Encelascope Ground Segment Final Report

Prepared by:
Advanced Space, LLC
1400 W 122nd Avenue, Suite 200
Westminster, CO 80234

Home Page: www.advancedspace.com

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1 Executive Summary

This analysis was performed by Advanced Space in support of and with funding from the ASTROBi Foundation. Additional analyses were performed studying the mission design and navigation for this mission, Encelascope, which are summarized in independent reports. The objective of Encelascope is to perform a low-cost mission that will send a spacecraft to Saturn's moon, Enceladus, in search of life in samples of water vapor and ice released from the moon's Tiger Stripes. Launching in 2026, the Encelascope spacecraft will take 9 years to travel to the Saturn system via an Earth-Venus-Venus-Earth (EVVES) gravity assist transfer. The spacecraft will be in the inner solar system for approximately 4 years and then will spend roughly 5 years cruising to Saturn. After arriving in the Saturn system, Encelascope will spend several years performing a series of gravitational assists using Saturn's moons to lower its orbit to roughly match that of Enceladus. The spacecraft will then do a capture burn to insert into orbit around Enceladus. Once in orbit around Enceladus, the science phase will begin.

Throughout the mission, the Encelascope spacecraft will need to maintain communications with Earth to command and receive data from the spacecraft. Deep space missions have traditionally used the Deep Space Network (DSN) for this purpose, but the growing congestion and extensive cost have made low-cost missions such as this prohibitive. Alternative ground segment options were evaluated for feasibility and cost and compared with using the DSN. These alternative options include commercial ground network providers as well as building and operating a phased array. Required uplink and downlink performance was first determined through link analyses and these metrics were used to evaluate these options. It was determined that Ka-Band would be the most suitable frequency for this mission and required performance was computed using the following communication system requirements:

1. The spacecraft / ground segment shall be able to achieve a 1 kbps data rate on both the uplink and the downlink.
2. The spacecraft shall have a 1-meter antenna that can both transmit and receive.
3. The spacecraft shall have a 10-Watt SSPA.
4. The uplink antenna shall have a transmit power below 1000 W.

From these requirements, it was determined that the downlink would require a ground segment G/T value of 57.27 dB/K. The required uplink ground segment EIRP is 124.35 dBm.

Based on the ascertained ground segment performance requirements, the cost of building and operating a phased array was studied as well as the potential for alternative commercial options. One alternative commercial ground segment provider was identified with performance near the requirements but would require additional upgrades to ground assets. The estimated cost of using this ground network was approximately $12.5 million. The cost and operation of the phased array was studied for several different downlink LNA cooling methods as well as various components selected based on high performance and low-cost. At the required data rates, the use of a phased array was estimated to cost between $11 and $19 million given the various trade studies considered. If the required data rate could be halved to 0.5 kbps, the estimated cost is then reduced to an estimated range of $7 to $10 million. It was assumed that if contact times could be doubled during the science phase of the mission, then halving the data rate would be feasible while still maintaining science data volume requirements. The data rate requirement was based on an expected contact time of 1.5 hours per day while in the science phase. A contact analysis showed that, in a worst-case geometry scenario, an average accumulated daily contact time of 3.3 hours could be achieved.

The cost of using the DSN to meet the mission's objectives was estimated to be between $15 to $17 million dollars. Comparing this to the cost of ground segment alternatives, these options are lower in cost but have a higher associated technical and schedule risk. Based on the analyses in this report, building and operating a phased array would offer the lowest cost solution, especially if the data requirements could be reduced. If the mission can accommodate and manage these risks, the recommendation would be to utilize the phased array for Encelascope. If additional funding is available to support the use of the DSN, the recommendation is to utilize this ground network as it would offer the least technical risk to the mission due to its proven heritage.

2 Link Analysis

The following section provides a detailed description of the analyses and computations used to determine the uplink and downlink parameters necessary to meet the mission's requirements. For the downlink, this involved analyzing the performance of a phased array. The uplink analysis considers a single ground aperture that can be used for both uplink and downlink. With the spacecraft parameters largely fixed by the requirements outlined below, the focus of this section is to determine the design of the ground segment necessary to meet the data rate requirements. The downlink also considers several different cooling methods which are used to lower the ground segment system noise temperature, specifically the Low Noise Amplifier (LNA). These cooling methods include uncooled (25°C), cooled (-50 to -75°C), and cryogenically cooled (<20°K). The performance and cost impacts of these different cooling methods are considered in later sections.

2.1 Mission Requirements / Assumptions

5. The spacecraft / ground segment shall be able to achieve a 1 kbps data rate on both the uplink and the downlink.
6. The spacecraft shall have a 1-meter antenna that can both transmit and receive.
7. The spacecraft shall have a 10-Watt SSPA.
8. The uplink antenna shall have a transmit power below 1000 W.

2.2 Link Analysis Computations / Assumptions

The following subsections describe the computations and assumptions used to generate the link analyses.

2.2.1 Frequency Selection

Traditional deep space frequencies are typically in the S, X, or Ka bands. For a deep space mission, defined as a mission going beyond 2,000,000 km from Earth, there are certain frequencies allocated within these bands that spacecraft must adhere to.

Table 2.1 - Defined frequencies bands for deep space communications

	Downlink (Space to Earth) (MHz)	Uplink (Earth to Space) (MHz)
S-Band	2290 - 2300	2110 - 2210
X-Band	8400 - 8450	7145 - 7190
Ka-Band	31800 - 32300	34200 - 34700

Each band has trade-offs that may or may not make it viable for a low-cost mission to Enceladus. For instance, S and X band components have more commercial components available which would help reduce cost. They also offer wider beam patterns to facilitate coverage and pointing constraints, but this is at the sacrifice of antenna gain performance. These bands are also less susceptible to atmospheric losses. Ka-Band offers improved performance at the cost of reduced beam widths, higher atmospheric losses, and less commercially available components. A preliminary study was performed on both the uplink and downlink to characterize which bands would be most feasible to use for this mission.

2.2.1.1 Downlink

To characterize the best frequency suited for the downlink, the number of nodes that would be needed in the phased array was estimated. The computations and assumptions used to generate the estimated number of nodes are the same ones outlined in the proceeding sections of this report. The required G/T value for each band was determined which allows the number of nodes to be estimated as a function of each node's antenna diameter. The thermal noise for each band was fixed using computations described in Section 2.2.4. Once the thermal noise was set, the required array gain and number of nodes were computed. The thermal noise for Ka-Band was computed using the results from section 4.1.3.2. For S and X band, which weren't as extensively studied, the system noise value was estimated using a low system noise figure of 1.0 dB. A summary of the inputs and results are shown below. From the results, it is clear that the S and X bands would require a prohibitive number of nodes or very large antennas. Ka-Band has the highest performance and, as a result, was used as the baseline downlink frequency (32.0 GHz) for the analyses presented in this report.

Table 2.2 - Inputs for downlink frequency trade study

Frequency Band	System Noise (K)	Atmospheric Noise (K) (20° elevation)	Operational Noise (System + Atmospheric)	Required G/T (dB/K)
S-Band	96.72 (Assumes system noise figure of 1.0 dB)	8.94	105.66	56.13
X-Band	96.72 (Assumes system noise figure of 1.0 dB)	10.92	107.65	56.36
Ka-Band	122.21 (Computed using uncooled components)	45.63	167.85	57.27

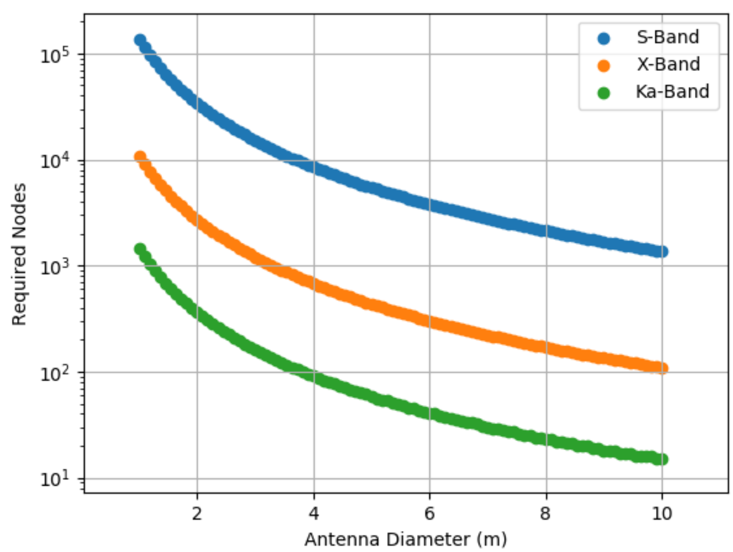

Figure 2.1 - Required nodes as a function of antenna diameter for deep space frequency bands

2.2.1.2 Uplink

When selecting the uplink frequency, two primary questions were considered:

1. What would be the best frequency to use for the 1-meter, high gain antenna

2. Could another frequency be used for monitoring the health and safety of the spacecraft using a low gain antenna?

2.2.1.2.1 Uplink on HGA

The first question can be answered by determining the Effective Isotropic Radiated Power (EIRP) required to close the link for a spacecraft in orbit about Saturn. The spacecraft receive antenna is assumed to be the same 1-meter transmit antenna and the receiver is assumed to have a noise figure of 3 dB for all uplink analyses. Based on these assumptions, the spacecraft communication system performance is fixed and the required EIRP can easily be computed. It was also requested that the transmit station have a transmit power below 1000 W. By setting this as the maximum value, the minimum required antenna size for the ground station can be determined.

Table 2.3 – Ground Station Diameter Estimate

Frequency Band	Spacecraft Antenna Gain (dBi)	Ground Station Transmit Power (W)	Required EIRP (dBm)	Required Ground Station Gain (dBi)	Estimated Ground Station Diameter (m)
S-Band	25.026	1000	123.20	63.21	81.1
X-Band	36.322		123.46	63.44	22.7
Ka-Band	48.491		124.36	64.37	6.2

Similar to the downlink results, an S-Band system would require a prohibitively large antenna or 81.1 meters in diameter. The X-Band antenna is a bit more reasonable at 22.7 meters in diameter, which would be possible if ASTROBi did want to consider that as an option, but this would also require the full 1000 W transmitter. Ka-Band again seems like the most realistic option, and the transmit power could be reduced for only small increases in the antenna diameter. For instance, if the antenna diameter was increased to 7.5 meters, the transmit power could be reduced to approximately 690 W.

2.2.1.2.2 Uplink on LGA

A low gain antenna is beneficial for several reasons. First, it drastically reduces your pointing requirements on the spacecraft as compared to a high gain antenna because of its wider beam pattern. This, in turn, reduces the attitude knowledge requirements on the attitude determination and control subsystem (ADCS) and the spacecraft's knowledge of its own state and the state of the Earth. For example, on the Cislunar Autonomous Positioning System Technology, Operations and Navigation Experiment (CAPSTONE) there is an LGA and HGA, but when using the LGA, the onboard ephemeris must be updated less frequently because of its wide beam pattern. The ephemeris is used to get the inertial state of the spacecraft and Earth which tells the spacecraft where to point.

To determine if an LGA was feasible to use for a spacecraft at Enceladus, a parameter sweep was run to determine the largest communication distance that could be achieved in each band. The parameters that were swept were the spacecraft's receive antenna gain and the ground station EIRP. The minimum and maximum sweep bounds were selected based on reasonably achievable values for each band. The results are shown in the figures below and summarized in a table. The results show a heatmap (left plot) of the total number of days during the mission that the spacecraft could conceivably communicate with Earth given the specified spacecraft antenna gain (y-axis) and ground station EIRP (x-axis). Additionally, the interplanetary transfer trajectory is plotted (right plot) with labeled flybys. The horizontal dashed line represents the maximum estimated communication distance corresponding to the parameters in the top right of heatmap plot.

S-Band

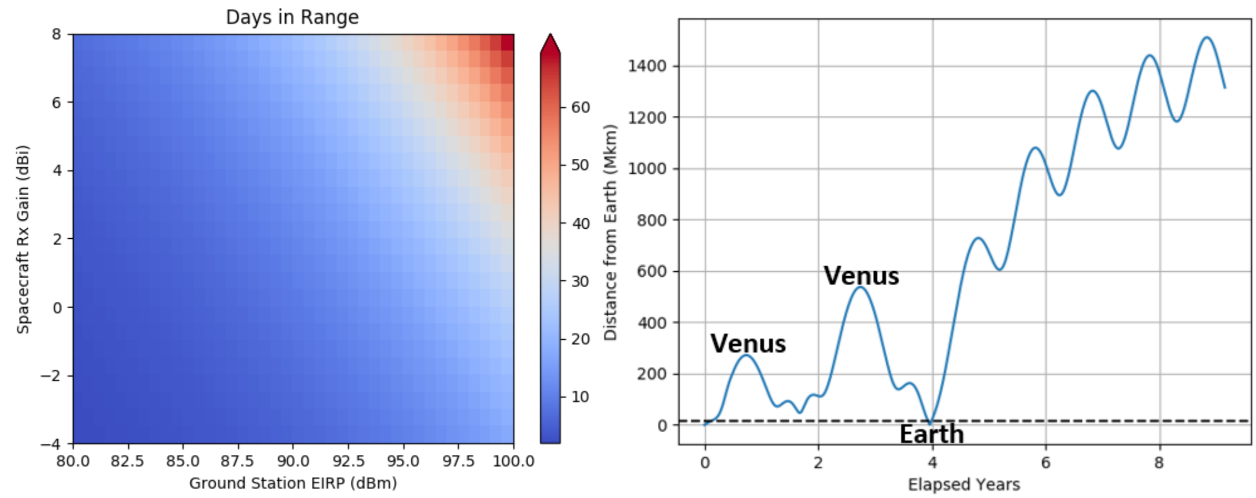

Figure 2.2 - S-Band LGA Communication Distances: days in range heatmap (left) and distance from Earth (right) for the interplanetary trajectory shown with maximum communication distance (dotted line)

X-Band

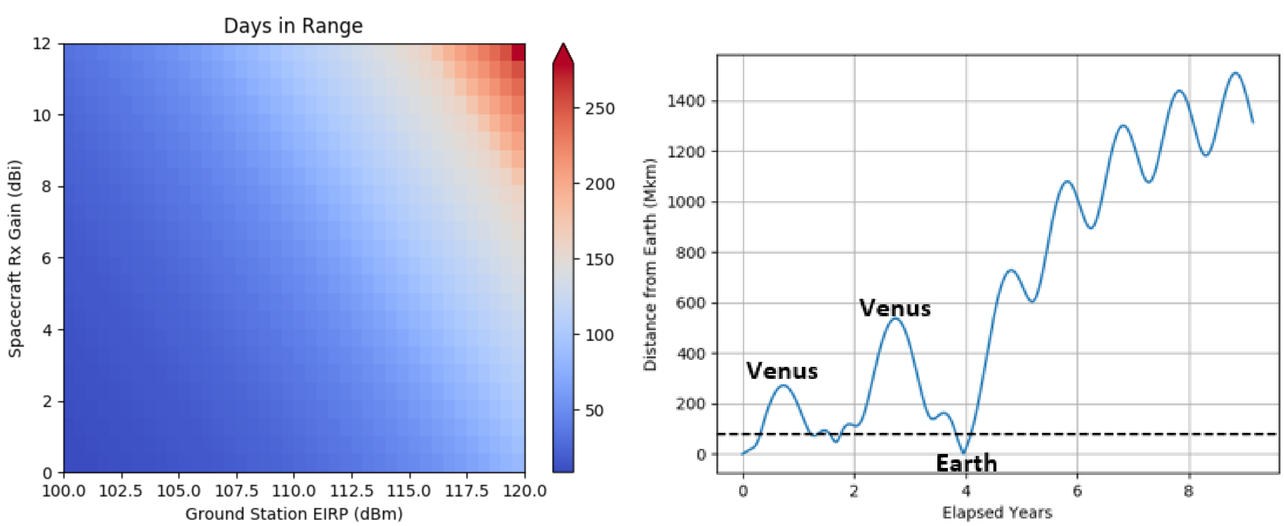

Figure 2.3 - X-Band LGA Communication Distances: days in range heatmap (left) and distance from Earth (right) for the interplanetary trajectory shown with maximum communication distance (dotted line)

