Cruise Control : A GEO Satellite System Design for Avancez Cruises

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1 Abstract

This project details the development of a satellite communication system for Avancez Cruises, ensuring reliable connectivity for ships across multiple regions. By utilizing four GEO satellites and operating within the Ku-band, the system meets high demands for internet access, real-time updates, and inter-ship communications. A comprehensive analysis of link budgets, including SNR and Eb/No metrics, verifies system resilience, maintaining signal integrity and low bit error rates in varying weather and coverage conditions. With these optimizations, the network aims to achieve dependable, uninterrupted service, meeting 99.999% reliability goals across all cruise routes. Keywords:

2 Introduction

This project aims to design a reliable satellite communication system for Avancez Cruises, a company that operates luxury cruise liners across Europe, the Caribbean, South America, and Africa. The system will enable smooth communication between ships and with the headquarters in Göteborg, while also providing essential services such as internet access for guests and crew, weather updates, and software transfers. With the goal of providing a data rate of several Mbps and 99.999% reliability, this system will play a key role in keeping cruise lines connected and operating. The headquarters of Avancez Cruises is considered to be in Säve Flygplats (57.7749 °, 12.2200 ° E) in Göteborg. This location was specifically chosen because it is a former airport with plenty of open space around and away from dense urban structures. It is assumed that Avancez Cruises operates with a fleet of 11 ships with 500 passengers on board each ship, including crew and staff.

3 Orbits and Satellites

In designing a satellite communication system for Avancez Cruises, global coverage and reliable connectivity even in cases of bad weather/ remote regions of the work are of importance. The possible orbits to satisfy these conditions are

- Geostationary Earth Orbit (GEO) at an altitude of 36,000km
- Medium Earth Orbit (MEO) at an altitude of 5000 - 20,000 Km
- Low earth Orbit (LEO) at an altitude of 500 - 1200 Km

For the purpose of this project, 30-40 LEO satellites would be needed mainly because they travel very fast and would zoom past the necessary area of coverage very soon. Hence we would also hae to design a complicated handover mechanism between satellites. In case of MEO, 10-20 satellites would suffice but would still need some thought towards handover. However, by considering 3 GEO satellites, the entire region of the cruise path could be covered with minimum number of satellites which provide constant coverage.

Therefore, this project is based on the use of 4 GEO satellites, 2 main satellites, hereby referred to as Main1 and Main2 and 2 backup satellites, hereby referred to as

Backup1 and Backup2. Main1 and Main2 cover the entire route of the cruise ships with a primary focus to provide connectivity throughout. In case of an outage of either Main1 or Main2, Backup1 or Backup2 will take over.

Figure 1 depicts a screenshot of SAVI that highlights the areas of coverage offered by the 4 GEO satellites taken into account in this project. It also shows the parameter values and a camera view of the 4 satellites. The 4 satellites are placed more than 22° apart, which is in accordance with the minimum ITU recommendation of 2° orbital separation.

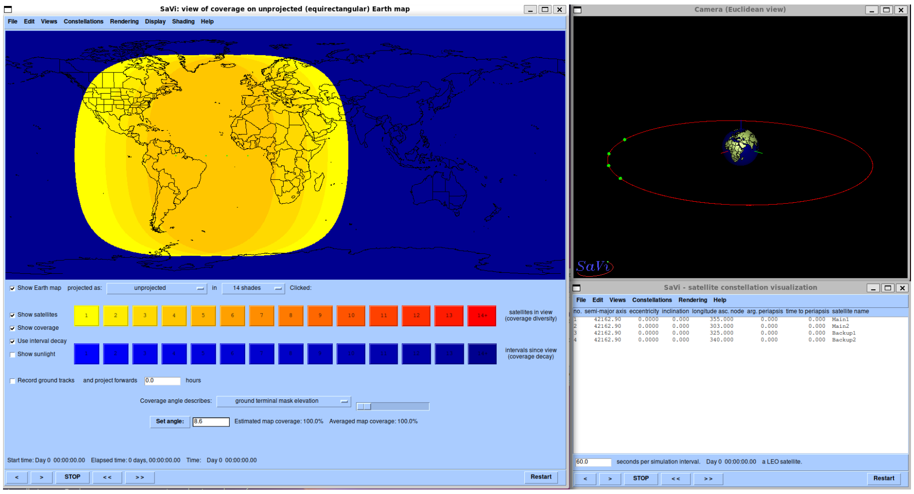

Figure 1: Screenshot of Global coverage of satellites, parameter values and camera view

