes through the ionosphere, it contacts the layers of ionized electrons that move according to the Earth's magnetic field. The direction these electrons move will no longer be parallel to the electric field of the wave and therefore the polarization is shifted, in what is called Faraday rotation (θ_F).
This is not a serious problem in frequencies above 10 GHz. It will not be a problem in the case of VORSat also because this problem arises only in linear polarization. As said before, VORSat is being designed for circular polarization, hence the Faraday rotation will only add to the rotation.

Scintillation effects

Differences in the atmospheric refractive index may cause may cause scattering and multipath effect, due to the different directions rays may take through the atmosphere.

They are detected as variations in amplitude, phase, polarization and angle of arrival of the radio waves.

It is often recommended the introduction of a fade margin so atmospheric scintillation can be a tolerated phenomenon.
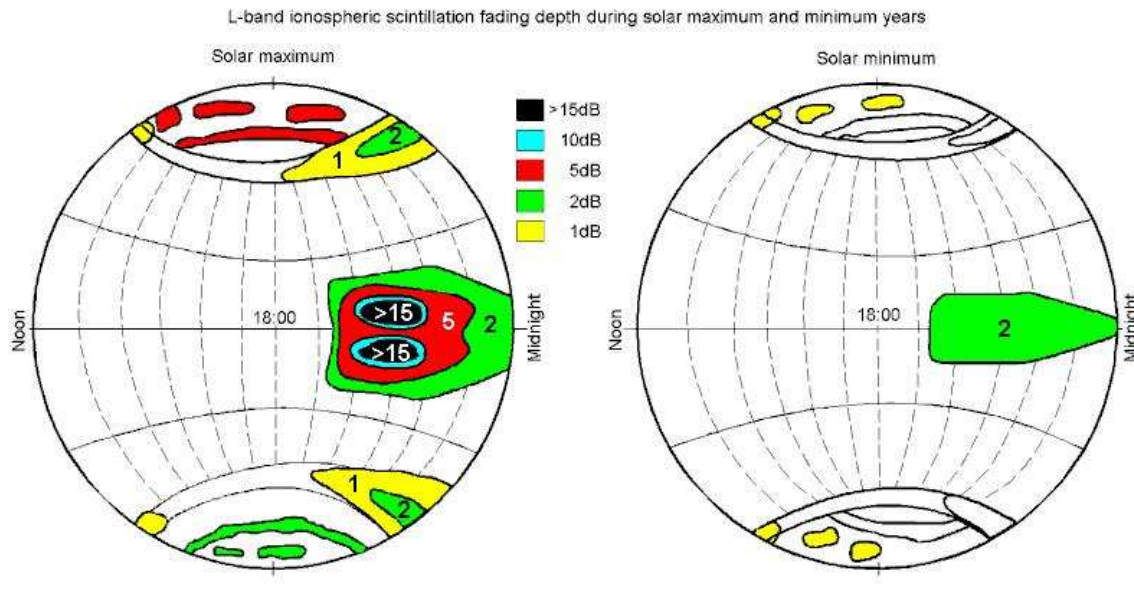

Figure 1.2 – Ionospheric scintillation fading depth.

The graphic above shows how ionospheric scintillation affects signals operating in the L-Band (1 GHz – 2 GHz). It is not exactly the frequency of VORSat, but it is close. It is possible to observe that Portugal, in its northern mid-latitude, is barely affected and this item may be neglected.

1.1.2.2 TROPOSPHERIC EFFECTS

Troposphere is composed by a miscellany of molecules of different compounds, such as hail, raindrops or other atmospheric gases. Radio waves that pass by troposphere will suffer their effects and will be scattered, depolarized, absorbed and therefore attenuated.

Attenuation

As radio waves cross troposphere, radio frequency energy will be converted into thermal energy and that attenuates signal.

They will also be scattered into various directions which means that there is a small percentage that doesn't reach the receiver antenna at the ground station. The main scatterer particles in troposphere are hydrometeors like raindrops, hail, ice, fog or clouds, and these particles represent a problem for frequencies higher than 10 GHz.

Both this kind of absorption and scattering rise with frequency, hence neither represent a serious problem for VORSat.