Ka-Band

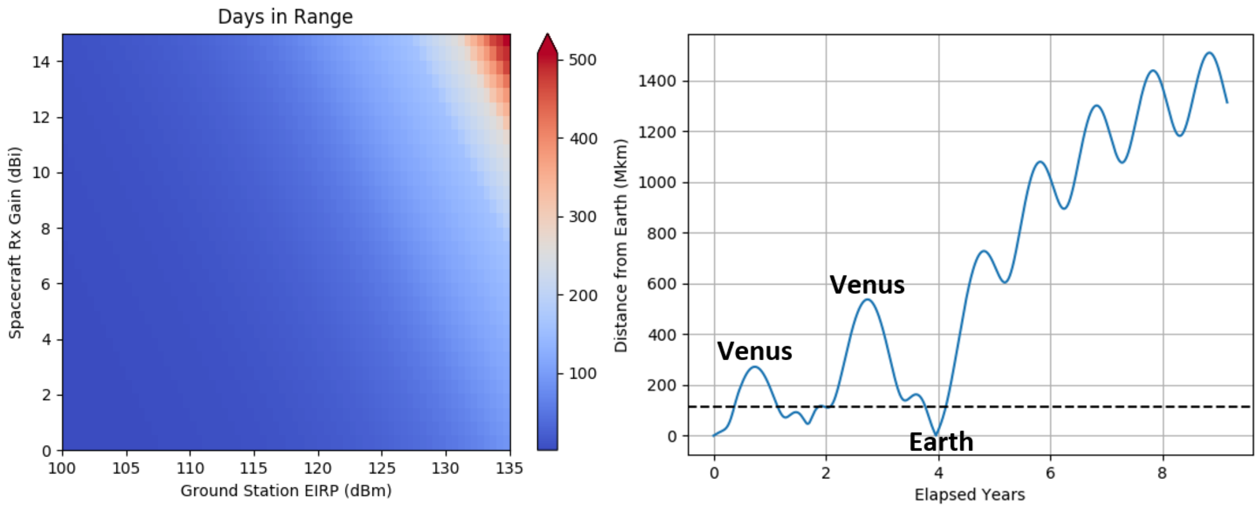

Figure 2.4 - Ka-Band LGA Communication Distances: days in range heatmap (left) and distance from Earth (right) for the interplanetary trajectory shown with maximum communication distance (dotted line)

Table 2.4 - Summary of the uplink LGA analysis

Frequency Band	Uplink Data Rate (kbps)	Maximum Spacecraft Antenna Gain (dBi)	Maximum Ground Station EIRP (dBm)	Maximum Communication Distance (km)	Days within Communication Range
S-Band	1.0	8	100	16.8e6	74
X-Band	1.0	12	120	76.5e6	318
Ka-Band	1.0	15	135	113.8e6	568
Ka-Band	0.1	15	135	365.6e6	1348

Given the above analysis, an LGA would only be useful for early in the mission and when the spacecraft returns to Earth for its final flyby. Using S and X band, it is expected that the LGA would only be of use for less than 1 year of the full 15-year mission duration. A Ka-Band LGA could be used for approximately 1.5 years. These distances could conceivably be increased by using a lower data rate, but even dropping the data rate by a factor of 10 still results in the LGA not expected to be able to close the link at Saturn. This result is also shown in the table above.

The use of a LGA is recommended to simplify the Launch and Early Operations phase of the mission. Acquiring the spacecraft on a narrow beam, HGA would be difficult, especially if the spacecraft doesn’t have an onboard method to resolve its state following separation. If the spacecraft cannot accurately determine where it is, then it is difficult to determine where to point its antenna. Additionally, when using a ground station designed to communicate with a spacecraft at Saturn, it’s likely that when the spacecraft is close to Earth, the designed EIRP of the ground station may overpower the spacecraft’s radio and damage it. The use of an LGA helps mitigate this issue, but it would also be beneficial if the transmitting ground station also has the ability to reduce its transmit power. The frequency of the low gain system would depend on the spacecraft’s ability to support additional communication equipment. S- and X-Band antennas would provide much wider beam patterns and less weather susceptibility than Ka but would require an additional radio that can operate in either of these bands. It would be most beneficial if the LGAs provided 4π steradian coverage, but this isn't strictly required. Gaps in antenna coverage could be mitigated through spacecraft ConOps following deployment such as a slow rotation that guarantees that the ground station would come into the antennas field of view following separation.

2.2.1.2.3 Conclusion

Based on the science data requirements, the mission would be nearly impossible to execute using S-Band and very difficult to complete in X-Band. These frequencies would require a large downlink array and uplink antenna. Using Ka-Band makes the communication aspect much more feasible, albeit the entirety of the mission would likely have to be completed using only a high gain antenna. Based on these studies, Ka-Band frequencies were used for all analyses shown in this report.

2.2.2 Link Distance

The planned arrival at Enceladus is June 2040 (October 2026 launch) with one year of science operations. The Saturnian distance from Earth was determined during this time frame in order to establish the link distance that would be used in the analysis. The distances are plotted in Figure 2.5 below. The maximum distance during this period, approximately 1.59 billion km, was used in the link analyses. The difference in the free space loss between the maximum and minimum expected distances is about 1.75 dB.

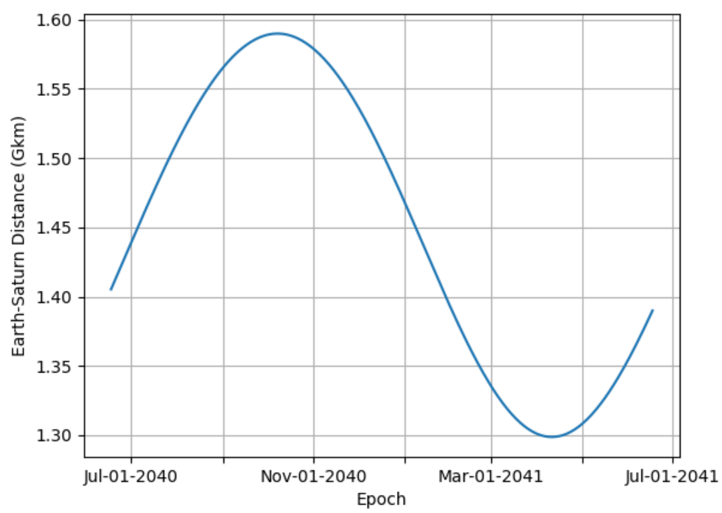

Figure 2.5 - Saturn's distance from earth for the year 2040

Free space loss is computed using,

$$L_{fsl} = 20\log_{10}\left(\frac{4\pi df}{c}\right)$$

where *d* is the spacecraft's distance from the ground station in km, *f* is the frequency of the signal in Hertz, and *c* is the speed of light in km/s.

2.2.3 *Antenna Gain*

2.2.3.1 Single Aperture Gain

The gain of a single aperture is computed based on its diameter using the equation

$$G_{dBi} = 10\log_{10}\left(\eta\left(\frac{\pi D f}{c}\right)^2\right)$$

where η is the antenna efficiency, D is the antenna diameter in meters, f is the frequency in Hertz, and c is the speed of light given as 299,792,500 m/s[1]. The figure below depicts the relationship between an antenna's gain and diameter assuming a Ka-Band frequency, 32 GHz, and an efficiency of 55%. An antenna's efficiency can vary depending on the type of antenna and the quality of manufacturing. When considering a parabolic reflector, efficiency losses can be attributed to spillover, feed blockage, and the surface properties of the reflector. Namely,

- Spillover – Radiation coming from the feed that extends beyond the size of the parabolic dish
- Feed Blockage – If a feed is inside on the concave side (reflector side) of the parabolic dish, this can block radiation from the surface of the reflective dish
- Surface Properties – If the dish has defects in its shape or uses poor materials this also impacts efficiency

Typical efficiency values range from 50-60%. The 55% efficiency value, used below and for all gain computations referenced in this report, is a commonly accepted value in industry. This is supported by using the DSN antennas as a reference point. The gain of a DSN 34-m parabolic antenna at 31.8-32.3 GHz is given as 78.4 dBi. Using the equation for gain shown above and solving for the DSN-34m efficiency equates to 53.22%.

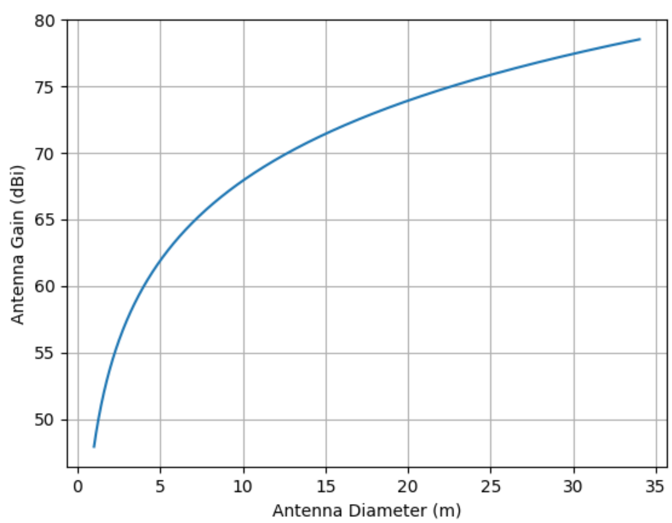

Figure 2.6 – Antenna gain as a function of diameter

[1] DSN Handbook, Module 214B, Equation 53

2.2.3.2 Phased Array Gain

The gain of the phased array is sum of gains of each individual aperture in the array. It is important that the sum is of the non-logarithmic gains. Similarly, the G/T value of the array can be computed in the same way using,

$$\left(\frac{G}{T}\right)_{Array} = \sum_{i=0}^{n} \left(\frac{G}{T}\right)_i$$

where *i* is each individual aperture's G/T value and *n* is the number of apertures in the array. The performance of the phased array is linear. If you consider the case where all nodes in the array have identical performance and you want to double the G/T value of the array, the array size would also need to be doubled. In its logarithmic form, this would translate to an approximate 3 dB increase in the G/T value. The figure below shows the diminishing returns from adding apertures to a phased array.

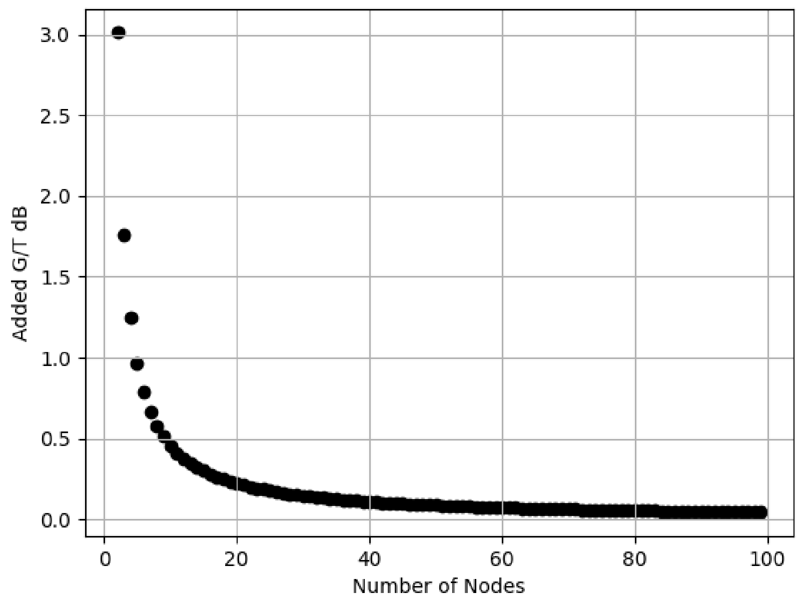

Figure 2.7 – Phased array dB increase for each added aperture (noise temperature fixed)

2.2.4 Operational Noise Temperature

The noise temperature is used to define the noise in a system. Fundamentally, the noise temperature can be broken down into two main categories for space to Earth communication: natural and hardware noise. Natural noise is a result of things like blackbody radiation from planets and stars, the Earth's atmosphere, etc. Hardware noise is a result of the equipment being used in the system. Splitting the noise into these two categories, the full operation noise temperature (T_{op}) can be modeled as

$$T_{op} = T_{sky} + T_{sys}$$

where T_{sky} is the effect of natural noise and T_{sys} is noise from the hardware. These two types of thermal noise will be different for the ground station and the spacecraft. They are described further for each in the sections below.

2.2.4.1 System Noise Temperature

The system noise describes the noise of hardware components in an RF chain. All physical components within the system will add to the overall noise of the system which makes it important to choose these components carefully. The noise temperature is considered for systems receiving the signal because in typical space to/from Earth communication systems, the signal being received is often very low in power and noise has a much more significant impact on the signal. For the receiving system, the signal will first get amplified by a Low Noise Amplifier (LNA) prior to be filtered and down converted to an intermediate frequency. The first LNA in the system has the largest impact on the overall system noise. Components following the LNA also have an impact, but it is much less pronounced. The system noise can be computed using the following equations,

$$T_{sys} = T_{ant} + T_{comp}$$

where T_{ant} is the noise in the system prior to the first RF component (antenna noise) and T_{comp} is the accumulated component noise. The antenna noise is given by,

$$T_{ant} = 290 \times 10^{\frac{L_{feed}}{10} - 1}$$

and the component noise is given by,

$$T_{sys} = L_{feed}\left[T_1 + \frac{T_2}{G_1} + \frac{T_3}{G_1 G_2} + \cdots + \frac{T_N}{G_1 G_2 \ldots G_{N-1}}\right]$$

T_n is the noise temperature of the nth component in the RF chain, G_n is the gain of the nth component in the chain, and L_{feed} is the loss prior to the first RF component. The gain of a component is the ratio of the power at the input of the component to the power at the output. This equation shows that the first component has the largest impact on the overall system noise temperature because noise temperature doesn't get degraded by other component gains. This is why the first component will typically be a LNA because LNAs can have low noise temperatures and moderate gain values. All noise prior to the first gain stage also gets amplified in each gain stage which is why it is important that noise prior to the LNA be minimized as much as possible. This is represented as L_{feed} in the equation above which accounts for losses such as feed and cabling losses prior to the LNA.

Typically, a spacecraft's communication system noise temperature is modeled as a single parameter called the noise figure. For commercially available radios, the vendor typically provides this value in the radio's data sheet. For the uplink analyses presented in this report, the noise figure of the spacecraft's radio is assumed to be 3 dB. This is equivalent to a noise temperature of approximately 288 K.

For a ground station, the system noise is usually combined with the receiving station's antenna gain to compute its G/T value. For commercially available ground providers, the system noise is measured for their ground stations and given to the user as this value. For the phased array, the RF backend of each aperture is being designed; therefore, the system noise must be computed using the equation above. Subsequent sections in this report describe selected components for the phased array receiving system and present the computed system noise values for those components.

2.2.4.2 Sky Noise Temperature

The sky noise temperature is a result of noise from blackbody radiation sources within the beam pattern of the receive stations antenna as well as the Earth's atmosphere. The blackbody sources primarily include planetary bodies, stars, and the cosmic microwave background (CMB) of space. The Sun is the primary star that must be considered when dealing with deep space missions in the Solar System. It can be an extremely noisy source if an antenna's beam pattern is pointing within the solar disk.