From Figure 1, parameters like coverage angles and semi-major angle need to be calculated. Table 1 indicates some of parameters that will be calculated/ used for calculating all the orbital parameters needed to form a satellite constellation for this project.

Table 1: Important considerations for orbital parameter calculations

Parameter	Value
Semi-major axis(a)	42162.90 km
Satellite Altitude (R_0)	35784.9 km
Mean Equatorial Radius (R_e)	6378 km
Latitude of ground station (l)	57.7749
Longitude of Satellite (L)	303.7

3.1 Semi-Major Axis (a)

Semi-major axis refers to the average distance from the center of an elliptical orbit to the satellite. For a geostationary orbit, semi-major axis (a) can be calculated using Kepler's 3rd law -

$$\frac{T^2}{a^3} = \frac{4\pi^2}{GM} \tag{1}$$

where T (time to complete 1 orbit) = 86164.1 s, G (gravitational constant) = $6.67430 \times 10^{-11}\,\mathrm{m^3\,kg^{-1}\,s^{-2}}$, M (mass of Earth) = 5.972×10^{24} kg and a (semi-major axis) = 42162.90 km

3.2 Eccentricity (e) and Inclination (i)

Eccentricity (e) indicates how close the orbit is to being circular. Inclination (i) defines the angle between the earth's equatorial plane and the orbital plane of the satellite.
For the sake of simplicity, both e and i have been assumed to be = 0 in this work.

3.3 Nadir Angle (θ) and Elevation Angle (E)

Nadir Angle (θ) is the angle between the satellite and the vertical downward direction to the surface of the earth from the satellite. If θ is 0°, it means that the satellite is directly overhead the Earth and as the satellite moves away, then θ increases.
Elevation Angle (E) is the angle between the line of sight of a satellite and the horizontal plane at the observation's position. Based on the below equations from [1] we get the values of θ and E -

$$\cos\phi = \cos l.\cos L \tag{2}$$

$$E = \arctan\left(\frac{\cos\phi - \left(\frac{R_E}{R_E+R_0}\right)}{\sqrt{1-\cos^2\phi}}\right) = 8.608^\circ \tag{3}$$

$$\theta = \arcsin\left(\frac{R_E\cos E}{r}\right) = 8.6017^\circ \tag{4}$$

where ϕ = angle between the satellite and the ground station as seen from the center of the earth.
It is important to remember that these θ and E angles are entered into SAVI to obtain the coverage angle describing ground terminal mask elevation (as depicted in Figure 1) and cones from satellite.

4 Frequency Allocations

There are many frequency bands that can be considered such as L, C, X, Ku and Ka. In satellite communication, usually Ku, Ka and C band is preferred.

For the Avancez Cruises satellite communication system, Ku band is the optimal choice due to its balance between performance, and practicality for maritime applications. Compared to the C-band, which requires larger and equipment, the Ku band's smaller antenna size makes it ideal for installation on cruise ships, where space and weight are critical factors. This band provides sufficient capacity for delivering high-speed internet to passengers, real-time communication, and essential ship operations without the high equipment costs associated with the C-band.

While Ku-band is more susceptible to weather interference than C-band, it still offers reliable service. It also avoids the significant rain fade vulnerability of the Ka-band, making it a better choice for maintaining service continuity during adverse weather at sea.

