Theseus' STRING

Signal sTrength Radiolocator and Independent Navigation Guide

"Helping you find your way out of the Labyrinth"

A Phase II proposal response to NASA093-007 Lunar Bread Crumbs Mission.

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1 Introduction

The *THESEUS* Signal sTrength Radiolocator and Independent Navigation Guide (STRING) Program is designed to assist astronauts walking on the lunar surface upon man's return to the Moon. The system uses a combination of antennas mounted on the lunar lander and the astronaut's backpack to determine the astronauts' location and relay position and path information to the astronaut. The astronaut uses cheap, expendable RFID tags to string along his trip, allowing the lander to accurately map out the path of the astronaut during sortie exercises. When the astronaut must return to the lander, the map of tags provides a guide to allow the astronaut to retrace his steps back to the lander.

1.1 Basic Design

There are several key components to THESEUS' STRING. A radar antenna is mounted to the lunar lander at the highest point possible. The height of the mount provides the largest field of view for the radar antenna and minimizes shadowing losses. The radar antenna provides a communication link between the lander and the astronaut. A closed loop control system on the rotating parabolic antenna points the antenna in the direction of the astronaut following the peak return gain from the astronaut's backpack antenna. The distance of the astronaut is determined with a hybrid radar Time-of-Flight (TOF) measurement augmented with a Received Signal Strength (RSS) measurement.

Communication with the astronaut is maintained via the radar antenna with a standard dipole antenna mounted on the astronauts backpack. The main data link between the astronaut and the lander provides a data rate of 100 kbps and support for telephony, command, and telemetry. The backpack provides two additional antennas mounted at the astronaut's shoulders to help determine the orientation of the astronaut in the azimuth direction with respect to the lunar lander and the RFID tags. Depending on the astronaut's current mode of operation, the lander communicates position and path information to the backpack computer. This information is interpolated and relayed in the form of verbal commands to the astronaut. A verbal interface is used to facilitate astronaut comprehension in an unpredictable environment.

1.2 Modes of Operation

In normal operation mode, a signal is relayed back to the lander whenever an RFID tag is dropped, allowing the lander to keep a running map of discrete points indicating where the astronaut has been. The location of the tag is given by the distance of the astronaut to the lander when the tag is dropped; no communication between the lander and the tag is possible. The astronaut continues transmitting the "new RFID tag" code until the astronaut has moved sufficiently far away from the tag that the signal has dropped off, a distance of about 5 m. The aggregate map of the RFID tags and the current position of the astronaut are periodically downlinked to the astronaut's backpack computer, allowing the astronaut to navigate to a specific destination and return to the lander independently of the lander's computer

The two RFID interrogator antennas on the astronauts back also have simple RFID tag positioning capabilities, by combing distance information obtained from a coarse RSS measurement and azimuthal information obtained from the phase difference of the signal received by the two antennas. In an emergency mode in which the astronaut has lost communication with the lander, this basic RFID location algorithm allows the astronaut to "follow the string" back into communication with the lander following simple "hotter/colder" commands – the astronaut is told whether he is getting closer to or farther from the nearest tag and whether or not the indices of the sequentially dropped tags are decreasing. In the unlikely event that the astronaut is caught outside of the communication capabilities of the lander, the backpack computer is fully capable of directing him back into full communication with the lander.

2 Assumptions

The design of THESEUS' STRING is heavily based on the requirements laid out by NASA's Exploration Systems Architecture Study Final Report [9], in which NASA describes a general summary of consecutive missions from earth to the International Space Station, from the earth to the moon, and ultimately from earth to Mars. Of particular relevance to the *THESEUS'* STRING are the requirements put forth in section 4.3.8.4:

"A crew member's location shall be known relative to the outpost to within 100 m during nominal operations. Position knowledge approaching 10 m is desired. The following scenarios describe nominal field operations:
• Within 3 km of the outpost, the EVA crew may travel by foot (without a rover)
• During off-nominal conditions, a crew member shall be able to find their way back to within 100 m of the outpost." [9]

This report is written to completely satisfy all of these requirements.