The sky noise temperature, T_{sky}, can be approximated using the equation

$$T_{sky} = T_{atm}(\theta) + \frac{T_{CMB}}{L(\theta)} + T_{BB}$$

where T_{atm} is the atmospheric noise at elevation angle Θ, T_{CMB} is the cosmic microwave background noise equivalent to 2.725 K, T_{BB} is the noise from other radiating black bodies, and $L(\Theta)$ is the atmospheric loss factor at elevation angle Θ. The noise effect when an antenna is pointed near radiating black bodies is covered in Section 2.2.4.2.1. The CMB noise gets attenuated by the Earth's atmosphere similarly to how the transmission signal gets attenuated. The atmospheric noise can be approximated using the equations given in the DSN Handbook, Module 104L, Appendix A.2. These are

$$T_{atm}(\theta) = T_p \left[1 - \frac{1}{L(\theta)}\right]$$

where T_p is the atmosphere's mean physical temperature approximated by,

$$T_p = 255 + 25 \times CD$$

The atmospheric loss factor is given by,

$$L(\theta) = 10^{\frac{A(\theta)}{10}}$$

where,

$$A(\theta) = \frac{A_{zen}}{\sin(\theta)}$$

The cumulative distribution (CD) is a number between 0 and 1 that represents the percentage of the year that a specified atmospheric zenith attenuation value (A_{zen}) is estimated to be valid for. For a CD of 0.90, it is expected that the zenith attenuation will be less than the provided value for 90% of year and exceed it for the other 10%. For reference, the CD values can generally be approximated as qualitative weather conditions. The DSN Handbook describes the following,

- CD = 0.0: clear dry, lowest weather effect
- CD = 0.25: average clear weather
- CD = 0.50: clear humid, or very light clouds
- CD = 0.90: very cloudy, no rain
- CD = 0.95: very cloudy, with rain

Substituting the above equations into the equation for T_{sky},

$$T_{sky} = [255 + 25 \times CD]\left[1 - \frac{1}{10^{\frac{A_{zen}}{10\sin(\theta)}}}\right] + \frac{T_{CMB}}{L(\theta)} + T_{BB}$$

For the analysis presented in this report, annual averaged values for Goldstone were used for the atmospheric zenith attenuation with a CD of 0.90. This attenuation value for Ka-Band is 0.239 dB. Thus, at an elevation angle of 20°, the atmospheric noise is approximately 41.24 K. Sky noise temperatures are shown below for varying CD values in Ka-Band.

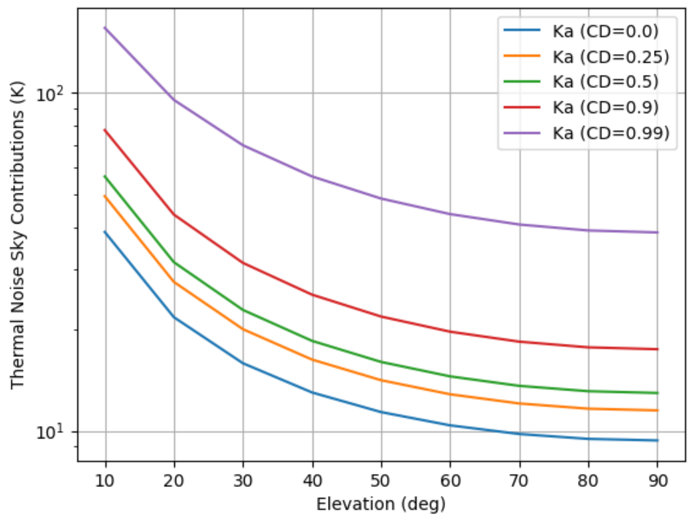

Figure 2.8 - Total sky noise temperature in Ka-Band for varying CD values

2.2.4.2.1 Other Sky Noise Contributions

The other primary noise source considered in the presented analyses are the noise sources of other bodies (planets and Sun) in the solar system. Noise from these bodies is increased when the beam pattern of the receiving antenna overlaps with the disk of these bodies. The equation for modeling this added noise is given by[2]

$$T_{body} = \left(\frac{T_k G d^2}{16R^2}\right) e^{-2.77\left(\frac{\theta}{\theta_0}\right)^2}$$

where T_k is the blackbody disk temperature of the body, *d* is body's diameter, *R* is the distance to the planet, Θ is the angular distance from the body center to the antenna beam center, Θ_0 is the half power beamwidth of the antenna, and *G* is the antenna's gain. This computed value gets added to the sky noise temperature when considering the link analysis. It isn't always included in the equation for sky temperature because the added noise from solar system bodies is often only applicable for specific, and often short, times throughout the mission. For a satellite at Enceladus, there are four scenarios to consider:

1. The spacecraft receiving a signal while pointed at Earth

[2] DSN Handbook, Module 105E, Equation 16

2. The spacecraft receiving a signal with the Sun in the beam pattern
3. The ground station receiving a signal with Saturn in the beam pattern
4. The ground station receiving a signal with the Sun in the beam pattern

All these cases were considered to determine the impact of each body on the noise temperature. When the spacecraft is receiving a signal from an Earth based ground station, it can be assumed that its antenna is directly pointed at Earth (*Θ*=0). Similarly, when a ground station is receiving from a spacecraft at Enceladus, it can be assumed that its antenna is pointed directly at Saturn. The only significantly varying geometry is the Sun with respect to both the ground station and spacecraft. To quantify the minimum angular distance between the Sun and the antenna beam center, the Sun-Earth-Probe (SEP) angle was plotted for the entirety of the mission (2026-2041). For a spacecraft in orbit about Saturn, the probe is assumed to be Saturn.

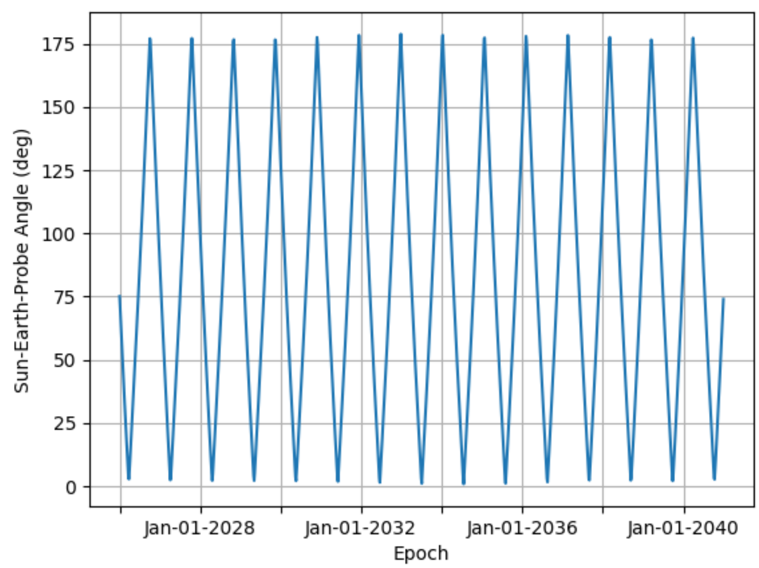

Figure 2.9 – Sun-Earth-Probe angle for a spacecraft at Saturn for the years 2026 to 2041

For angles near 180°, the Sun would be behind Earth while the spacecraft is receiving a signal from the ground. For angles near 0°, the Sun would be between the Earth and Saturn. Both of these scenarios would result in added noise, but with varying *R* values. The above analysis shows that the minimum angle that the antenna would get from the Sun's center is approximately 1°. The parameters used for each scenario to compute the added noise are given in the table below. The ground station gain and half-power beamwidth (HPBW) values used were the effective values of the phased array. Based on the cooling systems presented in Section 3.1.2, the gain and HPBW values vary slightly due to the changes in operation noise temperature for each system. With these differing values, the results below would vary slightly, but insignificantly; therefore, the gain and HPBW values used to compute the thermal noise contributions of solar system bodies were held fixed.

Table 2.5 - Summary of parameters used to compute added thermal noise when pointing at relevant Solar System bodies

Scenario	T_k (K)	G (dBi)	d (km)	R (km)	Θ_0 (deg)
Spacecraft pointing at Sun	5800	48.50	1.4e6	1.4e9	0.572
Spacecraft pointing at Earth	300	48.50	12,756	1.59e9	0.572
Ground Station pointing at Sun	5800	76.0	1.4e6	150e6	0.020
Ground Station pointing at Saturn	155	76.0	116,500	1.59e9	0.020

Using the above parameters, the off-pointing angle, Θ, was varied to determine the added thermal noise over very low angles. A table of computed values is also given with noise values at 0° and 1° for Θ. These tabulated values were used in the link analyses. When pointing at Earth and Saturn an off-pointing angle of 0° was used, and when pointing at the Sun an off-pointing angle of 1° was used. Of the four considered scenarios, the only situation in which appreciable noise is added is when the ground station is pointing at Saturn. This adds approximately 2 K of thermal noise on the ground station. When the Sun is between Earth and Saturn, which occurs once per year, the Sun can interrupt communications due to the increased noise. Because the Sun-Earth-Probe angle is never expected to drop below 1°, no outages are expected.

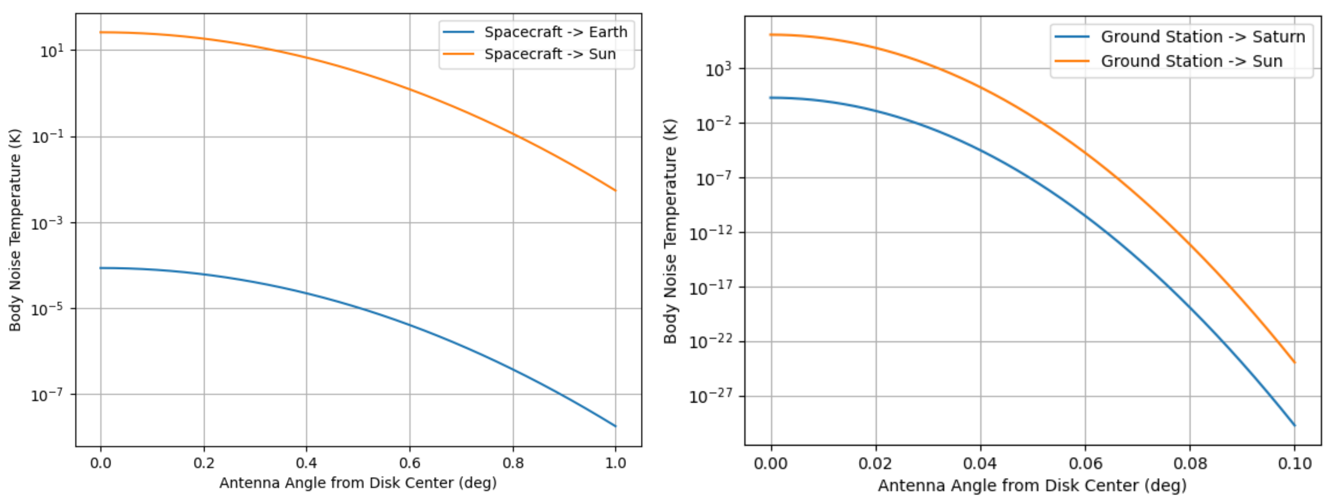

Figure 2.10 - Added spacecraft (left) and ground station (right) thermal noise when pointing near the specified body

Table 2.6 - Computed thermal noise values at the specified off-pointing angle

Scenario	Added Thermal Noise (K)	
	Off-Pointing Angle: 0°	**Off-Pointing Angle: 1°**
Spacecraft pointing at Sun	25.66	5.4e-3
Spacecraft pointing at Earth	8.5e-5	0
Ground Station pointing at Sun	1,257,133	0
Ground Station pointing at Saturn	2.07	0

2.2.5 Required Signal-to-Noise Ratio (SNR) and Margin

The required signal-to-noise ratio can be computed using the Shannon channel capacity. It is assumed that the coding scheme that can meet this limit will be used for both the uplink and downlink. The Shannon capacity is given by,

$$bps = B\log_2(1 + SNR)$$

where *bps* is the required bits per second, or maximum bit rate, supported by the channel, *B* is the bandwidth of the channel in Hz, and *SNR* is the signal-to-noise ratio of the received signal. To determine the required SNR that will meet the data rate requirements for both uplink and downlink, the above equation is solved for SNR. Additionally, 3 dB of margin is added because this is the theoretical upper limit on the bit rate which likely cannot be achieved in practice.

$$SNR_{req} = 10\log_{10}\left(2^{\frac{bps}{B}} - 1\right) + margin$$

The required bit rate on both the uplink and downlink is 1 kbps while the channel bandwidth is set to 10 kHz. This provides low spectral efficiency, 0.1 bps/Hz, but a higher energy per bit. Using these values to compute the required SNR yields -8.44 dB which was used for the analyses provided in this report.

2.2.6 Pointing Loss

Pointing loss is the result of either the ground station or spacecraft being unable to point its antenna's boresight directly at the object it is trying to communicate with. For a spacecraft, this is often limited by the pointing accuracy of the ADCS system, such as the spacecraft's attitude knowledge or reaction wheel jitter. On the ground station, pointing inaccuracies are often a result of the ground's state knowledge of the spacecraft (navigation uncertainty). The ground station pointing can also be affected by natural weather, such as wind.

For the presented link analyses, the pointing error was computed using the equation[3],

$$L_{ptn} = 10\log_{10}\left(e^{\left(-2.773\left(\frac{\theta_e}{\theta_{3db}}\right)^2\right)}\right)$$

where Θ_e is the pointing error and Θ_{3db} is the half-power beamwidth of the antenna. For all presented analysis in this report, it was assumed that the pointing error was 10% of the half-power beamwidth which results in a constant pointing loss of approximately 0.12 dB for both the spacecraft and ground station.

2.2.7 Atmospheric Loss

The atmospheric loss affecting the signal is given by[4],

[3] DSN Handbook, Module 104L, Equation A-3

[4] DSN Handbook, Module 104L, Equation A5

$$A(\theta) = \frac{A_{zen}}{\sin(\theta)}$$

where A_{zen} is the zenith atmospheric attenuation and Θ is the elevation angle of the satellite with respect to the ground station. A_{zen} is affected by both the global atmospheric conditions and the frequency of the signal. Higher frequency signals are attenuated more by the atmosphere than lower frequency signals. Measured annual values of the zenith attenuation are provided in the DSN Handbook[5]. These measured values are presented for various cumulative distribution (CD) values (between 0 and 1.0) which represent the percentage of the year that the zenith value is estimated to be valid for as previously described in section 2.2.4.2. For the analysis presented in this report, annual averaged values for Goldstone were used for a CD of 0.90. The associated zenith attenuation value for Ka-Band is 0.239 dB.

2.2.8 Insertion Loss

Insertion losses are passive losses from RF components in the communication chain. For the analyses in this report, only insertion losses on the spacecraft were considered. It was assumed that both the radio receiver and transmitter would connect directly to the antennas via one foot of coax cabling and two connectors. Losses from these components are based on low-loss COTS cabling providers. Based on these providers, it was assumed that Ka-Band coax cabling would have a loss of 0.7 dB/ft and the connectors would have 0.2 dB of loss each. Thus, the insertion loss used for the analyses presented in this report is 1.1 dB.

2.2.9 Modulation Loss

For the analyses presented in this report, it is assumed that both the uplink and downlink carrier signal is only being modulated with data and not a ranging signal. Due to the low data rate requirements, a subcarrier would likely be required to move the data harmonics away from the carrier signal. Using this information, the uplink and downlink modulation losses are given by,

$$L_{mod_{UL}} = 10\log_{10}\left(2J_1^2(\theta_D)\right)$$

$$L_{mod_{DL}} = 10\log_{10}(\cos^2(\theta_D))$$

where J_1 is the first order Bessel function and Θ_D is the telemetry modulation index. For this mission, a telemetry modulation index of 1.2 degrees was selected to try and maximize the power in the data signal as much as possible while not overly suppressing the carrier signal. With this modulation index, the modulation loss for the uplink and downlink data are -3.04 and -0.61 dB, respectively.

2.3 Link Analysis Overview

The above calculations and assumptions were used to generate link analyses which are summarized below.

[5] DSN Handbook, Module105E, Table 16

2.3.1 Uplink

Using the above equations and assumptions, a summary of the uplink analysis is presented below. The uplink analysis assumes that only data, and no ranging, is modulated onto the carrier. The spacecraft has a 1-meter parabolic antenna and is assumed to have a receiver with a noise figure of 3 dB. Using these spacecraft parameters, the required ground station EIRP value to meet the 1 kbps requirement is determined. Because EIRP is dependent upon both the transmit power and the antenna gain, Section 2.3.1.1 presents a figure showing how these parameters could be varied to meet the required EIRP.