5 Modulation Techniques

5.1 Required Bit Rates

Given that there are 11 ships in the Avancez Cruise fleet and 500 users per ship -

- Internet usage:
  Assume 5 Mbps per user
  The bit rate for all the users on all ships = 27.5 Gbps

- Weather / Software updates:
  Assume 10 Mbps per ship
  The bit rate for all the 11 ships = 110 Mbps

- Inter-ship and headquarters communication:
  Assume 1 Mbps per ship
  The bit rate for all the users on all ships = 11 Mbps

Therefore total required bit rate = 27.621 Gbps

5.2 Modulation

While selecting the modulation scheme, some important considerations are bandwidth efficiency, power efficiency and complexity. Among BPSK, QPSK, 16 QAM, 64 QAM, QPSK is he clear winner for the following reasons -

- QPSK is more bandwidth efficient than BPSK because it transmits 2 bits per symbol, for the same bandwidth.

- It requires less power compared to 16-QAM or 64-QAM and hence can be used for long distance communication between GEO satellites and ground stations.

- Modulation and demodulation is simpler for QPSK than higher order schemes and it performs decently well even in the presence of AWGN.

- Lastly, forward error correction(FEC) is highly recommended with QPSK to reduce the overall BER.

5.3 Multiple Access and Multiplexing

Assuming that each ship is a ground station, there will be a total of 12 ground stations and traffic from each of these will be directed to the antennas at once. This can be done in one of 2 ways as described in Section 6.3.1 of [1] and indicated in figure 2.

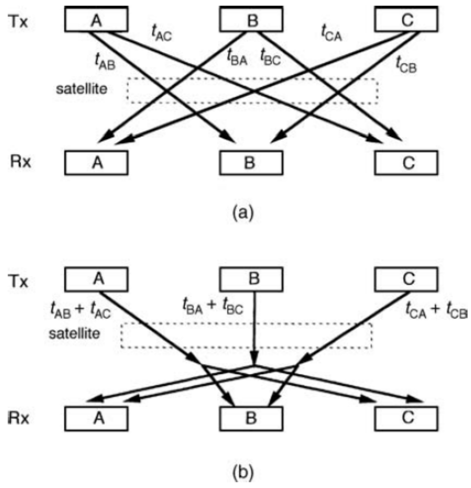

Figure 2: Traffic routing techniques from the textbook [1]: (a) one carrier per station-to-station link and (b) one carrier per transmitting station.

The choice between these 2 depends on various factors such as number of ground stations, bandwidth and multiple access technique. This project uses the 'one carrier per station-to-station link.

Based on this, there are 3 types of multiple access techniques that can be considered - Frequency Division Multiple Access (FDMA), Time Division Multiple Access (TDMA) and Code Division Multiple Access (CDMA). This project will focus on using FDMA for the following reasons -

- FDMA is one of the oldest and simplest multiple access techniques to implement
- It doesn't have the complexity of having to synchronize earth station and satellites.
- It needs lesser power than TDMA and CDMA because they deal with alternating bursts of uplink and downlink data transmissions, while FDMA has continuous access to data.
- FDMA isn't affected by additional problems such as considering the burst rate and code generation as in other multiple access schemes.
- Since FDMA is used, every user always had a designated frequency for usage which means the system availability is very high.

Frequency Division multiplexing (FDM) is used because it compliments FDMA well with mostly the same benefits over Time Division Multiplexing (TDM) and Code Division Multiplexing (CDM).

5.4 Bandwidth

Given that QPSK is used, the bandwidth (BW) required can be calculated from:

$$R_b = B \times \eta; \tag{5}$$

The overall BW needed in the worst case scenario where all users are active and through all the 3 forms of usages as discussed in Section 6.1 can be calculated by Equation 5 here R_b (total bit rate from section 6.1) = 27.621 Gbps, eta(QPSK spectral efficiency) = 2 bit/Hz and therefore BW = 13.8105 GHz. Given that Ku band is chosen as the frequency range for this project, the BW calculated in 5 lies within its specified range of 12-18 GHz.

6 Antennas

Antennas are an essential component of this project as they receive and transmit signals between satellites, ships, and the ground station. The antennas are used for the 3 use cases defined in the problem statement namely internet usage for passengers, software/ weather updates, and inter-ship communication.
The headquarters, all the ships and satellites have 2 antennas, 1 each for transmitting and receiving data. Table 2 gives an overview of the antenna types and dimensions used in different scenarios. The antenna diameters (d) are chosen based on trial and error in order to maintain decent Bit Error Rate (BER) which will be discussed in the upcoming sections. A constant antenna efficiency η of 0.7 is used since there is not restriction on the budget for this project.