THESEUS' STRING assumes the astronauts are returning to the moon with a lunar lander of similar physical characteristics to the Altair lander, proposed by NASA in December, 2007. The Altair lander stands at a total height of 9.7 m, providing a relatively high platform on which to mount the radar antenna. The higher the antenna placement, the less lunar terrain obstructs the radar field of view. This is taken into account in the Lander to Astronaut Link Budget.

Figure 1: Artist's Representation of Altair lander [3]

Dimension	Value
Height	9.7 m
Diameter	7.5 m
Landing Gear Span	14.8 m
Volume	31.8 m^3
Descent Module Mass	35,055 kg
Ascent Module Mass	10,809 kg

Figure 2: Altair Dimensions [3]

3 THESEUS' STRING Operation

3.1 Normal Operation

Normal operation of the STRING commences when the astronaut begins a lunar sortie exercise and has moved out of the umbra of the spacecraft. The radar antenna must be activated and begins to rotate until it receives a response from the astronaut's backpack communication antenna. The backpack communication antenna acts as a bent pipe relay, relaying the signal from the radar antenna. This relay is essential for the Time-of-Flight measurement portion of the position algorithm. The relay transmission is added to and transmitted with the backpack telemetry. Eight-bit Direct Sequence Spread Spectrum (DSSS) coding is used to separate the two unique signals at the lander.

Once communication has been established, the base station begins uplinking data, including lunar RFID maps and astronaut distance information, to the backpack station. The backpack station responds with telemetry data, including housekeeping data and the identifier of the closest RFID tag. As the astronaut drops RFID tags, deploying the STRING, the astronaut's backpack interrogators detect the RFID tag and estimate its location using a coarse RSS and phase measurement. This information is also relayed back to the lander to add finer resolution to the map. The RFID tags are deployed in sequential order by the astronaut and relay a unique identifier to the backpack.

As the sortie proceeds, the astronaut continues to deploy RFID tags approximately every 5 m and the backpack broadcasts the identifier information to the base station. As each subsequent RFID tag is deployed, the astronaut path map is updated and re-uplinked to the backpack station. This continues until the astronaut is required to return to the lander base station, at which time STRING goes into "Pull-Back" mode.

3.2 Pull-Back Mode

In "Pull-Back" mode, the astronaut indicates to STRING that he is returning to the lander and ceases to drop RFID tags. The most recent map of the RFID path is uplinked to the backpack and the backpack autonomously directs the astronaut back to the lander, using the map, live location of the RFID tags, and real-time feedback from the lander to verify course. Redundancy is included in this return trip to ensure high reliability of system accuracy. Verbal directions are given to the astronaut to ensure easy comprehension, even if the astronaut's vision is impaired.

There are two forms of non-Emergency "Pull-Back" mode. The astronaut can return directly to the lander following the most direct path or he can follow the path of the tags, called "Direct Path Pull-Back Mode". Using Direct Path Pull-Back Mode is moderately more risky in case lunar terrain obstructs the direct path of the astronaut. However, as long as the lander maintains contact with the backpack, the astronaut can take detours to reach the lander. This method is not recommended unless the astronaut can see the lander. The nominal return method is following the string of RFID tags from the astronaut's initial trek, called "String Pull-Back Mode".

3.3 Emergency Pull-Back Mode

In "Emergency Pull-Back" mode, the backpack has lost the communication link with the lander but proceeds to autonomously direct the astronaut back to the lander based on the closest tag information and the most recent map uplinked from the lander. The backpack calculates the index of the next tag along the return path and directs the astronaut towards this tag. The phase difference of the received backscattered signal is used to orient the astronaut towards the tag. As the astronaut passes the tag, the backpack searches for the next tag in the string and directs the astronaut towards this tag. This navigation continues until the astronaut is within communications distance of the lander, at which point the full Pull-Back algorithm is restored.