Table 2.7 - Uplink Analysis Summary

Parameter	Units	Value	Comments
Slant Range	Km	1.59e9	Farthest June 17^{th} 2040-2041 Saturn distance
Uplink Frequency	MHz	34,450	Deep Space Ka-Band
Transmit Station Parameters			
Nominal EIRP	dBm	124.35	Required for 3 dB margin
Tx Pointing Loss	dB	-0.12	10% of HPBW
Antenna Elevation	deg	20	20° worst case
Atmospheric Loss	dB	-0.70	Attenuation of signal through atmosphere
Signal Parameters			
Data Modulation Loss	dB	-3.04	Data modulation on carrier
Effective EIRP	dBm	120.49	Nominal EIRP – Losses
Free Space Loss (FSL)	dB	-307.16	FSL = (c/(4*pi*R*freq))^2
Receive Station Parameters			
Antenna Gain	dBi	48.49	1.0 meter parabolic at Ka-Band
Rx Pointing Loss	dB	-0.12	10% of HPBW
RF Passive Loss	dB	-1.10	Cabling/Connector losses
Antenna Thermal Noise	K	2.725	Cosmic Microwave Background
Receiver Noise Figure	dB	3.0	Estimated
Equivalent Rx Noise Temp	K	288.63	No = 290*(10^(NF/10)-1)
System Noise Temp	K	291.35	Antenna + Receiver Thermal Noise
Noise Power Density	dBm/Hz	-173.95	10log10(k_{bolz}*Sys No)
Receive G/T	dB/K	23.85	Gain – 10log10(Sys No)
Carrier Parameters			
Data Bit Rate	kbps	1	Requirement
Results			
Bandwidth (BW)	Hz	10,000	Power efficient bandwidth
Received Signal Power	dBm	-139.40	$EIRP_{eff}$ + $Gain_{RX}$ + Losses
Received Noise Power	dBm	-133.95	No + 10log10(BW)
Received SNR	dB	-5.44	Signal Power – Noise Power
Required SNR	dB	-8.44	Shannon Capacity + 3 dB
Uplink Margin	dB	3.0	Received – Required SNR

2.3.1.1 EIRP Study

From the uplink analysis it was determined that an EIRP of approximately 124.35 dBm would be required to meet the 1 kbps uplink requirement. EIRP is a combination of gain and transmit power of the ground station. The plot below shows the required power needed to meet the EIRP requirement as a function of antenna diameter. For reference, the associated gain, computed using the equation given in Section 2.2.3.1, is also shown.

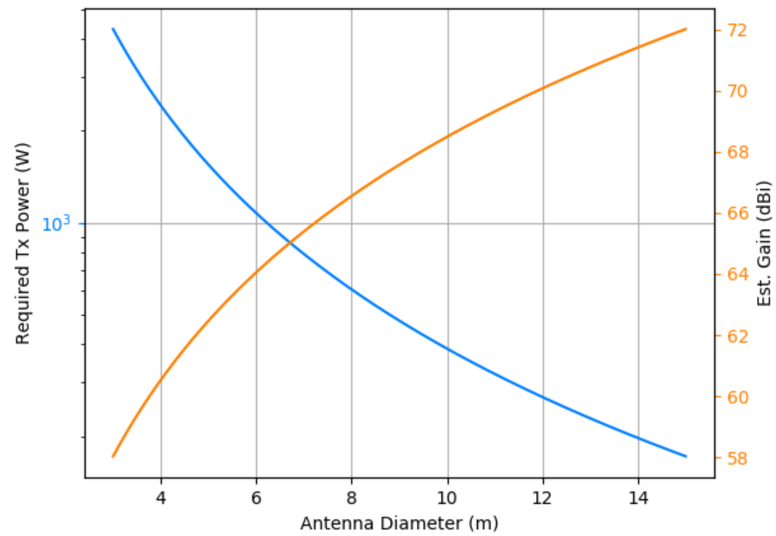

Figure 2.11 - Required transmit power to achieve required EIRP as a function of antenna diameter

2.3.2 Downlink

Using the above equations and assumptions, a summary of the downlink analysis is presented below. Similarly to the uplink, the downlink analysis assumes that only data, and not ranging, is modulated onto the carrier. The spacecraft has a 1-meter parabolic antenna and a 10W SSPA. Using these spacecraft parameters, the required ground station G/T value to meet the 1 kbps requirement is determined. The analysis shows that the required G/T is approximately 57.30 dB/K.

Table 2.8 - Downlink Analysis Summary

Parameter	Units	Value	Comments
Slant Range	km	1.59e9	Farthest June 17th 2040-2041 Saturn distance
Downlink Frequency	MHz	32,000	Deep Space Ka-Band
			Spacecraft Transmit Parameters
Transmitter Power	dBm	40	10 Watt. 10log10(Tx Power) + 30
Passive Losses	dB	-1.1	Cabling/Connector losses
Antenna Gain	dBi	47.91	1.0 meter parabolic at Ka
Tx Pointing Loss	dB	-0.12	10% of HPBW
Nominal EIRP	dBm	86.69	Tx Power + Antenna Gain + Tx Losses
			Signal Parameters
Data Modulation Loss	dB	-0.61	Data modulation on carrier
Effective EIRP	dBm	86.08	Nominal EIRP – Signal Modulation Loss
Free Space Loss (FSL)	dB	-306.58	FSL = (c/(4*pi*R*freq))^2
			Receive Station Parameters
Receive Gain	dBi	79.55	Required for 3 dB margin
Rx Pointing Loss	dB	-0.12	10% of HPBW
Antenna Elevation	deg	20	20° worst case
Atmospheric Loss	dB	-0.70	Attenuation of signal through atmosphere
Sky Noise Temp	K	45.63	Cosmic Microwave Background + Atmosphere + Planetary Body noise
System Noise Temp	K	122.21	Assumes uncooled, performance optimized. Based on component selection
Operational Noise Temp	K	167.84	Sky + System Thermal Noise
Noise Power Density	dBm/Hz	-176.35	10log10(k_{bolz}*Sys No)
Receive G/T	dB/K	57.30	Gain – 10log10(T_{op}). Required for 3 dB margin
			Carrier Parameters
Data Rate	kbps	1	Requirement
			Results
Bandwidth (BW)	Hz	10,000	Power efficient bandwidth
Received Signal Power	dBm	-141.79	$EIRP_{eff}$ + $Gain_{RX}$ + Losses
Received Noise Power	dBm	-136.35	No + 10log10(BW)
Received SNR	dB	-5.44	Signal Power – Noise Power
Required SNR	dB	-8.44	Shannon Capacity + 3 dB
Downlink Margin	dB	3.0	Received – Required SNR

3 Ground System Design

This section outlines designs for a single transmit and receive antenna as well as a phased array downlink only concept. Although the transmit and receive antenna is designed for both, only the transmit (uplink) design is considered and it is assumed that the downlink (receive) design would mimic the design outlined in the downlink section.

3.1 Phased Array Concept

To meet the mission requirements for receiving telemetry from the spacecraft, it was proposed that a phased array design would be an option to meet both performance and cost goals. Arraying antennas is a concept that involves combining the performance of several smaller antennas to equate to the performance of a much larger one. This concept has been used for deep space missions in the past to increase the throughput of telemetry from the spacecraft. The idea is that the signal being transmitted by the spacecraft is received by each aperture in the array at much lower power levels than would be received by a much larger antenna. Each of the lower power signals at each aperture is combined such that the signal power is raised above the noise floor and the signal can be decoded. The proposed method presented here combines these signals digitally using digital equipment after the signals have been down converted to an intermediate frequency. Using digital processes to beamform the array, signals can be constructively combined to resolve the signals on the ground.

Traditionally, analog beamforming has been used to create this phased array concept, but with advances in digital technology, digital beamforming can provide significant advantages over its analog counterpart. While analog arrays can be simpler and more robust, calibration of these components can be difficult. Analog components, namely the phase shifter, can depend significantly on temperature making it difficult to accurately calibrate both phase and amplitude due to the calibrations drifting with temperature and aging. Additionally, this would limit the array to a single beam, restricting the potential applications for the array. By using digital beamforming, the array would be much more flexible and would allow for several beams to be formed and used for several applications simultaneously. Calibration is simplified as it can be done in real time and automated removing any temperature or drift effects that may exist. The downside of digital beamforming is the additional cost and degraded lifetimes of these components, which result in added cost of building and maintaining the array.

Unfortunately, this same concept is difficult to achieve for uplink to the spacecraft. To achieve a successful uplink array, the signals from each aperture must be aligned either on the ground or at the spacecraft. Current technology and systems constraints make it difficult for this to be done at the spacecraft and thus must be done on the ground side. Instabilities, such as electronic stability and atmospheric variations, make this difficult. This is currently being studied in the field but would likely need further maturation before use in deep space communication applications.

3.1.1 Downlink System Design

The following describes the proposed downlink system design with suggested commercial options for each component. Many of the suggested components are connectorized and could be combined into a single module and housed together. This would help reduce the noise of the overall system and make the design more compact. Each node in the phased array is assumed to use identical designs. The highlighted components are those that were used to compute the phased array cost and performance given in Section 4 per the trade study outlined in Section 4.1.3.1 (performance vs. cost). The blue highlight represents the component selected for highest performance while the green highlight represents selection for low cost. A purple highlight represents a component with both the highest performance and lowest cost.

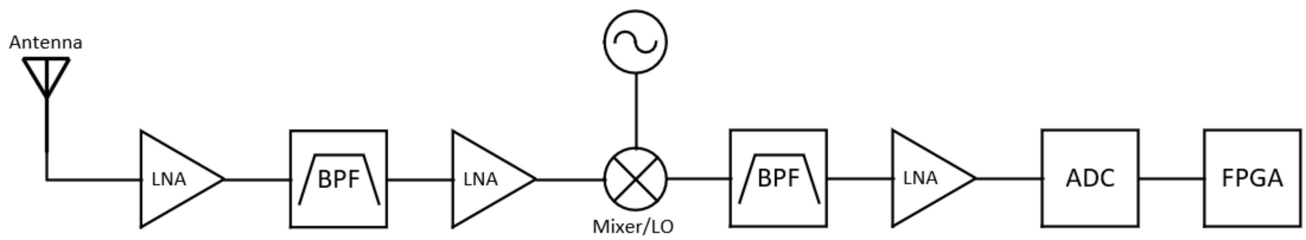

Figure 3.1 – Phased Array, single node (Downlink) system block diagram

3.1.1.1 Antenna

The antenna consists of the parabolic reflector, the feed, and any structural equipment for supporting them. The reflector focuses the incoming signal into the feed where it can then be processed by the downstream components. Several commercial vendors were inquired about antennas of varying sizes for the array. A list of the most comprehensive products is shown below with cost estimates. These quotes were used as a baseline to estimate the antenna cost in Section 4.1, but the provided information is given below for convenience.

Table 3.1 - Summary of antenna products received from vendors

Vendor	Direction	Antenna Diameter (m)	Price
Vendor 1	Uplink/Downlink	3.5	$200,000
	Uplink/Downlink	4.9	$225,000
	Uplink/Downlink	5.6	$300,000
Vendor 2	Uplink/Downlink	7.3	$515,677
Vendor 3	Downlink Only	3.8	$225,000
Vendor 4	Downlink Only	5.5	$800,000
Vendor 5	Uplink/Downlink	13.5	$3,300,300

3.1.1.2 Cooled RF LNA

The first LNA in the downlink chain is one of the most important components as it essentially sets the noise for the entire system as described in Section 2.2.4.1. This component should have the highest gain and lowest noise figure possible to keep the system noise low and improve SNR of the received signal. Additionally, it should be mounted as close to the feed as possible to reduce any noise/loss impacts between these two components. This component can also be cooled to further improve performance. The table below lists the recommended LNAs to use for this application. Note here that there are several highlights of the same color because of the cooling trade study that was conducted. The highlighted component was selected for the cooling type mentioned under the Type column header.

Table 3.2 - Recommended LNAs

Company / Product #	Type	Price (Quantity)	Input Frequency (GHz)	Frequency Type	Noise Figure (dB)	Gain (dB)	Data Sheet / Notes
Low Noise Factory - LNF-LNC23_42WB	Cryogenic - Connector	Restricted	23-42	RF	0.12	28	Link
TTI - TTI-CLNA-2040	Cryogenic - Connector	Restricted	20-40	RF	0.25	32 @ 32 GHz	Link1 Link2
RFLambda - R26G34GSMB	Uncooled/Cooled - Connector	Restricted	26-34	RF	2 @ 85C 1.5 @ 25C 0.6 @ -55C	18 @ 85C 19 @ 25C 20.3 @ -55C	Link
RFLambda - R24G40GSB	Uncooled/Cooled - Connector	Restricted	24-40	RF	1.25	19.5	Link

3.1.1.3 RF Band Pass Filter

The radio frequency band pass filter (BPF) is used to filter any unwanted amplified signals coming in through the antenna. The filter is ideally centered around the carrier frequency of the incoming signal and has the same bandwidth. For this ground application, it is desired that the system can receive all signals in the deep space Ka-Band which is 500 MHz wide. A smaller bandwidth would attenuate desired signals in this band. The deep space Ka-Band is 31.8 to 32.3 GHz, which is ideally what the filter's passband would also be. Additionally, a good filter would have high rejection levels (40+ dB) outside of this band to reduce the noise and trim the signal. When searching the commercially available components, there were not many BPFs that met this specification. The closest match was the filter listed below by Anatech Electronics.

Table 3.3 - Recommended RF Band Pass Filters

Company / Product #	Type	Price (Quantity)	Center (GHz)	Passband (GHz)	Bandwidth (MHz)	Insertion loss (dB)	Attenuation / Rejection (dB)	Data Sheet / Notes
Anatech Electronics - AE32050B11851	RF Filter - Cavity	Restricted	32.05	32-33	1000	1.0	60	Link

3.1.1.4 Uncooled RF LNA

The second LNA in the chain is less important than the first and is used to further amplify the signal after it has been filtered. Amplifying the signal a second time helps further reduce the noise effects of downstream components which usually have negative gains. This LNA is assumed to be uncooled and the same LNAs in Table 3.2 that are labeled as uncooled are used for this application.

3.1.1.5 Mixer/Local Oscillator

The mixer and local oscillator are used to down-convert the RF signal into an IF signal. This down conversion is required to be able to sample the signal with a high-speed analog-to-digital converter (ADC) and not experience aliasing. The incoming RF signal has a frequency of approximately 32 GHz. The IF frequency can vary depending on the desired downstream hardware, but for this application we are assuming an IF frequency of 1875 MHz. This IF frequency was chosen because we are assuming a minimum ADC sampling rate of 1.5 Gsps. The Nyquist zone boundaries for this sampling rate occur at $f_s/2$, f_s, and $3f_s/2$, or 750 MHz, 1500 MHz and 2250 MHz, respectively. The third Nyquist zone will contain a spectral replica of the signal which can be used by the ADC to sample; therefore, the IF should be centered in this zone that extends from 1500 MHz to 2250 MHz.

Knowing these two frequencies helps select the necessary local oscillator because

$$IF = RF - LO$$

Using the above equation, it can be observed that the local oscillator would need to have a frequency of 30.25 GHz. The following recommendations break out mixers and local oscillators separately. A potentially viable out of the box solution by SignalCore is also listed as it was difficult finding local oscillators that operate at the required frequency. A few Waveguide Gunn Oscillators were found that have the stated specifications to meet the required frequency, but there is a question as to whether these would be stable enough to successfully down-convert the signal to the accuracy required. Determining whether they were stable enough was not studied. An additional alternative, that is not presented here, would be to use a multi-stage down conversion with several mixer and LO combinations. This would require LOs at a lower frequency and would be more widely available in the commercial market. The trade-off would be the need for more components and potentially more cost. It would also likely mean added loss/noise to the system.

Table 3.4 - Recommended Mixer/LOs

Company / Product #	Type	Price (Quantity)	Input Frequency (GHz)	Output Frequency (GHz)	Conversion Loss (dB)	Noise Figure (dB)	Data Sheet / Notes
Mixers							
Pasternack - PE86X1010	Connector	\$3,290 (1) \$3,026 (5-9)	24 - 40	DC-18	8	8*	Link
Fairview Microwave - FMMX1031	Connector	\$1,530 (1) \$1,408 (5-9)	24-32	DC-8	10.5	10.5*	Link
Fairview Microwave - FMMX1010	Connector	\$3,145 (1) \$2,893 (5-9)	24-40	DC-18	8	8*	Link
Local Oscillators							
Fairview Microwave - FMWGN1011	Waveguide	\$8,533 (1) \$7,850 (5-9)	N/A	35 GHz +/- 3 GHz	N/A	N/A	Link
Fairview Microwave - FMWGN1010	Waveguide	\$9,000 (1) \$8,280 (5-9)	N/A	35 GHz +/- 3 GHz	N/A	N/A	Link
Mixer/LOs							
Signalcore – SC5319A/SC5320A	Connector Module	Restricted	20 - 40	0.1-4.5	6	6*	Link May still required an additional external

							LO to mix down to ~2 GHz

*Noise Figure assumed to be equivalent to conversion loss

3.1.1.6 IF Band Pass Filter

The down-converted signal gets filtered one last time by the IF BPF. This filter would ideally have a 3 dB bandwidth of 500 MHz and high attenuation at frequencies in the other Nyquist zones. For instance, the second Nyquist zone is centered at 1125 MHz and for a 500 MHz wide signal there would potentially be some signaling near 1375 MHz that could get into the ADC as unfiltered. This data would be replicated data from the third Nyquist zone and could potentially interfere with data interpretation. The replicated signals in the other Nyquist zones would ideally be filtered off completely. This means that the filter should have high attenuation at 500 MHz on either side of the center frequency of 1875 MHz. No exact matches for IF filters were found, but one filter, listed below, nearly met all these specs.