Table 2: Antenna types and dimensions

where	Type of antenna used	diameter	efficiency
Satellite	Corrugated Horn Antenna	3.2 m	0.7
Headquarters	Electronically Phased Array Antenna	8 m	0.7
Onboard ship	Electronically Phased Array Antenna	8 m	0.7

6.1 Corrugated Horn Antenna

A Horn antenna is a type of aperture antenna that is specially designed for microwave frequencies. The end of the antenna is widened or in the horn shape. Because of this structure, there is larger directivity, so that the emitted signal can be easily transmitted to long distances.

Corrugated horn antenna is a type of horn antenna that has periodic corrugations on the internal surface of the horn, altering the characteristics of wave propagation. This ensures a more powerful beam, which is essential for long-distance communications such as from the satellite to the ground station / ships.

6.2 Electronically Phased Array Antenna

Phased Array Antenna is a group of antennas that work as a large antenna. It consists of an array of dipoles which work mainly by beamforming [3]. Each element of the antenna can be manipulated to create a beam in a particular direction without having to move the entire antenna. Another advantage of beamforming is that it can minimize interference that is coming from any direction other than the direction of the signal. This helps prevent jamming to any other interference. Beam steering takes beamforming a step further by allowing real time changes in the beam pattern through phase shifting. This is done electronically from anywhere to ensure energy conservation and improve communication.

Therefore, Electronically Phased Array Antennas are used at the headquarters of Avancez Cruises as well as on board all their ships. This is because while the satellite is not moving much, the ships will be. So using an electronically phased array antenna helps the ship to constantly direct its beam towards the satellite wherever it moves. This also ensures that, in the event that one of the satellites is unavailable, the communication is still possible by simply redirecting the beam in the direction of the backup satellite.

6.3 Polarization

The polarization of an antenna is loosely defined as the direction of the electromagnetic fields produced by the antenna as energy radiates away from it. Generally, there are 3 types of polarization - linear, circular and elliptical.
For this project, linear polarization(horizontal) is considered since most of the available resources and equations for calculations assume linear polarization. Linear polarization is advantageous because it allows better control of the antenna's beam shape and steering performance. It also offers simpler phase control when steering the beam electronically, as the polarization remains fixed.

7 Uplink and Downlink calculations

This section deals with uplink and downlink budget calculations for Avancez Cruises. These performances are calculated keeping in mind the various gains and losses which are discussed below. Sections 7.1 - 7.6 deal with general losses in clear sky conditions. Beyond that, section 7.7 deals with additional losses that occur during bad weather conditions. Lastly, Section 7.8 gives the overall Carrier-to-Noise Ratio and concludes the calculation of the link budget.

7.1 Wavelength for Uplink

The first basic parameter evaluated is the wavelength (λ) which depends on the speed of light (c) and uplink frequency. (f)

$$\lambda = \frac{c}{f} \text{ (m)} \tag{6}$$

7.2 Gain of Ground Station Antenna

The gain of the ground station antenna is then calculated and converted to dB using Equation 7. This depends on the antenna's physical dimension (diameter D), antenna efficiency (η) and λ

$$G_{\max} = \frac{\pi^2 D^2 \eta}{\lambda^2} \tag{7}$$

Table 3: Antenna Parameters

Parameter	Uplink	Downlink
f	14.4 GHz	13 GHz
λ	0.0208 m	0.0231 m
Dist. b/w sat. and center of Earth	42162.9 Km	42162.9 Km
Dist. b/w sat. and HQ	39099.42 Km	39099.42 Km

7.3 Effective Isotropic Radiated Power(EIRP)

EIRP represents the effective power radiated by the ground station antenna, which gives the strength of the signal transmitted toward the satellite.

$$\mathrm{EIRP}_{\mathrm{max}} = P_t + G_{\mathrm{max\ (dB)}}\ (\mathrm{dBW}) \tag{8}$$

From Table 4 it is seen that EIRP values are pretty good for this system. Higher the EIRP value, better the system quality.