Rain attenuation

It makes no sense to determine the attenuation caused by rainfall because they will be very punctual events, since rain only causes severe attenuation in situations of heavy rain. Thus, even though one satellite transmission may be strongly affected due to rain, its orbit period of nearly 90 minutes minimizes that loss because the same ground station will have several other opportunities to receive VORSat's signals.

For GEO satellites it becomes mandatory to perform these calculations, once the satellite's position in relation to the GS is permanent.

Gas absorption

Under normal conditions, only oxygen and water vapour have a significant contribution in absorption. Other atmospheric gases only become a problem in very dry air conditions above 70 GHz.

Thereby, losses caused by atmospheric absorption vary with frequency and the collection of data already received allows the elaboration of the graphic that follows:
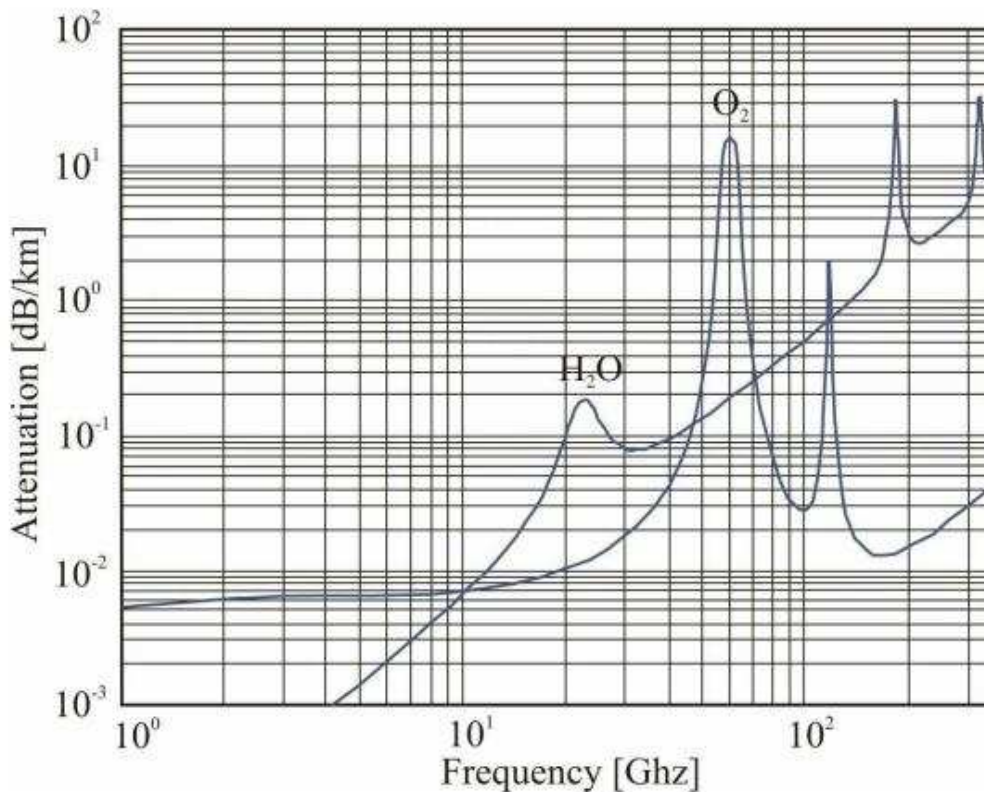

Figure 1.3 – Attenuation vs. frequency

As it is possible to verify, both two peaks are observed at the frequencies 22.3 GHz for water vapour (H_2O) and 60 GHz for oxygen (O_2), wide far of the frequency of VORSat signals, at 2.45 GHz. At this frequency, the atmospheric absorption is extremely low, around 0.006 dB/km, depending almost exclusively from oxygen because the water vapour contribution is significantly smaller.

Once these values depend on atmosphere thickness, it becomes necessary to perform all calculations taking into account troposphere's thickest layer (T_{trop}), which has 20 km.

It is also mandatory to refer that this graph represents the absorption for a satellite in the zenith, in other words, for an elevation angle of 90º (θ = 90º). For lower angles, the atmospheric absorption (AA) is given by:

$$AA \text{ (dB)} = AA_{|90º} \text{ (dB/km) cosec } \theta \cdot T_{trop} \text{ (km)}$$

When VORSat is near the zenith, AA is 0.12 dB, but since it will pass through its sub-satellite point in several elevation angles, one ought to determine the AA also for the worst case, the threshold of visibility, θ = 10º.