Table 3.5 - Recommended IF Band Pass Filter

Company / Product #	Type	Price (Quantity)	Center (MHz)	Passband (MHz)	Bandwidth (MHz)	Insertion loss (dB)	Attenuation / Rejection (dB)	Data Sheet / Notes
Anatech Electronics - AM1900B1527	IF Filter - Ceramic, Surface Mount	Restricted	1900	1675-2125	450	2.0	30	Link

3.1.1.7 IF LNA

The intermediate frequency LNA provides one last signal amplification stage prior to being converted into a digital signal. An ideal LNA would again have a low noise figure with a high gain, but these parameters are not as important for this LNA as the first two. There appear to be many commercially available components that would meet the needs for this application. Recommended IF LNAs from several providers are shown in the table below.

Table 3.6 - Recommended IF LNAs

Company / Product #	Type	Price (Quantity)	Input Frequency (GHz)	Frequency Type	Noise Figure (dB)	Gain (dB)	Data Sheet / Notes
RF-Lambda RLNA01G02G60	Connector	Restricted	1-2	IF	0.5	63 @ 25C 64 @ -40C	Link Includes Heatsink
RF-Lambda RLNA18M19M	Connector	Restricted	1.8 - 1.9	IF	1.0-1.2	27	Link Includes Heatsink
Fairview Microwave - FMAM1068	Connector	$929 (1-4) $836 (10-24)	0.5 - 4	IF	0.7	24	Link
Fairview Microwave - FMAM1009	Connector	$881 (1-4) $793 (10-24)	0.01-3	IF	1.4	34	Link
Pasternack - PE15A1009	Connector	$837 (1-4) $753 (10-24)	0.01-3	IF	1.4	34	Link
Pasternack -	Connector	$393 (1-9)	0.5-3	IF	2	14.5	Link

PE15A1017		$354 (25-49)					
Pasternack - PE15A1019	Connector	$1,175 (1-4) $1,058 (10-24)	1-2	IF	0.8	40	Link
NuWaves - HILNA-LS	Connector	$2,390 (1)	1-3	IF	1.7	50	Link

3.1.1.8 Analog-to-Digital Converter

The ADC is where the signal gets converted from an analog signal into a digital one. This allows the signal to be digitally processed by the FPGA. Traditionally in a ground network, signals will be processed in their analog form, but given the aforementioned benefits of processing them digitally, the ADC is necessary. The recommended ADC is given below.

Table 3.7 - Recommended ADCs

Company / Product #	Price (Quantity)	Sample Rate (Gsps)	Max Input Signal (GHz)	Bit Resolution (bits)	Data Sheet / Notes
TI - ADC12J1600, ADC12J2700	$1,100 (1)	2.7	3	12	Link

3.1.1.9 Field Programmable Gate Array

The FPGA performs all the digital signal processing of the incoming signal. Many space-based radios now use FPGAs for this same purpose. These radios can both process and generate the signals. By using an FPGA, the total amount of digital components can be reduced because the logic blocks in the FPGA can be programmed for many purposes. Advanced Space doesn't have much experience with FPGAs, so the recommended FPGA is the recommendation made by ASTROBi.

Table 3.8 - Recommended FPGA for signal processing

Company / Product #	Price (Quantity)	Data Sheet / Notes
Xilinx - XC7K70T-1FBG484C	$200 (1)	Link

3.1.2 Cooling System Designs

The cooling of RF components significantly impacts their performance. While the cost of cooling systems may be expensive, the performance benefits can significantly outweigh these costs by requiring fewer nodes in the array. Three different cooling methods were analyzed to determine the impacts of performance and cost of each. These methods are described below with their associated costs analyzed in the proceeding sections.

For each of the described cooling systems, it was assumed that only the first LNA would be affected in the downlink RF chain. Although more components may be cooled if desired, the system noise is primarily set by the first LNA and cooling further components would have little impact on the overall noise temperature.

3.1.2.1 Uncooled System

An uncooled system is the simplest configuration. Components are left at the environment temperature, which for the analyses presented here is assumed to be 25 ^{o}C. This is the most cost-effective option, but can result in significantly degraded performance, specifically of the LNA, and drastically raises the system noise temperature of the ground system.

3.1.2.2 Cooled System

For the cooled system, a Peltier cooler is used to remove heat from the LNA. The Peltier cooler is combined with dry Nitrogen which helps remove moisture from the system. Housing around the LNA will be required to keep the nitrogen in the system. With this method, it is expected that the temperature of the LNA can get down to between -50 °C and -75 °C. Additionally, a storage container will also be needed to store the Nitrogen.

3.1.2.3 Cryogenically Cooled System

A cryogenically cooled system uses liquid Helium to drastically cool the LNA to below 20 °K. This system requires housing and a Dewar for the purposes of cooling the system and storing the liquid Helium. At these temperatures, a specialized cryogenic LNA is needed, which can be expensive. This system also requires additional equipment such as a cold head, compressor, drive cable, and Helium lines. The cold head uses a Gifford-McMahon refrigeration cycle which uses expansion to further cool the liquid Helium as it enters the housing containing the LNA. As the cooled liquid enters the system, a low-pressure valve opens to remove heat from the system. This process repeats to keep the LNA cool. The compressor is used to drive liquid Helium through the lines for continued operation.

3.1.3 Uplink System Design

The following describes the proposed uplink system design with proposed commercially available components and their functions. The highlighted components are those that were used to compute cost and performance given in Section 4.

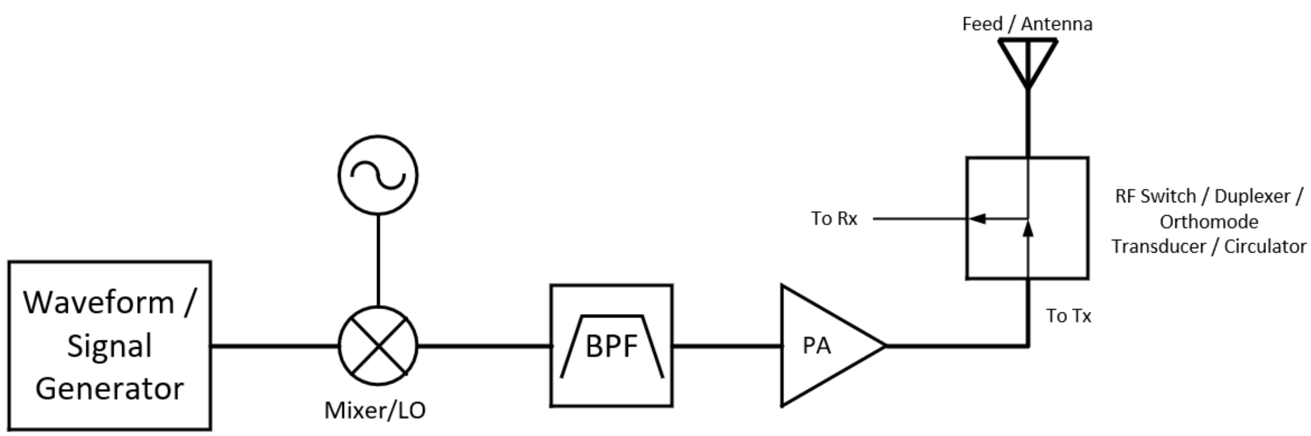

Figure 3.2 – Transmit antenna system block diagram

3.1.3.1 Waveform / Signal Generator

The waveform/signal generator is the source of the signal creation. It generates a carrier wave at an intermediate frequency that then gets modulated with the necessary signals to be sent to the spacecraft. These secondary signals are primarily commands/data uploads and ranging, if required. The signal generator is often combined with the receiver into a single package. This process can be done similar to the downlink where an FPGA is used to generate the necessary signals and then it gets converted from a digital signal to an analog signal using a digital-to-analog converter (DAC). Unfortunately, this would require additional FPGA development. There weren't many commercially available options found that suit this purpose but the one found below likely meets this need. It is estimated that a component such as this would likely cost $5,000 - $7,500.

Table 3.9 - Commercially available signal generator

Vendor	Price (Quantity)	Data Sheet / Notes
Makesat	$7,500* (1)	Link *Estimated Cost

3.1.3.2 Block Up-Converter / Mixer/Local Oscillator

The second stage in the uplink chain is mixer/local oscillator (LO). This serves the same purpose as the downlink chain but in the opposite direction. Instead of down-converting the signal from RF to IF, it up-converts the IF signal into an RF signal. The same mixer/LO could be used for both purposes. There is also an option to use a Block Up-Converter (BUC). This component takes the IF signal, up-converts it, and then amplifies it. Depending on the BUC, it may also filter the signal removing the need for additional downstream components. No BUCs were found that meet the specific need for this application, but one could likely be custom made by a vendor. The issue with the commercially found BUCs was that they didn't have the deep space Ka-Band frequencies.

3.1.3.3 RF Band Pass Filter

Similar to the downlink RF BPF, the uplink BPF should filter out signals that are not in the Ka bandwidth. The center frequency of the BPF should be centered in the deep space band at 34,450 MHz with a 3 dB bandwidth of 500 MHz. The desired attenuation beyond this bandwidth should be at least 40 dB. Like previous components, the commercially available components that were found, shown below, were not an exact match, but a BPF with these required specifications could likely be custom made.

Table 3.10 - Commercially available uplink BPFs

Company / Product #	Type	Price (Quantity)	Center Frequency (GHz)	Passband (GHz)	Bandwidth (GHz)	Insertion loss (dB)	Attenuation / Rejection (dB)
RFLambda - RBPF33G35G	RF Filter - Cavity	Restricted	34	33-35	2	1.2-2.5	40
RFLambda - RBPF34G37G	RF Filter - Cavity	Restricted	35	33-37	4	1.1-2.5	40
RF Lambda - RWBPF28A	RF Filter - Waveguide	Restricted	37	36.8-37.2	0.4	1.0	40
Fairview Microwave - SFWR28-0333	RF Filter - Waveguide	$489 (1-9) $440 (25-49)	30.5	30-31	1	1.5	60

3.1.3.4 Power Amplifier

The power amplifier (PA) is an important component that helps determine the EIRP of the ground station. Previous analyses have shown that the required EIRP is approximately 124 dBm. Given an antenna diameter of 7.5 meters, the transmit power of the PA would need to be at least 680 W. High power applications such as this may require a Traveling Wave Tube Amplifier (TWTA) which traditionally offer higher power outputs over a Solid-State Power

Amplifier (SSPA), but usually with less reliability. Unfortunately, no commercially available components in the desired frequency band were found with output powers above 500 W, but the below table lists PAs close to the required specification.

Table 3.11 - Commercially available power amplifiers

Company / Product #	Type	Price (Quantity)	Frequency Range (GHz)	Power Output (W)	Data Sheet
SSPA					
RF Lambda RFLUPA26G40GG	SSPA	Restricted	26-40	160	Link
TWTA					
Comtech - XTD-500KaL	TWTA	Restricted	27.5 - 31	500	Link
Comtech - XTD-250KaL	TWTA	Restricted	27.5 - 31	250	Link
AI Sat	TWTA	$91,343 (1)	27.5 - 31	250	Link Used

3.1.3.5 RF Switch / Duplexer / Orthomode Transduce / Circulator

The final component prior to the antenna in the uplink chain is needed to be able to both transmit and receive signals on the antenna. Depending on whether the desire is to transmit and receive these signals at the same time will determine which component is the most useful. If the goal is to transmit and receive simultaneously, then either a duplexer, orthomode transducer (OMT), or circulator could work. Otherwise, a switch could be used to select either the uplink or downlink channel of the antenna. Based on this high power and frequency application, an orthomode transducer would probably be most suitable to separate the uplink from the downlink. A list of OMTs is provided below.

Table 3.12 - Recommended Orthomode Transducers

Company / Product #	Price (Quantity)	Frequency (GHz)	Insertion Loss (dB)	Data Sheet / Notes
Pasternack - PWEOT0003	$5,656 (1)	30-42	15	Link
Pasternack - PWEOT0007	$5,350 (1)	26.5-40	15	Link

3.1.3.6 Antenna

The antenna that would be used for the uplink is the same antenna that would also be used for downlink. The feed would reflect the signal off the parabolic dish towards the spacecraft. The antennas listed in Table 3.1 that specify both downlink and uplink directions could be used for this application.

4 Ground System Performance and Cost

There were two options identified to potentially be feasible for a mission to Enceladus:

1. Design and build a Ka-Band phased array
2. Work with a commercial ground segment provider to operationalize a single ground station for Encelascope support

These options were studied for performance and cost. The results of these studies are given in the sections below

4.1 Phased Array Performance and Cost

The following sections break out the various costs of designing, constructing, and operating a phased array. Each section describes how each cost is estimated and the assumptions made for that estimate.

4.1.1 Phased Array Cost Estimations

4.1.1.1 Ground Segment Usage

When estimating the cost of designing, constructing, and use of a phased array, ground segment usage becomes an important factor in these estimates, namely when estimating the cost of cooling systems. An estimate of the ground segment usage is shown here and referenced in later sections for cost estimations.

The usage of the ground segment is largely dependent upon the different mission phases and the criticality of these phases. Phases that require more contact with the spacecraft for mission planning, telemetry, and commanding purposes will use the ground segment much more than quieter phases, such as the interplanetary transfer. The mission was broken up into the phases listed in the table below with an estimated usage of the array in these phases. The phase durations are based upon the trajectory generated by the mission design team. The ground segment usage is an estimate based on operational experience from Advanced Space. The total hours for each phase are computed to generate the hours used per node in the array. This allows for later cost analysis, which use a varying number of nodes, to more easily compute cost based on the size of the array.

Table 4.1 - Ground segment usage by mission phase

Operations Phase	Description	Phase Duration	Ground Segment Usage	Hours / Node
Transfer	Low use period during interplanetary cruise	9 years	2 hr/week of use	936
SOI / PRM	Saturn Orbit Insertion (SOI) through Periapsis Raising Maneuver (PRM). Increased contact times to ensure successful Saturn insertion.	1 year	2 hr/day of use	730
Moon Tour	Increased contact time for rapid flyby	3.5 years	2 hr/day of use	2555

	cadence of Saturnian moons			
Science	Increased contact durations to downlink science data to Earth	1 year	4 hr/day	1460
Flybys	Increased contact durations for targeting and correction of interplanetary flybys	4 week / flyby (3 flybys total)	4 hr/day of use	336
TCMs	Increased contact durations for planning and executing Trajectory Correction Maneuvers (TCMs)	15 years	20 hr/year of use	300
			Total	6317 hr/Node

The expected total ground segment usage for the lifetime of the mission is estimated to be approximately 6317 hours per node in the array.

4.1.1.2 Design and Software Development Costs

The design and software development costs are simply an estimate of the number, duration, and cost of engineers needed. Each engineer is estimated to cost approximately $130,000 annually. For the design of the phased array, it is estimated that it would take two engineers working for one year for a total cost of $260,000. The design work would include furthering the RF chain implementation of each node and the layout of the nodes in the array. Additionally, this would include designing the infrastructure of the ground apertures which would include housing and board layout of the RF components. This work would likely require an electrical engineer with expertise in RF design and a mechanical engineer.