3.4 Location Algorithm

The STRING approach to location finding utilizes a combination of TOF and RSS measurement specifically calibrated to take advantage of the strengths of both algorithms. The TOF measurement of the radar can be corroborated with the RSS because the gain and power output of the astronaut's communication antenna is known. In normal radar measurements, physical properties of the objects being located are usually not known, and therefore the signal strength of the scattered response off of the object is based on the physical properties of the object. In this case, the TOF measurement is based on the time from the lander through the bent pipe of the backpack antenna. The strength of the telemetry communications from the backpack is measured to provide the RSS

information. The angular position of the object is given by the azimuth angle of the radar antenna, which must be calculated with the use of a resolver to digital converter or equivalent.

The RSS is calculated below in the Lander to backpack antenna and scales logarithmically with distance as shown below. The time of flight, t, is calculated using delay lines and scales with distance according to d = c/t, as shown below. The time ranges from 0 to ~14 us and must be measured with precision equipment for high accuracy. Several methods of using radiation hardened FPGAs to measure time of flight are presented in [5] with accuracies up to 130 ps.

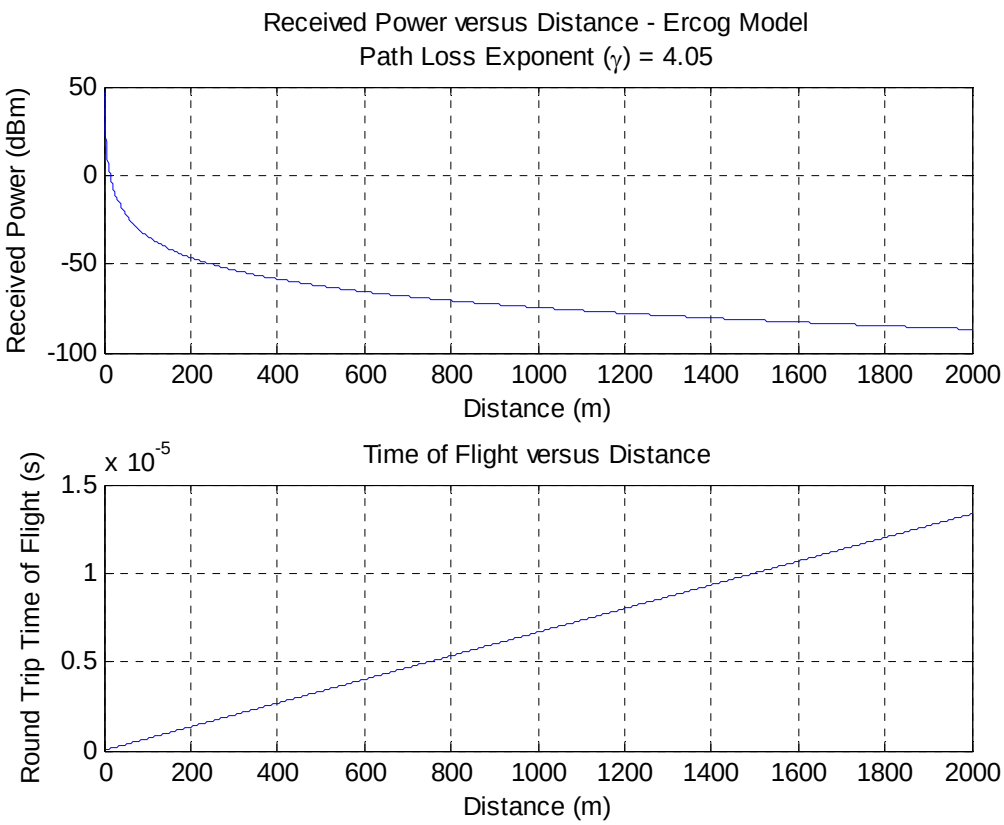

Figure 3: Received Signal Strength and Time of Flight Measurements scaled with Distance

The RSS measurement is proportional to the distance between the backpack and the transmitter to the fourth power, and drops off rapidly with distance. The time of flight measurement is driven by the time resolution of the delay lines and loses accuracy at shorter distances. Therefore, the two methods compliment each other nicely, as RSS has higher resolution at close distances and the radar time of flight has higher resolution at farther distances.