Then, applying the previous formula, $AA_{|10º} \approx 0.69$ dB. This value is superior to the $AA_{|90º}$ and it makes sense, once the atmospheric layer the signal has to overcome is thicker. The values for attenuation decrease rapidly with the increase of the elevation angle, according to the graphic shown below.
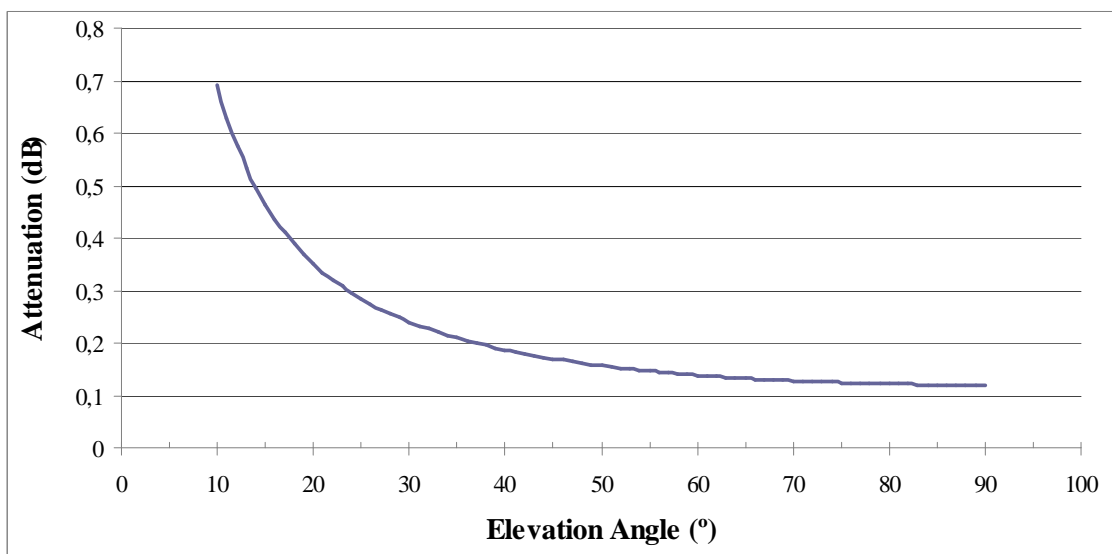

Figure 1.4 – Variation of the attenuation with the variation of the elevation angle of the satellite.

A value of 1 dB will be used for calculations.

Polarization

Satellite communications use linear and circular polarization, but undesirable effects may transform it into an elliptical polarization.

VORSat is being designed to transmit in circular polarization, what makes it less prone to depolarization issues.

Depolarization may occur when an orthogonal component is created due to the passing of the signal through the ionosphere. There are two ways to measure its effect, cross-polarization discrimination (XPD) and polarization isolation (I).

- Cross-polarization discrimination

When an electric field of magnitude E_1 is transmitted through a depolarizing medium, the received signal will have a copolar component (E_{11}) and a cross-polar component (E_{12}).

It is defined as follows:

$$XPD \text{ (dB)} = 20\log \left(\frac{E_{11}}{E_{12}} \right)$$

- Polarization isolation

This applies to two orthogonal signals that go by the same depolarizing medium. Both will have copolar and cross-polar components at the receiver. Polarization isolation is the ratio of the received copolar power to cross-polar power, and it is defined as:

$$I \text{ (dB)} = 20\log \left(\frac{E_{11}}{E_{21}} \right)$$

- Rain and ice depolarization

Drops of rain also add depolarization. The ideal drop of rain has a spherical shape so that the necessary energy to keep it together is minimal. However, the real shape of a drop is flattened, where there is a major axis relatively to the others, forming a spheroid. Since rainfall results in random directions of rain drops, which will vary even with the wind, they will be canted. This results in the rotation of polarization of the radio waves. This rotation may reach up to 10º, what may become a quite serious problem in linear polarization, but not that much in circular polarization because, such as in ionospheric depolarization, this value will only add to the rotation.