The software development would involve both processing of the phased array signals and control of the nodes in the phased array network. Once a signal has been received from the nodes in the array, the signal gets down converted to an intermediate frequency where it can then be converted to a digital signal. It is assumed that once the signal is digital there will need to be software in place to process the signal into usable data. In addition to the software needed to process signals from the spacecraft, software will be needed to operate the array. It is estimated that this will take one software engineer one year to develop, totaling $130,000.

4.1.1.3 Aperture Assembly and Test Cost

This is the cost associated with shipment of materials, construction of the apertures, and verification of performance. The estimated cost of these activities is approximately $40,000 per aperture and is based on a provided quote from a commercial vendor for a 3.8-meter antenna. This estimate was used as the assembly and test cost for antennas of all sizes.

4.1.1.4 Certification, Licensing, and Permit Costs

These are the costs associated with licensing and certifying the ground network with the proper authorities. This excludes any estimates for building permits that may be needed for constructing the ground station. Additionally, the estimated costs given are based on a brief study and may not include all required licenses and certifications.

All US based ground networks transmitting RF signals must register with the FCC. Licenses are required for all transmitting stations while receiving stations may be excluded. All transmitting stations must meet the FCC performance criteria and requires a coordination study to prevent interference. Additionally, each transmitting station also requires site approval and a spectrum license. There are regulatory and application fees associated with this process. The application fees are a fixed fee required for processing the application, while regulatory fees are the cost of operating the station in the US. The FCC states that regulatory fees can be waived for non-profit organizations which would otherwise be approximately $125,000 per year for each station[6]. Assuming that these fees will be waived, the estimated cost for this work is $100,000. This includes $50,000 for licensing fees and an additional $50,000 for the engineering and filing work for filling out the applications/licenses.

4.1.1.5 Land Costs

The construction of the ground segment requires land area to build upon. The area required for a phased array is highly dependent upon the number of nodes in the array. Based upon the area required, land purchasing costs can be estimated using the average price of land in the US. Assuming the array would be built in a rural area, the average farmland cost was used based on data for 2021, shown in the plot below to be $3,380 per acre.

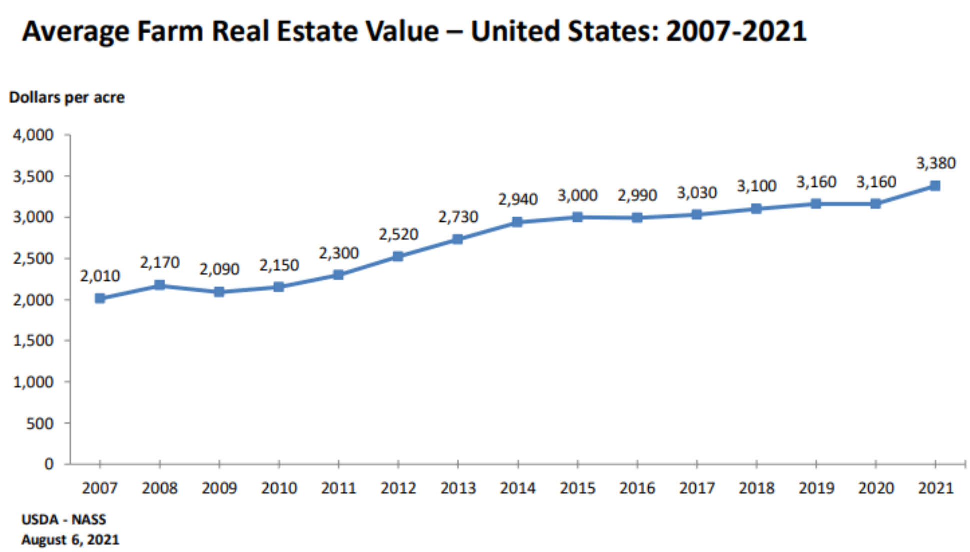

Figure 4.1 - Average farmland cost in the US over the past 15 years

To estimate the land area (acres) needed, the following equation was used,

[6] FCC Regulatory Fees Fact Sheet, DOC-375657A1, Sept 2021

$$A_{acres} = N\left(\frac{d_{ft}}{PF} \times \frac{acres}{ft}\right)^2$$

where *N* is number of nodes, d_{ft} is the diameter of each node in feet, and *PF* is the packing factor. The packing factor represents how efficiently each node is spaced with respect to one another. A packing factor of 100% would represent no spacing between each node. This above equation also assumes that the array is laid out in a square matrix. There are approximately 208.7 ft per side of an acre, so once the one-dimensional distance for a node is determined, this value is squared and multiplied by the number of nodes to give the total area. The cost of land per acre is then multiplied by the estimated area to arrive at the total cost.

Consider the example where an array consists of the following parameters:

- 100 Nodes
- Packing Factor: 25%
- Nodes Antenna Diameter: 6 meters (19.685 feet)

Substituting these values into the above equation results in a required area of 0.1423 acres for a single aperture and 14.23 acres for the full 100 nodes. Applying the cost per acre, the total land cost is roughly $48,097.

4.1.1.6 Maintenance Cost

For each node in the array, there is an associated maintenance cost estimated for keeping that node operational. Throughout the lifetime of a station there will be times when components need to be replaced or mechanical repairs that may be needed. This cost is estimated as

$$N\big(1 - R(t)\big) \times C_{avg}$$

where *N* is the number of nodes in the array, *R(t)* is the reliability of each node as a function of time, and C_{avg} is the estimated average cost of each repair. The reliability of each node is an estimated probability that a single node will need repairs throughout the course of a year. It is assumed that at the beginning of life (BOL) for a node, the reliability will be higher than at its end of life (EOL); therefore, the reliability is a function of time that decreases linearly by year from BOL to EOL. The assumed mission duration is 15 years for this analysis. Both the reliability and average repair cost varies for the type of cooling system used for each node. It is assumed that lower cooling techniques will have higher associated repair costs as well as more frequency repairs (lower reliability). The table below summarizes the estimated values used in the cost analysis based on the cooling methods presented in Section 3.

Table 4.2 - Estimated maintenance cost parameters for each cooling method

Type	Base Cost	BOL Reliability	EOL Reliability
Uncooled	$5,000	99%	90%
Cooled	$7,500	90%	75%
Cryogenic	$10,000	85%	70%

4.1.1.7 Antenna Cost (Theoretical)

JPL's Descanso series published a study suggesting that the cost of an antenna could be modeled using the equation,

$$C = kD^{2.7}$$

where *k* is the cost scale factor and *D* is the antenna diameter in meters. To estimate the cost of current antennas, quotes were gathered to determine a reasonable value for the scale factor, *k*, that accurately represents antenna costs today. An additional base cost was also included in the equation to account for additional antenna capabilities such as mounting and motorization. Using the quotes, a least squares curve was fit to the data using a log scale. The exponent, 2.7, was also allowed to vary to better fit the data. The new equation used to fit the data is given by,

$$C = Base + kD^{x}$$

The quoted values all include varying specifications and services, but it was determined that these values would provide an accurate interpolation for the actual cost based on an antenna's diameter. The quote values used in the curve fit are given in the table below with the fit and curve values shown in the figure. These values were used for estimating antenna costs in proceeding sections.

Table 4.3 - Vendor quotes with estimated fit cost

Vendor	Antenna Diameter (m)	ROM Cost	Fit Cost
Vendor 1	3.5	$200,000	$201,491.72
Vendor 3	3.8	$225,000	$208,642.39
Vendor 1	4.9	$225,000	$251,686.25
Vendor 1	5.6	$300,000	$297,290.12
Vendor 2	7.3	$515,677	$494,805.37
Vendor 5	13.5	$3,300,000	$3,340,915.40

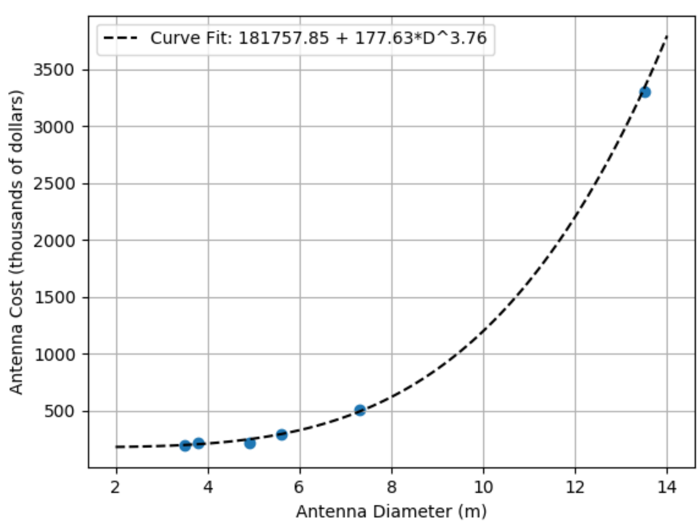

Figure 4.2 - Vendor quotes with overlayed antenna cost fit

4.1.1.8 Mechanical Housing / Board Fabrication Cost

The ground apertures for the phased array would be located in an outdoor environment. It is important that the backend components described in Section 3.1.1 be as close to the antenna as possible to reduce the noise of the system, so it is expected that these components would be located outdoors as well. To protect these components from the outdoor elements, it is recommended that they are concealed in a mechanical housing. This would also include any cooling infrastructure necessary to cool the first LNA. As the cooling becomes more complex, it is assumed that the mechanical housing costs would increase. This estimated cost also includes any hardware or board fabrication needed to connect and mount each component. The cost is broken out by cooling type and given in the table below.

Table 4.4 - Estimated mechanical housing costs for phased array

Cooling Type	Estimated Housing Costs
Uncooled	$1,000
Cooled	$1,500
Cryo-Cooled	$2,000

4.1.1.9 Cooling Costs

The cost of cooling the first LNA incorporates costs for the desired cooling systems, the coolant, and any supporting equipment needed. The following sections attempt to characterize these cost categories, with the stated assumptions, for both the cooled and cryogenically cooled systems. There is no added cost for the uncooled system because the aforementioned cost categories do not apply.

4.1.1.9.1 Cryogenically Cooled Costs

For a cryogenically cooled system, a cold head is used to reduce the temperature around the LNA and to remove heat from the system. To support the cold head, a compressor, drive cables, Helium lines, and a storage Dewar are necessary to flow helium into and out of the cooling chamber. Quotes for these systems were obtained from several commercial vendors to estimate these costs. A single stage cold head is expected to meet the cooling needs and has the ability to cool the chamber down to below 25 K. Additional cold heads stages can be used to further reduce the cooling down to below 10 K, but the cost more than doubles. For the costing analysis, a single staged cold head is used. A Dewar is also needed to store the liquid Helium but is not included in the quotes provided by the commercial companies. The estimated cost of a 100 L Dewar is $1,000 which would likely be required for each node.

In addition to the cooling equipment, the coolant is also required. For a cryogenically cooled system, liquid Helium is used. The cost of Helium is estimated to be $20 / liter. To determine the amount of Helium that is needed, an article published by Lakeshore was used[7]. This article describes the annual cost of liquid Helium needed as a function of hours per day of operations. The system is closed loop, but inefficiencies result in Helium loss through natural processes like evaporation. Helium evaporates at temperatures above approximately 4 ^{o}K. Because the operational temperature of the cooling chamber will be above this temperature, some Helium is expected to boil off and be lost. This process also occurs in the transfer of Helium from the Dewar to the cooling chamber via the Helium lines which will likely not be fully cooled. This can be minimized by designing the system to have the Dewar

[7] https://www.lakeshore.com/products/categories/overview/janis-products/cryostats/4-k-cryocoolers

as close to the cooling chamber as possible. The actual amount of Helium used could very likely be less than what is being estimated here, but this was used as the best estimate.

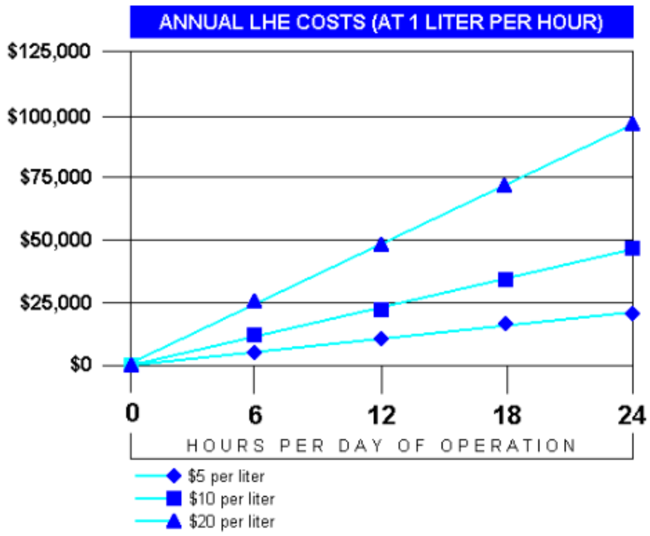

Figure 4.3 - Estimated annual cost of liquid helium as a function of hours per day of operation as given by Lakeshore

From this analysis, the operating cost of a liquid Helium cooled system is derived per hour of operation. Using the above plot, six hours per day of operation costs approximately $25,000 per year. Using these numbers, the cost per hour is derived using,

$$Cost\ per\ Hour = \frac{25{,}000\,\frac{\$}{yr}}{365\,\frac{days}{yr} \times 6\,\frac{hr}{day}} = 11.416\,\frac{\$}{hr}$$

This estimate is used in conjunction with the ground segment usage assessment provided in Section 4.1.1.1 to compute the estimated cost of operation per node. The cost per node is simply the cost per hour multiplied by the expected hours of operation, which excludes any time it would take to use Helium to cool the LNA prior to use. A summary of the cryogenic cooling costs summed up to the cost per node is shown in the table below.

Table 4.5 - Estimated cost per node for cryogenic cooling for the full Enceladus mission

Line Item	Cost per Node	Notes
Cryo System	$20k (20 K)	Single stage cold head ROM costing
Helium & Operational Use	$72,100 / Node* ($11.416 / hr / Node)	Assumes 1L / hr of operation, $20 / L for He, 6317 hours / Node of operational lifetime *Doesn't include any "cool down" times
Dewar	$1,000 / Node	100 Liter Volume Dewar at each node
Total	$93,100 / Node	20 °K system

4.1.1.9.2 Cooled Costs

The cooled cost is estimated much in same way as the cryogenically cooled cost. The primary difference is that instead of a Helium cryogenic system, the cooling is done with a Peltier cooler supported by dry Nitrogen. Dry Nitrogen is used to remove moisture from the system and is far less expensive than Helium at an estimated cost of $2 / liter. Assuming the same usage computations as liquid Helium, the price for using Nitrogen is $7,210 / Node for the lifetime of the mission. The Peltier cooler is also much less expensive than a cryogenic system but provides far less cooling capability and is expected to reduce the temperature of the LNA by approximately 75 to 100 ^{o}C based on data provided in the Peltier Cooler datasheet. Assuming the baseline temperature is 25 ^{o}C, the resulting temperature in the chamber would be -50 to -75 ^{o}C.

Table 4.6 - Estimate cost per node for Peltier cooling

Line Item	Cost per Node	Notes
Peltier Cooler	$615 (dT ~100 deg)	Link
Nitrogen Use	$7,210 / Node ($1.142 / hr / Node)	1L / hr, $2 / L, 6218 hours / Node Assuming same usage as helium: $1.142 / hr / node
Storage System	$1,000 / Node	100 L
Total	$8,835 / Node	~-50 ^{o}C

4.1.2 Uplink Cost Estimations

To estimate the uplink cost, the size of the antenna must first be determined. From the commercially available power amplifiers, the 500 W TWTA was selected to reduce antenna costs which scale exponentially. Given that the required EIRP of the uplink antenna needs to be 124.35 dBm, the required gain then becomes 67.36 dBi. This translates into a required diameter of 8.78 meters. Using these values, as well as the components selected in Section 3.1.3, the cost estimate for the uplink is given below.