3.5 Accuracy

The Cramer-Rao Bound for this hybrid system was calculated in [11]. The hybrid TOF-RSS system is more accurate than RSS alone, Time Difference of Arrival (TDOA) alone,

or a TDOA-RSS hybrid, especially for short distances. As distance increases, the Cramer-Rao bounds of the systems converge, and at the extremities of the lunar system, the two measurements should corroborate the actual distance location of the astronaut.

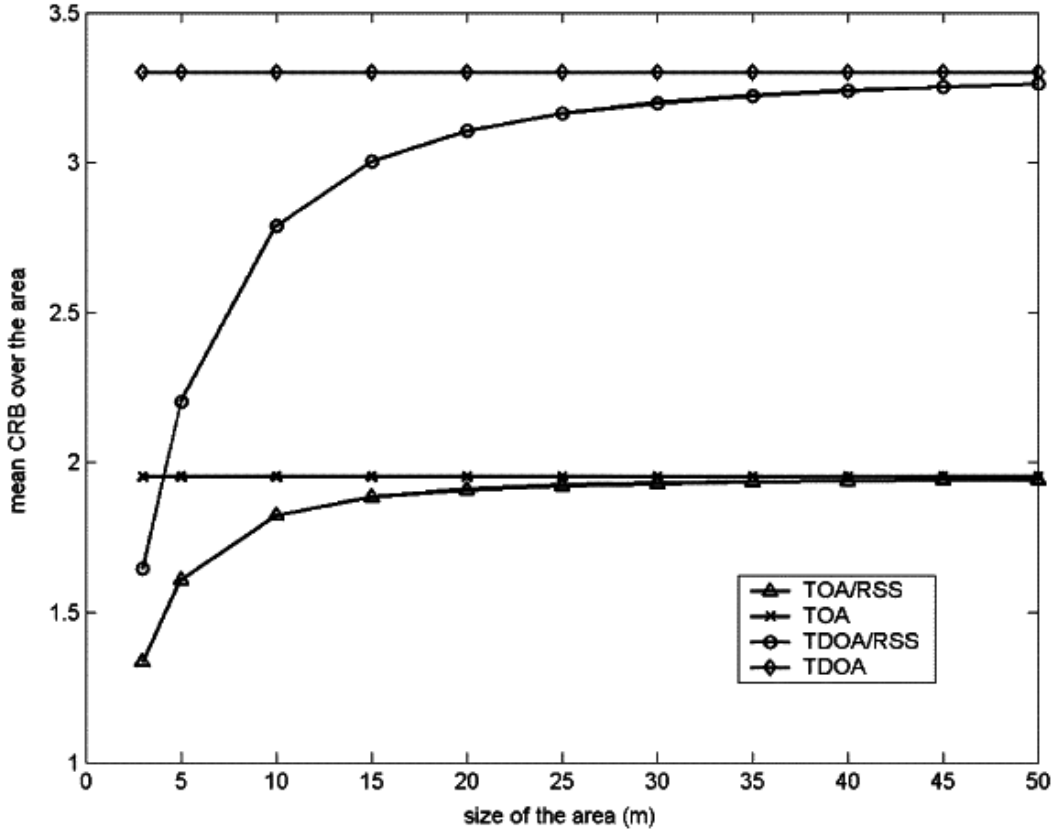

Figure 4: Cramer-Rao Lower Bound of Time-of-Arrival and TOA/RSS Hybrid and Time-Distance-of-Arrival and TDOA/RSS Hybrid Models for Position Estimation

4 Antennas

4.1 Radar Antenna

Communication between the Lander and the astronaut is accomplished by a pivoting curved dish antenna with 30 dBi gain, incorporating features of the two antennas shown below:

Figure 5: Possible Radar Antenna Designs

The antenna will have a parabolic shape in the horizontal direction only, focusing the beam width in this direction. The antenna will be as short as possible, to maximize beam width in this direction while still maintaining a high gain.