On the top of each rain area there is an ice layer which can cause depolarization. Ice crystals usually have the shape of a needle or a plate. When their disposition is random there is no depolarization, but when there's an alignment it may occur.
International Radio Consultative Committee (CCIR) recommends the use of a statistical value of 2dB added to the XPD determined for rain. Furthermore, ice effects may be despised for time percentages inferior to 0.1%.

Sky noise

Sky noise is a combination of galactic and atmospheric effects, according as both these factors influence the quality of the signal in the reception.

Galactic effects decrease with the increase of frequency (Fig 1.4). They are due to the addition of the cosmic background radiation and the noise temperature of radio stars, galaxies and nebulae. This value is quite low and a good approximation is 3 K.
Figure 1.4 shows also an optimal window between 1 GHz and 10 GHz, rather useful for satellite transmissions due to its fairly low noise temperature.
Considering VORSat's operation at 2.45 GHz, the temperature of cold sky can be approximated of 10 K.

Atmospheric effects in satellite transmissions increase with the increase of frequency (Fig 1.5). As said previously, the effects of the atmosphere in signal attenuation become serious for frequencies above 10 GHz, and the same applies for noise temperature.
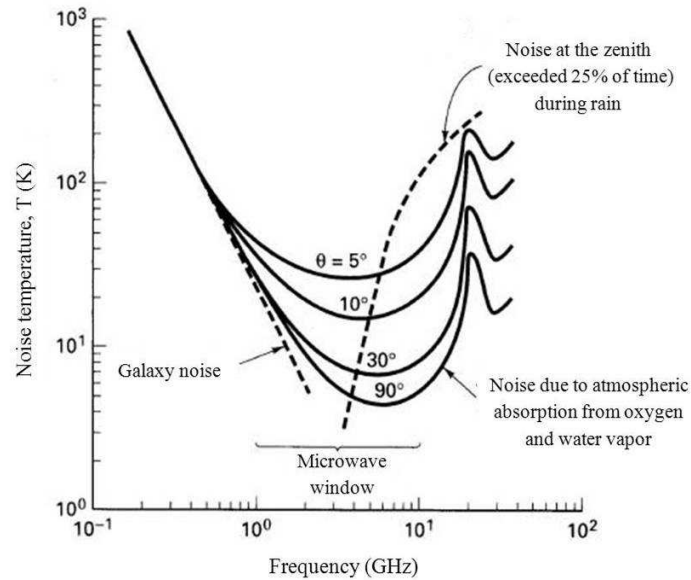

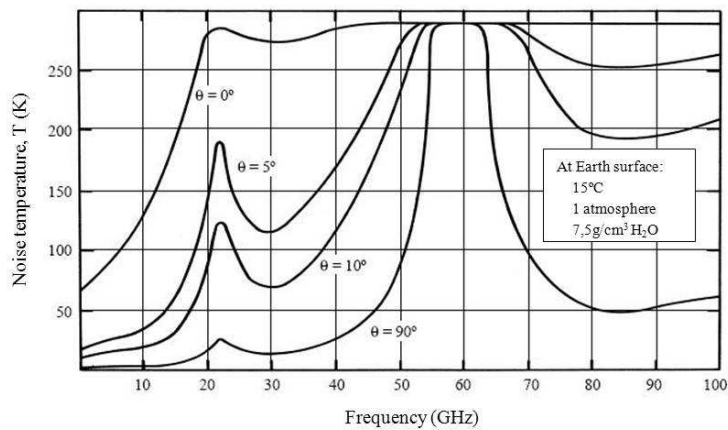
Figure 1.5 – Galaxy noise influence in noise temperature.

Figure 1.6 – Noise temperature variation with frequency.

For the frequency f = 2.45 GHz, this value is much more reduced.

1.1.2.3 LOCAL EFFECTS

These effects refer to the proximity of the local ground stations, possible sources that may interfere with the received signal and buildings that may block the signal.
This is not the case for the ground station placed at FEUP, once it is free of possible external interferences and it is localized at an elevation of 125 m above the sea level,

what makes it one of the highest points nearby. That allows this GS to be able to receive VORSat's transmission from its lowest elevation point.