Table 4.7 - Summarized uplink cost estimate

Component	Cost	Notes
Components	$123,960	Signal Generator, Mixer / LO, Band Pass Filter, Power Amplifier, Orthomode Transducer
Antenna	$810,063	$181757.85 + 177.63 \times 8.78^{3.76}$
Total	**$934,023**	

4.1.3 Phased Array Performance Estimations

4.1.3.1 High Performance vs Low Cost Trade

Based on the full list of commercially available components that were found that either match or closely match the required specifications, the components were down selected into two categories for each cooling type. The categories were based upon performance and cost. The highest performing and lowest cost components were selected for each individual component in order to trade the number of nodes required and their associated cost. Higher performing components may be more expensive, but the performance savings may require less nodes and end up saving cost. Conversely, lower cost components may have degraded performance and require more nodes, but the cost savings may result in a less expensive phased array overall. It should be noted that the low-cost components that were selected weren't the absolute lowest cost of the commercially available components. Some of the lowest cost components had terrible performance and it was expected that these components would not fit the need for the phased array; thus, components with moderately higher cost and significantly improved performance were subjectively selected for the low-cost category.

Based on the components selected for each category and each cooling method, the performance metrics and associated costs were used to estimate the required number of nodes and total cost for each trade category. A table overviewing the performance of each selected component is shown below. For the components that didn't specify a gain value, it was assumed that the gain was the negative of the of the noise figure.

Table 4.8 – Performance of selected components for each trade category

	Uncooled – High Performance	Uncooled – Low Cost	Cooled – High Performance	Cooled – Low Cost	Cryo – High Performance	Cryo – Low Cost
Cooled RF LNA	Gain: 19.5 NF: 1.25	Gain: 19.0 NF: 1.5	Gain: 20.3 NF: 0.6	Gain: 20.3 NF: 0.6	Gain: 28.0 NF: 0.12	Gain: 32.0 NF: 0.25
RF Band Pass Filter	Gain: -1 NF: 1.0					
Uncooled RF LNA	Gain: 19.5 NF: 1.25	Gain: 19.0 NF: 1.5	Gain: 19.5 NF: 1.25	Gain: 19.0 NF: 1.5	Gain: 19.5 NF: 1.25	Gain: 19.0 NF: 1.5
Mixer/Local Oscillator	Gain: -6.0 NF: 6.0					
IF Band Pass Filter	Gain: -1.2 NF: 1.2					
IF LNA	Gain: 63.0 NF: 0.5	Gain: 14.5 NF: 2.0	Gain: 63.0 NF: 0.5	Gain: 14.5 NF: 2.0	Gain: 63.0 NF: 0.5	Gain: 14.5 NF: 2.0

4.1.3.2 Thermal Noise Contribution Summary

Operational noise temperature for the downlink system was determined for each of the three cooling systems. The estimates are based on commercially selected components based on each trade type, given in Table 4.8. The noise temperatures for these designs are shown in the table below. These same estimated parameters are given for a DSN 34-meter antenna operating in Ka-Band as a reference.

Table 4.9 - Estimated noise temperatures based on selected components and cooling scenario

Scenario	System Noise Temperature (K)	Sky Noise Temperature (K)	Operational Noise Temperature (K)
Uncooled – High Performance	122.21		167.85
Uncooled – Low Cost	147.37		193.00
Cooled – High Performance	64.84		110.47
Cooled – Low Cost	65.22	45.63	110.85
Cryo – High Performance	26.15		71.79
Cryo – Low Cost	35.56		81.89
DSN – 34m (Ka-Band)	47.50		93.13

4.1.4 Phased Array Cost Summary

When computing the number of nodes required in the downlink array, and subsequently the cost, it can be assumed that the uplink antenna, which will also be configured for downlink, is also part of the array. This helps further reduce the size of the array. The array size is computed using the required G/T value given in Section 2.3.2, which is 57.30 dB/K. Assuming that the transmit and receive node is using the high performance components and is cryogenically cooled, the G/T value for this antenna is easily computed using the gain computation in Section 4.1.2 (67.36 dB) and the thermal noise values computed in Table 4.9 for this scenario. The results provided below incorporate this antenna into the array. It should be noted that only the cost of receive components for the transmit/receive node were included in the phased array cost estimation. Transmit components are included in the uplink cost which is included as a separate line item in Section 4.5.

The following table summarizes all cost factors considered for the phased array cost. Using these cost estimates and the performance numbers given in Section 4.1.2, the number of nodes needed to meet the data rate requirement and the associated costs are shown in Figure 4.4.

Table 4.10 - Phased array cost summary

<table>
<tr><th colspan="2" rowspan="2"></th><th colspan="6">Scenario</th></tr>
<tr><th colspan="2">Uncooled</th><th colspan="2">Cooled</th><th colspan="2">Cryo-Cooled</th></tr>
<tr><th colspan="2">Cost Category</th><th>High Performance</th><th>Low Cost</th><th>High Performance</th><th>Low Cost</th><th>High Performance</th><th>Low Cost</th></tr>
<tr><th colspan="2">Design</th><td colspan="6">$260,000</td></tr>
<tr><th colspan="2">Software</th><td colspan="6">$130,000</td></tr>
<tr><th colspan="2">Certifications, Licenses, Permits</th><td colspan="6">$100,000</td></tr>
<tr><th colspan="2">Land</th><td colspan="6">$N\left(\frac{d_{ft}}{PF}\times\frac{acres}{ft}\right)^2\times 3380\,\frac{\$}{acre}$</td></tr>
<tr><th colspan="2">Maintenance</th><td colspan="2">$N(1-R(t))\times C_{avg}$
C_{avg}: $5,000
BOL R: 99%
EOL R: 90%</td><td colspan="2">$N(1-R(t))\times C_{avg}$
C_{avg}: $7,500
BOL R: 90%
EOL R: 75%</td><td colspan="2">$N(1-R(t))\times C_{avg}$
C_{avg}: $10,000
BOL R: 85%
EOL R: 70%</td></tr>
<tr><th rowspan="4">Components</th><th>RF Components</th><td>$17,232 / Node</td><td>$13,150 / Node</td><td>$16,432 / Node</td><td>$13,650 / Node</td><td>$95,132 / Node</td><td>$90,350 / Node</td></tr>
<tr><th>Cooling</th><td colspan="2">$0 / Node</td><td colspan="2">$8,835 / Node</td><td colspan="2">$93,100 / Node</td></tr>
<tr><th>Antenna</th><td colspan="6">$181757.85 + 177.63D^{3.76}$ / Node</td></tr>
<tr><th>Installation</th><td colspan="6">$40,000 / Node</td></tr>
</table>

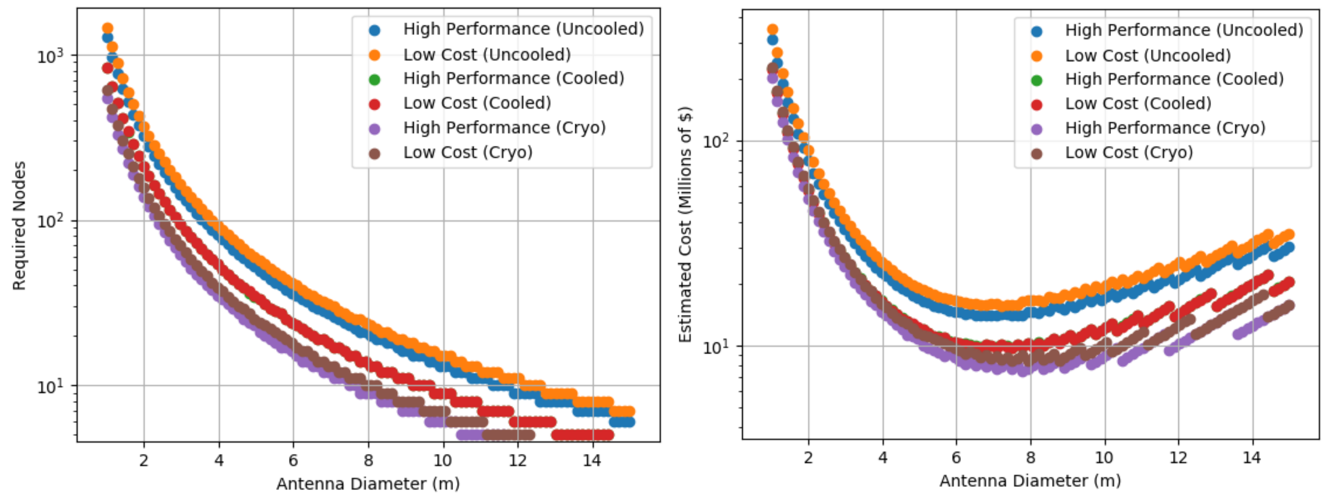

Figure 4.4 - Phased array required nodes (with Tx/Rx aperture included) and estimated cost as a function of antenna diameter

Based on the results shown above, the minimum cost was found for each scenario. The associated antenna diameter and required number of nodes was also determined and reported below. It is interesting to note that in the uncooled cases, when including the transmit/receive antenna, the number of nodes is higher when minimizing the cost. This can likely be attributed to the cost savings of using a smaller antenna while having comparatively inexpensive backend components. The cost savings from using the larger uplink antenna as a receive node is approximately $1 to $2 million in each scenario.

Table 4.11 - Minimized phased array cost for each scenario

	Without Tx/Rx Antenna			With Tx/Rx Antenna		
Scenario	Minimized Cost (Millions of $)	Antenna Diameter (m)	Number of Required Nodes	Minimized Cost (Millions of $)	Antenna Diameter (m)	Number of Required Nodes (w/ Tx/Rx Node)
Uncooled – High Performance	15.65	7.08	29	14.12	6.52	31
Uncooled – Low Cost	17.78	7.22	32	15.81	7.22	29
Cooled – High Performance	10.94	7.51	17	9.90	7.51	16
Cooled – Low Cost	10.90	7.51	17	9.86	7.51	16
Cryo – High Performance	8.49	7.93	10	7.63	7.79	10
Cryo – Low Cost	9.37	7.65	12	8.55	7.51	12

4.2 Commercial Ground Segment Cost

To compare the cost of building a phased array to a commercial solution, several commercial ground station providers were contacted in an attempt to get a rough order of magnitude (ROM) costing for the mission. The difficulty with current commercially available ground station providers is that they almost exclusively operate in the Near-Earth frequency bands. This was the case when reaching out to several commercial providers who said they would be unable to support a mission like this. One commercial provider that was contacted has a global network of ground stations that also operate primarily in the Near-Earth bands, but they were still willing to provide a ROM cost. As inputs to the cost estimate, they required an estimate of how much time the mission would like to use the ground stations.

The mission was broken out into three phases: Interplanetary Transfer, Saturian Moon Tour, Enceladus Science Phase. Based on each of these phases and the activities occurring in each phase, a rough ground station schedule was built, similar to the usage shown in Table 4.1.

Another assumption made for the use of this ground network is that by the time the spacecraft launched, the commercial provider would have made one of their ground stations operational and functioning in the deep space Ka-Band. They have the ability to upgrade a station but have stated that they may need customer backed support to get internal funding to do so.

The estimated performance of upgrading the station to Ka-Band is expected to be under the requirements for the Encelascope mission. This could be accommodated by either increasing spacecraft communication performance or lowering the current data rate requirements. If the data rate requirements are lowered, the same amount of data could still be downlinked by increasing contact time, but then this may increase the cost of using this commercial provider. Given the current contact time estimates provided in Table 4.1, the quoted commercial ground segment cost is $10,243,276.

4.3 Deep Space Network (DSN) Cost

To estimate the cost of using the DSN for this mission, its publicly available aperture fee tool was used[8]. The mission was built into the tool using the phases and contact times defined in Table 4.1. All scenarios were included with the exception of increased tracking around Trajectory Correction Maneuvers (TCMs). With the defined mission, the DSN tracking pass time estimate was 6237 hours. Comparing this to the 6317 hours estimate given in Table 4.1, the usage is only 80 hours less than expected phased array usage. The tool also includes setup and teardown time for each track. The amount of time for setup, tracking, and teardown are shown in the table below.

Using the aperture fee tool, it was assumed that the mission would only be using the DSN's 34-meter antennas in K-Band. Cost estimates were computed for scenarios that included and excluded ranging as a service. It's important to note that even if ranging is not used, the mission could still get Doppler measurements from the DSN to be used for spacecraft navigation. For these scenarios, the DSN cost was computed to be $15,844,859 and $17,013,243 for the non-ranging and ranging cases, respectively.

[8] https://dse.jpl.nasa.gov/ext/

Table 4.12 – DSN usage and cost estimation for ranging and non-ranging mission scenarios

	No Ranging	Ranging
Setup Time (hr)	1956.2	2608.0
Tracking Time (hr)	6237.2	6237.2
Teardown Time (hr)	652.2	652.2
Total DSN Usage (hr)	8845.6	9497.4
Total DSN Cost	$15,844,859	$17,013,243

4.4 Operations Cost

Also included in the cost of a ground segment is the cost of operating the spacecraft. Operators are responsible for a multitude of activities such as planning mission activities, navigating the spacecraft, monitoring the health and safety of the spacecraft, sending commands to the spacecraft, etc. Advanced Space had reached out to several operation centers, as stated in the contract, in an attempt to get an estimated cost for operating a mission to Enceladus but it became difficult to work with these companies due to either extensive amounts of required mission information or unresponsiveness. Advanced Space performs several operations activities for their CAPSTONE mission, so it was decided to use this experience to estimate the operations cost for a mission to Enceladus.

For this cost estimate, it is assumed that there are two distinct roles for operators: a Mission Operations Manager (MOM) and generic Operators. The MOM supervises operators, reviews operations products, and is ultimately responsible for directing all operations and mission decisions. The operators are on console performing/following mission procedures based on the direction of the MOM. These procedures are for things such as maneuver planning and execution, navigation, and payload operations. The two roles were estimated to cost $250 and $180 per hour for the MOM and operators, respectively.

In addition to the two different roles, the mission was broken out into 3 different categories for each phase: critical time periods, interplanetary cruise, and the science phase at Enceladus. These categories were selected based on the amount of operations interaction that was expected to be necessary. Critical time periods during the mission involve 24 hr/day operations with four operators and a MOM on shift. For the current mission design, the Launch and Early Operations (LEOP), Saturn Orbit Insertion (SOI), and Periapsis Raising Maneuver (PRM) were designated as time periods requiring critical staffing. Due to the unique and non-traditional planned navigation, one additional week around these time periods was added to the time estimate which resulted in a total time for critical operations of 30 days.

For the interplanetary cruise, it is expected that the spacecraft can remain mostly in a coast or dormant mode which would require significantly reduced staffing. Operations would occur on weekdays and during business hours with only a single operator and MOM on duty for 4 hr/week. There would be elevated operations around non-critical maneuvers and flybys. The final period, the science phase, is expected to last one year in duration. This phase is expected to require two operators, in addition to the MOM, for two hours per day during weekdays.

Based on the above criteria, the price was estimated for each phase. These estimates are shown in the table below with the sum of each phase totaling $2,245,400.

Table 4.13 – Operations cost estimate broken out by phase

	Critical Time Periods	Interplanetary Cruise	Science Phase
Operators (Rate: $180/hr)	4 operators on console Rotating shifts for 24 hours/day ~672 hours/week	1 operator on console for 4 hours over the course of M-F ~4 hours/week	2 operators on console for 2 hours per day M-F ~20 hours/week
Mission Operations Manager (MOM) (Rate: $250/hr)	1 MOM per shift, 24 hours/day ~168 hours/week	1 MOM for 4 hours over the course of M-F ~4 hours/week	1 MOM for 2 hours per day M-F ~10 hours/week
Number of Totals Days in Mission (approximated)	30 days	5000 days	365 days
Total Hours (Operator(s) / MOM)	2880 / 720	2860 / 2860	1040 / 520
Total Cost (Operator(s) / MOM)	$518,400 / $180,000	$514,800 / $715,000	$187,200 / $130,000
Total	$2,245,400		

4.5 Ground Segment Cost Comparison

Given all the cost and performance data presented in this section, the total cost of the ground segment is estimated in the table below. The estimates are broken up into the three driving cost categories: downlink, uplink, and operations. When considering the phased array, downlink costs were divided into the six different costs categories that have been previously discussed. The uplink cost was kept as a separate line item, but the antenna used for the uplink was also used in the downlink array. The alternative to using a phased array, utilizing a commercial station, was also considered. Here it is assumed that the quoted costs include both uplink and downlink, and therefore these costs were combined. The operations cost which includes the labor estimate for operators working the 15-year mission to Enceladus is an additional cost to both the uplink and downlink costs.