The grid antenna is light, which cuts down on launch costs. The shape of the antenna, wide and short, provides a gain pattern that has a large vertical beam width and a very narrow horizontal beam width. The curved shape gives the antenna additional directionality in the horizontal direction, focusing the beam on the horizon.

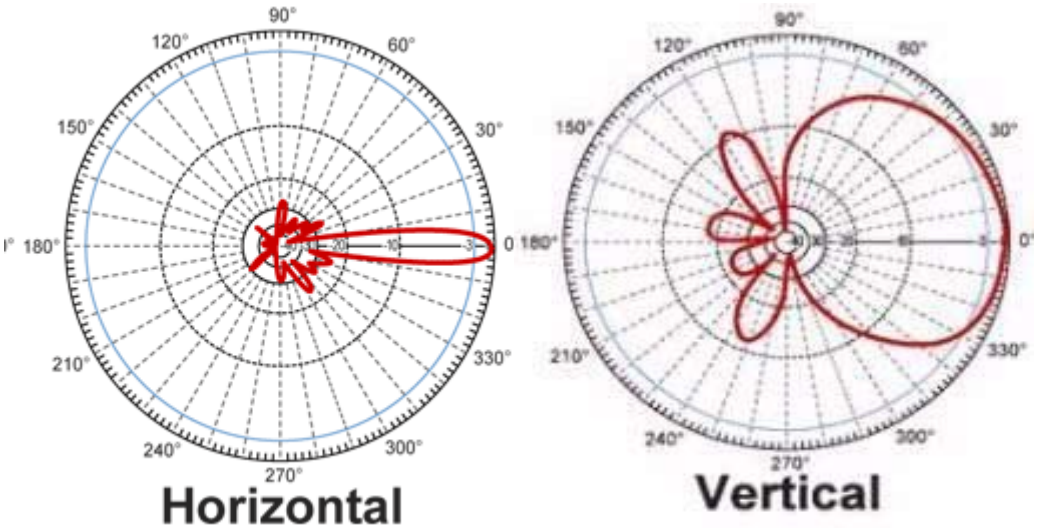

Figure 6: Radar Antenna Example Gain Patterns

Based on the equations given in [6] where the dimensions, either length or width, of a radar antenna are given by $q = \lambda / L$, the rough dimensions of the radar antenna can be estimated, where q is the half-power beam width (-3dB) in radians, λ is the wavelength, and L is the dimension of interest of the antenna. For angular resolution, the wider the antenna is the better. However, practicality demands this dimension be restricted. For a wavelength of $\lambda = 0.112245$ m, to obtain a horizontal beam-width of 2.4°, we need an antenna with a vertical length of 2.9 m. The antenna reflector can be separated into pieces for easy transportation to the moon. A magnesium alloy will be used for minimal mass.

	Size (m)	Resolution (°)
Horizontal	2.9	2.419244737
Vertical	0.6	11.69301623

Figure 7: Radar Antenna Dimensions

Angular resolution is greatly affected by the width of the radar antenna. For a radius of 50 m away from the spacecraft, a 2 m wide antenna gives a total angular resolution of 2.2 m, but as the astronaut gets farther away from the lander, the angular resolution diminishes. At the full distance of 2000 m, the horizontal resolution increase to 87.3 m. This angular resolution meets the NASA requirement of position knowledge to within 100 m. Because the beam signal strength will still be maximized when pointed directly at the astronaut, this is a worst case value for angular resolution. In addition, NASA's design goal of position knowledge to within 10 m is possible when the astronaut is within 229 m of the lander.