Nevertheless, this problem is much weightier in other communications systems, such as mobile services.

For satellite communications this factor may be negligible.

1.1.3 POINTING LOSSES

Ideal reception implies that the value for misalignment losses would be 0 dB which means maximum gain at the ground station is achieved when both the transmitter and the receiver antennas are 100% aligned. Realistically it is virtually impossible to achieve a perfect alignment between the antennas of the ground station and the satellite, especially in the case of CubeSats, due to their fast movement of nearly 8 000 ms^{-1}.

There are two ways for misalignment:

- Off-axis loss at the satellite;
- Off-axis loss at the GS.

The first one is considered during the design of the satellite.

The second type of misalignment is the antenna pointing loss and it is usually quite small, not reaching even 1 dB, being this value a good approximation for pointing misalignment loss.

Antenna misalignment losses (AML) are calculated using statistical data, so these values are an approximation based on real data observed in several GS. Ergo, these values are not calculated, but estimated.

1.2. LOCAL LOSSES

These losses refer to loss of signal quality in each ground station.

1.2.1 EQUIPMENT LOSSES

The receiving and emitting equipments also introduces some losses to the signal.

Feeder Losses

Feeder losses occur in the several components between the receiving antenna and the receiver device, such as filters, couplers and waveguides. These losses are similar to the ones which occur also in the emission, between the emitting antenna and the output of the high power amplifier (HPA).

Receiver feeder losses (RFL) added to FSL and are not necessary but to relate EIRP with the HPA output, which means that knowing the EIRP will allow the calculations without being aware of the RFL values.

So, for the calculation of the link budget of VORSat, these losses are not taken into account.

1.2.2 ENVIRONMENT LOSSES

This item is related to the specific region of the globe where the ground station is placed (equatorial, tropical, polar…). Depending on its latitude, each region has its own characteristics (e.g. temperature, moisture, thickness of atmospheric ice layer…), which may provoke variation in signal reception.

Portugal has mid latitude and is at the temperate northern region, which has no extreme values for atmospheric conditions. Hence this factor may be neglected.

1.3 OTHER IMPAIRMENTS

There are also other factors that may condition satellite communications. Even though they may have a minor importance in CubeSat's transmissions, they may become relevant in other cases.

Sun Outage

Sun outages are punctual losses of communication between satellites and the Earth due to satellite's obscuration by the sun. It means that the ground station *sees* the sun behind the satellite, in what is called a "transit".
It occurs in 5 or 6 days near the equinoxes and last for a maximum of 8 minutes each, in a total of 60 minutes per year. The noise temperature of the system becomes very high and communications suffer negative consequences at about 100 minutes per year (0.02%).
Sun outage affects other kinds of satellites, but not LEO's.

Satellite eclipses

These eclipses happen when the satellite crosses the cone of shadow of the Earth. They occur within 23 days before and after the equinoxes, at March 21st and September 23rd.
They last 70 minutes at their maximum and some strong thermal variations are produced. During the eclipse, the satellite operates only with batteries and some transponders are disconnected.
However, this problem only affects geosynchronous satellites due to their fixed position relative to the Earth.
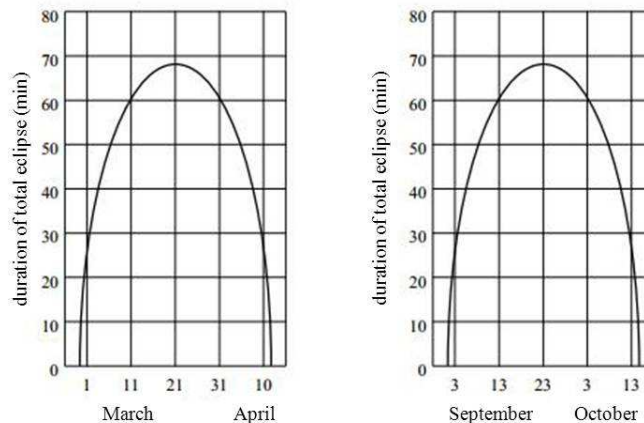

Figure 1.7 – Dates and duration of eclipses

LIST OF REFERENCES

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