When considering cost alone for all scenarios, the phased array is predicted to reduce the ground segment cost when it is cryogenically cooled. It should also be pointed out that no intentional margin is added to these costs, meaning that anything that has been underestimated may end up growing these costs, including for the commercial provider. When considering the technical and schedule risks involved in each option, the DSN likely has a lower risk posture for both. Building and operating the phased array is likely the highest risk option due to its high cost and schedule uncertainties. In order to reduce the technical risk of this option, it is recommended that significant testing be performed prior to the launch of Encelascope. These tests would add additional costs which were not considered in the estimates below. If testing is delayed or unsuccessful, this could further increase schedule risk due to the strict launch date for the mission. Additionally, for both the phased array and commercial provider, the ground stations used to communicate with the spacecraft would be located at a single site on Earth. This adds additional technical risk because critical mission events or periods may have to be carefully scheduled around periods where the spacecraft is within view of the ground segment. Further, if these assets become unavailable for any reason, the mission could be jeopardized if no back-up options exist.

Table 4.14 – Total ground segment cost estimation for all considered scenarios

	Phased Array						Commercial	DSN
	Uncooled – High Performance	Uncooled – Low Cost	Cooled – High Performance	Cooled -Low Cost	Cryo – High Performance	Cryo - Low Cost		
Downlink	$14,114,894	$15,812,767	$9,904,184	$9,862,454	$7,627,280	$8,547,372	$10,243,276	$15,844,859
Uplink	$934,023							
Operations	$2,245,400							
Total	**$17,294,317**	**$18,992,190**	**$13,083,607**	**$13,041,877**	**$10,806,703**	**$11,726,795**	**$12,488,676**	**$18,090,259**

5 Contact Analysis

5.1 Mission Requirements / Assumptions

5.1.1 Data Volume Assumptions

In discussions with ASTROBi, Advanced Space was provided with the following information:

1. Required daily contact duration is 1.5 hours
2. Required data rate is 1 kbps (for science data)

From these assumptions, the total daily science data volume can be computed to be 5.4 Mbits (0.675 MBytes) of data per day. In addition to science data, the spacecraft health and safety data volume must be considered. This information is used to help operators monitor the state of spacecraft, plan future activities, and resolve any issues that may arise. For reference, the CAPSTONE spacecraft generates several MBytes of daily critical health and safety information that must be downlinked to the ground. This is generally a continuous time history of sensors onboard the spacecraft. For this analysis it is assumed that operators for the Enceladus mission could better optimize the health and safety data load such that the spacecraft is only required to downlink health and safety data that equates to the science data volume; thus, the total required daily data volume is 10.8 Mbits (1.35 MBytes). The following analyses show how this compares to the expected contact times throughout the mission and how feasible achieving this data volume is.

5.1.2 Modeling Planetary/Ground Station Geometry

The following contact analyses determine the amount of time that the spacecraft is expected to be within view of a ground station on Earth. It is assumed that the ground station that the spacecraft will be communicating with is located in the continental United States; therefore, DSN station DSS 26 (Goldstone), located in the Mojave Desert, was used for this analysis. The exact location of this station is (degrees, minutes, seconds)[9]:

- Latitude: 35°, 20', 8.48118''
- Longitude: 243°, 7', 37.14062''
- Height: 695.686 meters

At the time of writing, a science orbit at Enceladus had not yet been finalized. The goal of this analysis was to determine theoretical maximum contact times for orbits with varying longitudinal nodes. This would provide best and worst-case contact times that could be used to inform whether assumed data volumes could be met. The science orbit for the spacecraft is also assumed to be a polar, circular, two-body orbit given by,

- Eccentricity: 0
- Inclination: 90°
- Argument of Periapsis: 0°
- True Anomaly: 0°

[9] DSN Handbook, Module 301L, Table 5

The contact durations vary with both the Longitudinal Node and the altitude of the orbit. The following variations in these parameters were studied,

- Longitudinal Node: 0°, 45°, 90°
- Orbital Altitude: 100 km, 50 km, 10 km, 1 km

These orbits were constructed in the Earth-Enceladus rotating coordinate frame. This frame is defined as having the X-axis always in the direction of Earth, the Z-axis defined as the angular momentum vector of the Enceladus relative to Earth, the Y-axis is the Z-axis crossed with the X-axis, and the frame is centered about Enceladus. Defining the orbit in this frame ensures that the orbit is not precessing around Enceladus. This is beneficial because it allows the orbit geometry to remain fixed with respect to Earth and the contact time trends to be more precisely studied. The downside to defining the science orbit in this manner is that it would be difficult to fly an orbit of this nature due to the dynamics of the Earth-Saturn-Enceladus system. Additionally, the body on Enceladus is assumed to be perfectly circular with a radius of 256.6 km.

In addition to the orbital parameters, the elevation mask of the ground station also impacts the expected contact durations. The elevation mask of the ground station is the minimum elevation of the spacecraft with respect to the ground station that can be achieved. There are primarily two restrictions that impact the elevation mask: physical restrictions on the ground station motorization and atmospheric noise added to the signal. As the elevation of the spacecraft with respect to the ground station decreases towards zero, additional noise and attenuation is added which degrades the signal. This is also further degraded for higher frequency signals. This is covered in more detail in Section 2.2.4.2.

5.2 Estimated Contact Times

Given the above assumptions, the estimated contact times for each scenario were studied. Each scenario varied both the node and altitude of the orbit as well as the elevation mask of the ground station. Each scenario was analyzed for a full year from January 2040 to January 2041. The study took into account the occultations from Earth, Saturn, and Enceladus such that whenever the line-of-sight between the spacecraft and ground station was impeded by any of these bodies, the contact time was no longer taken into account. The first study, shown in Table 5.1, analyzed how long each individual contact was, while the second study, shown in Table 5.2, measured the average contact duration per day. The differences in the two studies highlight how occultations shorten average pass durations, but several tracks per day can be accumulated to accommodate data volume requirements.

Table 5.1 - Average Contact Duration

	Longitude of Node	0 deg (S/C orbit in the Earth's Plane)			45 deg			90 deg (S/C orbit perpendicular to Earth)		
	Elevation Mask	10 deg	20 deg	30 deg	10 deg	20 deg	30 deg	10 deg	20 deg	30 deg
Saturn Only Occultations		7.60	6.60	5.46	7.60	6.60	5.46	7.60	6.60	5.46
Saturn / Enceladus Occultations	Altitude: 100 km	2.20	2.11	1.97	2.59	2.46	2.28	7.60	6.60	5.46
	Altitude: 50 km	1.74	1.68	1.61	1.94	1.86	1.75	7.60	6.60	5.46
	Altitude: 10 km	1.30	1.28	1.24	1.37	1.34	1.30	7.60	6.60	5.46
	Altitude: 1 km	1.15	1.12	1.08	1.17	1.14	1.10	7.60	6.60	5.46

Table 5.2 - Average Daily Accumulated Contact Time

	Longitude of Node	0 deg (S/C orbit in the Earth's Plane)			45 deg			90 deg (S/C orbit perpendicular to Earth)		
	Elevation Mask	10 deg	20 deg	30 deg	10 deg	20 deg	30 deg	10 deg	20 deg	30 deg
Saturn Only Occultations		9.51	7.92	6.26	9.51	7.92	6.26	9.51	7.92	6.26
Saturn / Enceladus Occultations	Altitude: 100 km	7.08	5.90	4.66	8.95	7.45	5.88	9.51	7.92	6.26
	Altitude: 50 km	6.51	5.42	4.28	7.44	6.20	4.89	9.51	7.92	6.26
	Altitude: 10 km	5.58	4.65	3.69	5.94	4.95	3.93	9.51	7.92	6.26
	Altitude: 1 km	5.02	4.18	3.30	5.14	4.28	3.38	9.51	7.92	6.26

The information in Table 5.1 isn't as informative as Table 5.2 for mission planning purposes but gives a good sense of how long expected contacts are. The trends in both studies are the same. As the minimum elevation increases, contact durations decrease. Increasing the Longitudinal Node and the altitude of the orbit increases the contact time. For all these orbits around Enceladus, the Saturn occultations remain constant. This means that the Saturn only occultations are the highest achievable contact duration given the specified minimum elevation mask. As the altitude of the orbit increases from 1 to 100 km, the daily accumulated contact durations begin to approach this upper limit. The most Enceladus occultations occur when the Longitudinal Node is 0°. In the Earth-Enceladus rotating frame, the plane of this orbit around Enceladus intersects Earth meaning that during every orbit, the spacecraft travels behind Enceladus with respect to Earth. As the node is rotated to approach 90°, the plane of the orbit begins to face Earth. Once at 90°, the orbital plane is directly perpendicular to the Earth vector and the spacecraft is always in view of Earth (i.e., no Enceladus occultations). In this scenario, the daily accumulated contact durations are directly equal to the Saturn only contact durations for all altitudes. As previously stated, this orbit is not practically feasible in practice and the Longitudinal Node of the orbit would likely precess around Enceladus throughout the science phase. Daily contact durations would fall between these two extremes.

5.3 Data Rate vs Contact Time Trade

The daily data volume requirement assumes that the spacecraft can downlink data at 1 kbps for 1.5 hours per day. From the information provided in Table 5.2, even in the worst-case scenario, the spacecraft would be able to communicate with the ground for more than two times longer than 1.5 hours. If we assume, due to other system constraints, that the average daily contact duration is three hours, the required data rate could be halved and still meet the data volume requirement. This would reduce the required G/T value of the phased array by approximately 3 dB and would require roughly half of the apertures. The downlink analysis was re-run with these reduced values and the cost was recomputed.

Table 5.3 – Phased array minimized cost comparison for required 1 and 0.5 kbps downlink

	1 kbps			0.5 kbps		
Scenario	**Minimized Cost (Millions of $)**	**Antenna Diameter (m)**	**Number of Required Nodes (w/ Tx/Rx Node)**	**Minimized Cost (Millions of $)**	**Antenna Diameter (m)**	**Number of Required Nodes**
Uncooled – High Performance	14.12	6.52	31	6.35	7.46	11
Uncooled – Low Cost	15.81	7.22	29	7.13	6.66	15
Cooled – High Performance	9.90	7.51	16	4.51	7.08	8
Cooled – Low Cost	9.86	7.51	16	4.49	7.08	8
Cryo – High Performance	7.63	7.79	10	3.66	7.65	5
Cryo – Low Cost	8.55	7.51	12	3.98	8.07	5

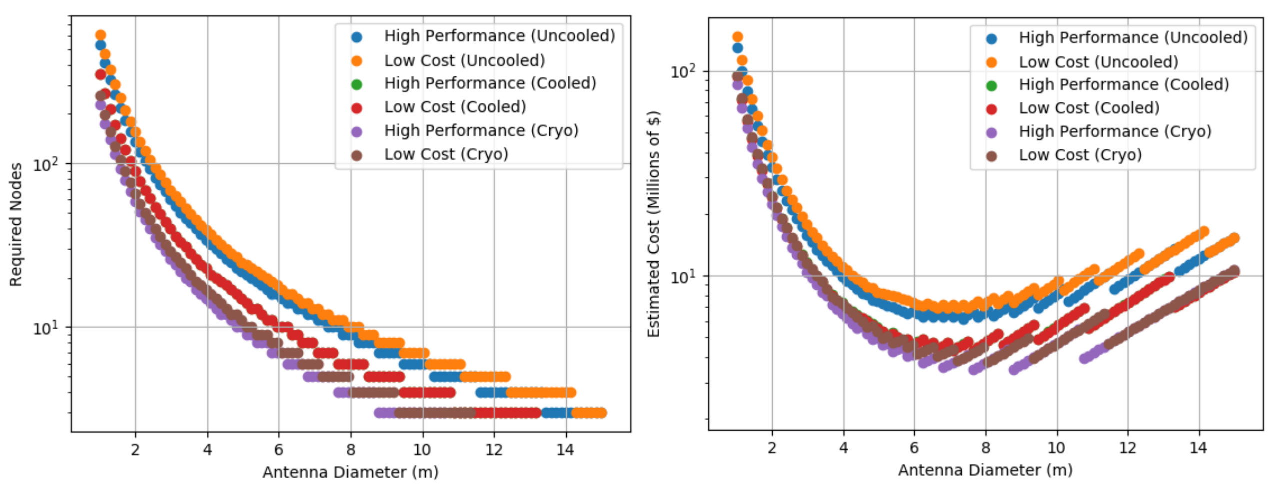

Table 5.4 – Required number of nodes and estimated cost of phased array for 0.5 kbps downlink data rate

With the newly reduced phased array size, the total ground segment cost was recomputed for each scenario. The phased array costs are drastically reduced which may now make it a more enticing option over the commercial provider.

Table 5.5 – Estimated ground segment cost with halved downlink data rate

<table>
<tr><th rowspan="2"></th><th colspan="6">Phased Array</th><th rowspan="2">Commercial</th><th rowspan="2">DSN</th></tr>
<tr><th>Uncooled – High Performance</th><th>Uncooled – Low Cost</th><th>Cooled – High Performance</th><th>Cooled – Low Cost</th><th>Cryo – High Performance</th><th>Cryo – Low Cost</th></tr>
<tr><td>Downlink</td><td>$6,353,733</td><td>$7,133,648</td><td>$4,506,696</td><td>$4,487,222</td><td>$3,661,793</td><td>$3,978,593</td><td rowspan="2">$10,243,276</td><td rowspan="2">$15,844,859</td></tr>
<tr><td>Uplink</td><td colspan="6">$934,023</td></tr>
<tr><td>Operations</td><td colspan="8">$2,245,400</td></tr>
<tr><td>Total</td><td>$9,533,156</td><td>$10,313,071</td><td>$7,686,392</td><td>$7,666,645</td><td>$6,841,216</td><td>$7,158,016</td><td>$12,488,676</td><td>$18,090,259</td></tr>
</table>

6 Conclusion

The results and analyses presented in this report provide performance and cost metrics for several ground segment options supporting a mission to Enceladus. Determination of the required ground network performance and capabilities was ascertained using the given communication requirements. Performance trade studies were conducted where specific requirements were not provided. Based on the results of these analyses, a survey of ground segment options determined feasible communication architectures that could be used to enable mission success. The cost of the two identified options, the construction and operation of a phased array and the use of a non-DSN commercial ground network provider, were estimated to determine the lowest cost option that could support the mission objectives and timeline.

The construction and operation of a phased array was studied extensively. The phased array would be used for downlinking information from the spacecraft but included a single antenna for uplink which would also have downlinking capabilities to include in the array. Analysis included designing a preliminary architecture for both the uplink and downlink antennas, studying the number of nodes required for the array, and using this analysis to determine antenna sizes that would minimize the cost of the array. In addition to this, ground segment performance was also traded against varying cooling and component architectures to further minimize cost. Given the current data volume requirements, the results estimate that the phased array option would cost between $11 and $19 million. If the data rate requirement can be reduced by increasing contact times with the spacecraft, this cost could be reduced to an estimated $7 to $10 million.

The second ground segment option that was studied utilizes a non-DSN commercial ground network consisting of a single, large aperture antenna. Given estimated contact times with the ground throughout the mission, the estimated cost of using this asset was estimated to be approximately $12.5 million. The performance of this ground asset is not expected to fully meet all communication requirements, but the same strategy of reducing required data rates and increasing contact times could be employed to achieve mission objectives. The mission must also consider the risk of using a single aperture. If for any reason, the asset becomes unavailable, specifically during critical mission periods, the mission could be jeopardized if no back-up options exist. Additionally, mission events and operations would have to be carefully scheduled around the view periods that exist with the ground station. These same challenges also exist for a phased array.

Use of the DSN was estimated to require between $15 and $17 million. Comparing the cost and risk of each option, the phased array is the lowest cost option with the most risk, while the DSN is the highest cost option with the least amount of risk. To minimize the risk associated with the phased array, extensive testing and technical demonstrations must be conducted prior to launch which would further increase the cost of this option. These tests also induce schedule risk and could delay the launch date if testing is delayed or is unsuccessful. Given the strict launch period for this mission, this risk would also need to be considered. The associated costs with these risks were not analyzed in this report. Given these considerations, if the mission can accommodate and manage these risks, based on the mission objective to minimize cost, the recommendation would be to build and operate the phased array using cryogenically cooled LNAs. If additional funding is available to support the use of the DSN, the recommendation would be to use the lowest technical risk option of the DSN and utilize its proven heritage.