7.4 Power Flux Density(PFD)

PFD represents the power per unit area of the satellite. This is essential to understand how much power is available to the receiving satellite.

$$\mathrm{PFD} = \mathrm{EIRP}_{\mathrm{max}} - 10\log_{10}(4\pi R^2)\ (dBW/m^2) \tag{9}$$

7.5 Free-Space Path Loss

Space where no matter exists is called Free Space. Free Space Path Loss L_{FS} is the loss when a wave passes through free-space(vaccuum)

$$L_{\mathrm{FS}} = \left(\frac{4\pi R}{\lambda}\right)^2\ (dBW/m^2) \tag{10}$$

7.6 Power Received by receiving antenna

Based on the above parameters, the final power received by the receiving antenna P_R can be calculated using equation 11.

$$P_{\mathrm{R}} = \mathrm{EIRP}_{\mathrm{max}} - L_{\mathrm{FS\ (dB)}} + G_{\mathrm{max\ rec}}\ (dBW) \tag{11}$$

Table 4 summarizes the uplink and downlink parameters in clear sky conditions. These have been calculated based on basic equations as discussed in lecture 2 of this course.

7.7 Total Power Received by Satellite Antenna after Losses

Given that the calculations are to be done considering the worst-case scenario, there will be a number of additional losses such as due to rain, atmospheric losses and

Table 4: Clear Sky performance Characteristics

Parameter	Uplink	Downlink	Source
Power Transmitted	150 W	120 W	Assumption
G_{maxup}	60.080602 dBi	-	L-02
$G_{maxdown}$	-	51.233419 dBi	L-02
EIRP	81.840602 dBW	72.025231 dBW	L-02
PFD	-81.051698 dBW/m^2	-90.867069 dBW/m^2	L-02
L_{FS}	207.509223 dBW/m^2	206.620841 dBW/m^2	L-02
P_R	-73.798621 dBW	-82.725609 dBW	L-02

feeder losses which are summed up as 'Additional Losses' in equation 12. The contribution of these losses are individually detailed in Table 5.

$$P_{\mathrm{R\ tot}} = P_{\mathrm{R}} - AdditionalLosses\ (dBW) \tag{12}$$

Table 5: Additional loss parameters

Parameter	Uplink	Downlink	Source
Feeder Loss	2 dB	2	Assumption
Polarization Loss	1 dB	1	Assumption
Atmospheric Loss	1 dB	1	Assumption
θ_{off}	0.1°	0.1°	Section 5.6.2 of [1]
θ_{3dB}	0.2431°	0.6462	L-02
Antenna Pointing Loss	3.611167 dB	0.287415 dB	Section 5.4.4.3 [1]
Rain Attenuation	4.562879 dB	4.324621 dB	[10], [11], [12]
$P_{\mathrm{R\ tot}}$	-85.972668 dBW	-91.521131 dBW	L-03

7.8 Carrier-to-Noise Ratio

Finally, Carrier-to-noise ratio (C/No) is used to evaluate the overall quality of the uplink / downlink signal strength relative to the noise power at the receiver. Equation 13 indicates the calculation of C/No where G/T is the Figure of merit and K is the Boltzmann's constant(in dB). The final figures of uplink and downlink C/No is indicated in Table 6.

$$C/No = \mathrm{EIRP}_{\mathrm{max}} - L_{\mathrm{FS\ (dB)}} + \frac{G}{T}_{Sat} + K\ (dBHz) \tag{13}$$

7.9 Signal-to-noise ratio and Energy per Bit to Noise Power Spectral Density

In this project, (SNR) and (Eb/No) are key parameters assessed to evaluate the link quality and efficiency for the satellite communication system supporting Avancez Cruises. They have been calculated using the equations 14, 15, 16 -

$$\mathrm{SNR}_{\mathrm{dB}} = C/N_0 - 10\log_{10}(\mathrm{Bandwidth}_{\mathrm{Hz}})\ (dB) \tag{14}$$

$$\eta = \frac{\log_2(M)}{1+\beta} \tag{15}$$

$$E_b/N_0 = \mathrm{SNR_{dB}} - 10\log_{10}(\eta)\ (dB) \tag{16}$$

From Table 6 the SNR values indicate strong signal clarity with respect to noise, which is needed to maintain good communication with the 11 ships and HQ. The Eb/No values seem to be reasonable and ensure a low BER for reliable data transfer in conditions where bandwidth efficiency and power management are critical. By achieving high SNR and Eb/No values, the system can sustain robust communication links under various operating conditions, which satisfies the project's goal of having robust communication.