4.2 Astronaut Dipole Antennas

The astronaut back pack is equipped with three dipole antennas, each having a gain of 9 dBi. These antennas are omni-directional antennas, much like WiFi antennas, which allow communication in all 360° azimuth. They are light enough for the astronaut to carry several antennas.

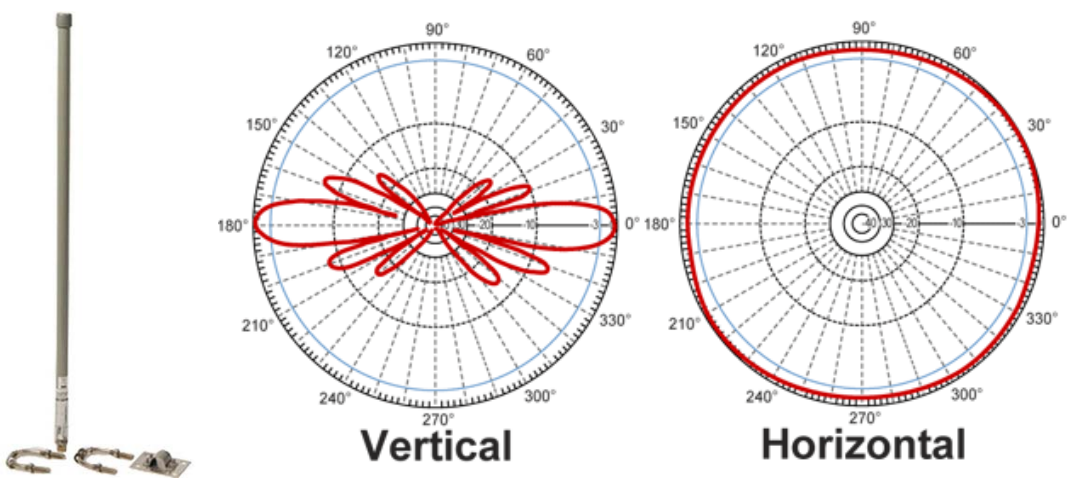

Figure 8: Astronaut Dipole Antenna (left) with Example Gain Patterns

One antenna is used as the main communication antenna with the lander. The other two antennas provide the RFID tag interrogator stimulus and response reception. They provide a coarse RSS measurement to determine distance of the most recently dropped RFID tag. In addition to distance information, having two antennas provides phase information about the RFID tag. The RFID response is received at 2.4 GHz which has a wavelength of 12.5 cm. If the astronaut is standing so that the distance between the antennas is not exactly equidistant from the RFID tag, they will receive the responses at slightly different times and in slightly different phases. If the two responses are directly in phase, the tag is either directly in front or directly behind the astronaut. The phase

difference will be less than or equal to one wavelength distance because the antennas are spaced exactly one wavelength apart.

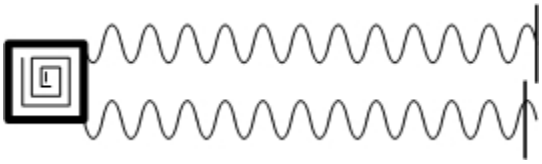

Figure 9: RFID to Dual Astronaut Dipole Antennas. The lower antenna receives the signal prior to the upper antenna, implying that the lower antenna is closer to the RFID tag. This difference provides approximate angular position of RFID tag with respect to ast

Knowing the phase difference requires a third piece of information to differentiate between the two possible positions that lie 180° away from each other. This third data point is provided by the dip in receiver antenna gain corresponding with the shadowing from the astronauts head as the astronaut rotates.