Table 6: Carrier-to-noise ratio parameters

Parameter	Uplink	Downlink	Source
Antenna Noise Temperature	290 K	290 K	Assumption
Figure of Merit	18.235720 dBK^-1	24.534913 dbK^-1	Section 5.6.2 of [1]
Carrier-to-Noise ratio	121.167099 dBHz	118.539304 dbHz	Section 5.6.2 of [1]
Signal-to-noise ratio	19.77 dB	17.14 dB	[1]
E_b/N_0	17.89 dB	15.27 dB	[1]

7.10 Latency

In satellite communication, one important consideration is to ensure latency is minimized. GEO satellites have a latency of about 600 ms [6]. The latency in the worst case would be between the headquarters and the satellite furthest away from it i.e Backup2 and can be calculated by -

$$\text{Latency} = \frac{\text{Distance of Backup2 from HQ}}{\text{c}} \tag{17}$$

Where distance of Backup2 from HQ = 39099.42 Km, $c = 3 \times 10^8$ m/s. Therefore one way Latency = 130.33 ms. For a single uplink and downlink communication, the latency will be around 260.66 ms.

8 Satellite link

The 4 satellites in this project now form a satellite network which are used for communication with the HQ and the ships. This network can be of many types, with mesh and star being the basic types. It also depends on the type of link they support and the connectivity to the Earth station. In mesh topology, every node communicates with every other node over different frequencies(FDMA). However, in Star topology, a single node(satellite) can only communicate with a single central node(also called the hub). So all the traffic from the earth station is directed to a central hub and the hub passes the traffic on to the respective satellite. This project makes use of mesh topology in order to allow all satellites to communicate with the HQ and ships.

9 Discussion

This section details some comments about different aspects of this project and may also offer some suggestion on how the current work can be improved.

- GEO satellites have been considered in this project due to their almost stationary position relative to the earth which makes simulation less complicated. However, LEO, MEO or a combination of the 2 would reduce latency massively, improve throughput and reduce path loss because they're at a lower altitude from the earth. They would also be a good option to use after analyzing data usage patterns in specific times/places where a higher data rate is needed.

- This project considers 4 satellites out of which 2 are considered to be backup satellites. This is done purely for the sake of redundancy and having an unlimited budget. Ideally, having 3 main satellites would suffice.

- Ku band has been used for this project but it is still vulnerable to bad weather and lower data rates. A combination of Ku and C band could be used in hurricane prone regions[7] and combination of Ku and Ka band can be used when high data rates are needed such as for weather/software updates, given good weather prevails.

- The calculated total bit rate of 27 Gbps is extremely high for satellite communication, especially for GEO satellites. While unrealistic, it might be possible to reach a little close to it by using high frequency bands like Ka or V, by increasing the modulation scheme to 64 QAM or higher, by using MIMO techniques or by using specially designed satellites. These are options that can be further looked into.

- While this project uses the 'one carrier per station-to-station link' traffic routing, generally 'one carrier per transmitting station' is often preferred despite having a larger capacity per channel since it is a better option than having a large number of carriers being relayed by the satellite. This also means that a star topology would be preferred over mesh, which could be considered while working with LEO or MEO satellites.

- While using FDMA, the efficiency decreases as the number of access increases. In case of Avancez Cruises, there will be many users at a single time. In that case, in order to compensate for performance degradation, power to the system can be increased or TDMA/CDMA or a combination of TDMA and CDMA can be used. Also, CDMA and TDMA face less interference noise while that is one of the main drawbacks of FDMA given that the guard band must be selected carefully.