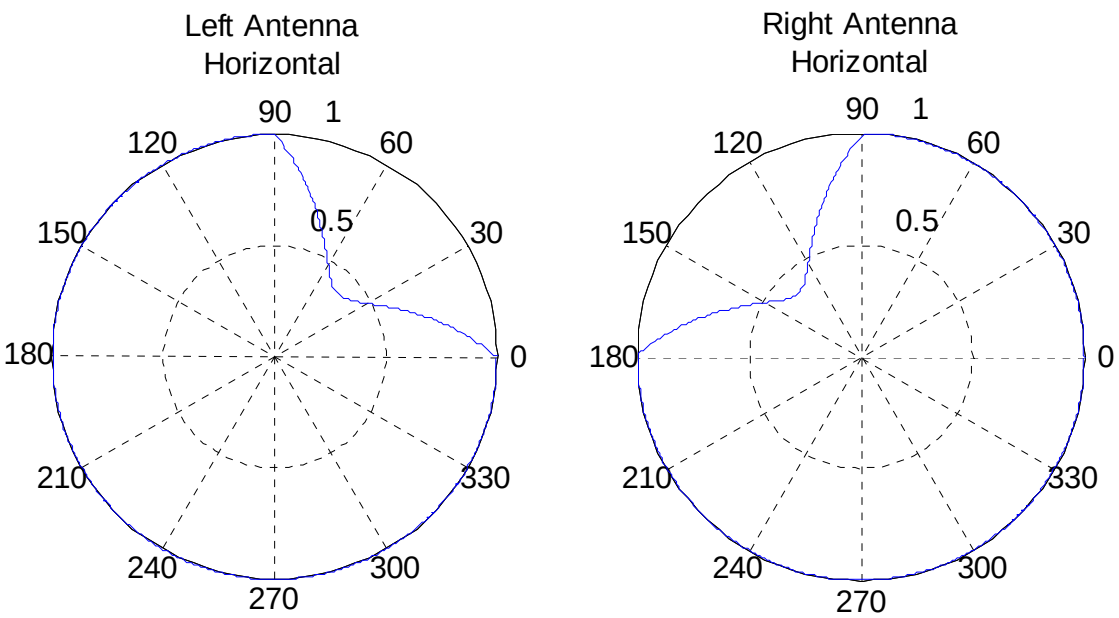

Figure 10: Dipole Horizontal Example Gain Pattern. The antennas are omnidirectional antennas in the horizontal direction, but the pressents of the astronauts' head will cause shadowing in one quadrant of the gain pattern

The astronaut can determine the azimuth angle between himself and an RFID tag by rotating a full 360°. As the astronaut rotates the antennas will go from being slightly out of phase in direction, to being in phase, to being slightly out of phase in another direction. Correlating this to when the gain pattern is weakest with the antennas will provide the azimuth of the RFID tag.

As an example, if the backscattered signals are received as $S_L = A * \sin(2\pi (1 / f) t)$ and $S_R = A * \sin(2\pi (1 / f) t + (3\pi / 4))$, the system can not tell if S2 is out of phase by $+ (3\pi / 4)$ or $+ (7\pi / 4)$, a difference of π or 180°. If S2 has a reduced amplitude of (A / 3), it can be determined that the RFID tag is roughly in the quadrant containing interference from

the astronauts head. This eliminates one of the possible phase angle locations of the RFID tag and provides the location of the tag with respect to the astronaut.

5 Modulation and Coding

5.1 Lander/Astronaut Communication

For communication from the lander to the astronaut, raised cosine Quadrature Phase Shift Keying (QPSK) with a Grey Code signal constellation (shown below) is used as the modulation scheme, ensuring efficient bandwidth usage and minimum bit error rate.