- It is worth noting that while equation 5 gives the BW, this is a general value and does not take into consideration additional factors like roll-off and modulation/ filter effects. The BW also decides how many transponders will be needed on the satellite. Assuming 155 Mbps of traffic is processed by a single transponder, this setup would need about 85 transponders per satellite, while the average is 24-72 transponders per satellite [5].

- This project uses 2 separate antennas to transmit and receive data and ensure full-duplex communication. However, this could be replaced by a single antenna for both tasks, which would ensure duplex-communication and there will be maybe 0.5 - 1 second gap to make the switch between UL and DL communication. The other possibility is to have a split beam on the antennas on the HQ and the ships. This would mean that the the antennas are always listening to both the main satellites for information and traffic can be divided.

- Ideally, corrugated horn antenna works best with cross polarization [8] but was not considered in this project to prevent any case of polarization mismatch.

- The calculations done in Section 8 are done by hand and may vary based on some assumed parameters. For example, values like thermodynamic temperature, antenna noise temperature and effective input noise temperature are all assumed to be 290 K, as seen in the lectures. However this can be improved based in real time values.

- While calculating link budget, noise contribution from the sun and clouds/fog is not included. Adding those losses will lead to a more accurate result of carrier-to-noise ratio.

- During the Equinoxs in September and March, the sun crosses the equatorial plane and casuses a sun outage of GEO satellites for about 2-8 minutes. This happens when the satellite is lined up between the earth and the sun which increases the noise temperature from the sun and effects downlink communications to the earth[9].

References

[1] Maral, G., Bousquet, M., & Sun, Z. (2020). Satellite communications systems: Systems, Techniques and Technology. Wiley.

[2] Geostationary Satellite - an overview ; ScienceDirect Topics," www.sciencedirect.com. https://www.sciencedirect.com/topics/earth-and-planetary-sciences/geostationary-satellite

[3] "What's so special about phased array antennas?," viasat.com, Dec. 18, 2023. https://news.viasat.com/blog/corporate/whats-so-special-about-phased-array-antennas

[4] D. Happiness and I. Ezenugu, "Analysis Of Antenna Point Loss In Satellite Communication Link," vol. 3, 2019.

[5] "Introduction to Satellite Communications." Available: https://itso.int/wp-content/uploads/2018/04/Basics-of-Satellite-Communications.pdf

[6] A. Miller, "Satellite internet latency: What's the big deal?," viasat.com, Nov. 30, 2021. https://news.viasat.com/blog/satellite-internet/satellite-internet-latency-whats-the-big-deal

[7] D. I. Widjanarko and D. Gunawan, "A hybrid C/Ku-band high throughput satellite systems as an optimal design for Indonesia," 2017 International Conference on Signals and Systems (ICSigSys), pp. 168–174, May 2017, doi: https://doi.org/10.1109/icsigsys.2017.7967034.

[8] "What is a corrugated horn?," TICRA. https://www.ticra.com/corrugated-horn-design/

[9] V. B. R. Utami, I. MPB, and S. Romadhona, "Analysis the impact of sun outage and satellite orbit at performance of the telkom 3S satellite communication system," JURNAL INFOTEL, vol. 13, no. 3, pp. 134–142, Aug. 2021, doi: https://doi.org/10.20895/infotel.v13i3.626.

[10] International Telecommunications Union [ITU-R], "Characteristics of precipitation for propagation modelling," ITU, Jun. 2017. $https : //www.itu.int/dms - pubrec/itu - r/rec/p/R - REC - P.837 - 7 - 201706 - I!!PDF - E.pdf$

[11] International Telecommunications Union [ITU-R], "Specific attenuation model for rain for use in prediction methods," ITU, 2003. $https : //www.itu.int/dms_pubrec/itu-r/rec/p/r-rec-p.838-3-200503-i!!pdf-e.pdf$

[12] International Telecommunications Union [ITU-R], "Rain height model for prediction methods," ITU, Nov. 2013. $https : //www.itu.int/dms_pubrec/itu - r/rec/p/r - rec - p.839 - 4 - 201309 - i!!pdf - e.pdf$