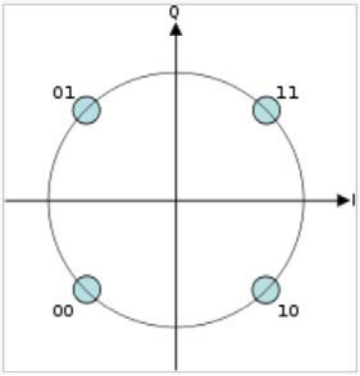

Figure 11: π/4 QPSK Grey Coded Signal Constellation

The roll-off factor for the raised cosine pulses will be 0.9. The frequency of communication from the lander to the backpack will be 2.5 GHz in the S-Band. A data rate of 100 kbps is required, which requires a Nyquist sampling rate of 200 kbps. Since two symbols are sent simultaneously in QPSK, a total bandwidth of 100 kHz is required. In order to provide margin on the sampling, twice the Nyquist sampling rate is used, for a total bandwidth requirement of 400 kbps. The data is encoded with a rate ⅓ Turbo Code to further improve the BER. This triples the bandwidth requirement to 1.2 MHz. Data will be sent as 8 bit words.

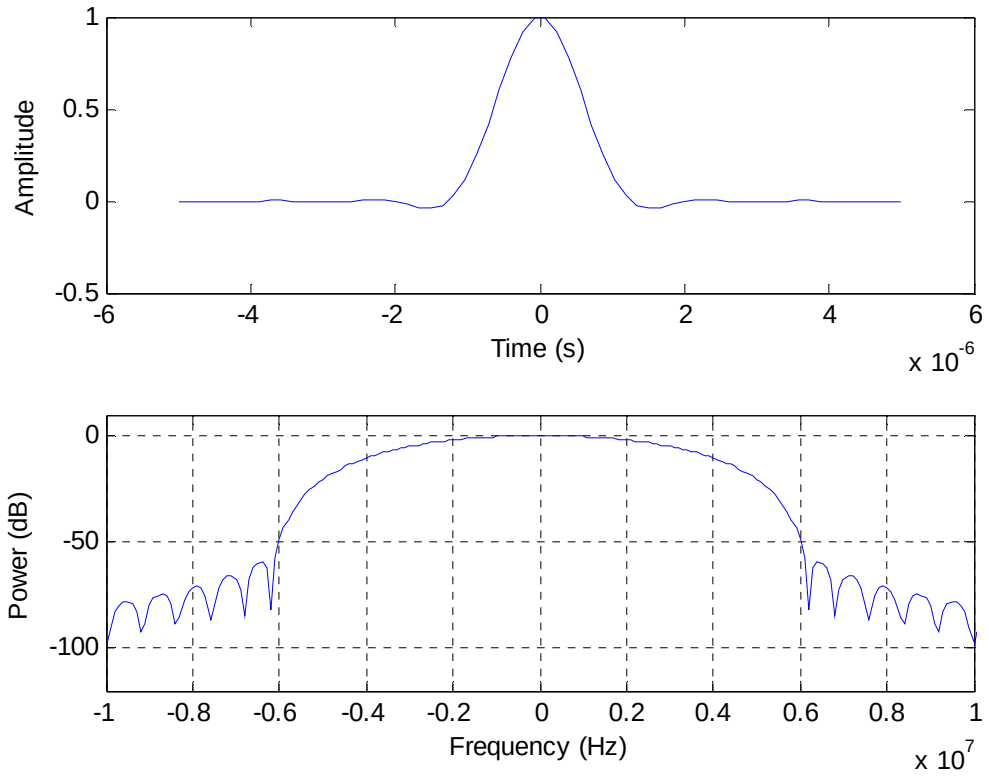

Figure 12: Raised Cosine Pulse with roll off factor of 0.9 (top) and the frequency domain plot of a pulse with 2.5 µs period (400 kbps).

In order to measure an accurate time of flight measurement from the lander to the astronaut, the astronaut's main communication antenna must act as a bent pipe with the lander's distance poling transmissions. To facilitate normal communication on the same link as the distance poling, Direct Sequence Spread Spectrum (DSSS) Code Division Multiple Access is used. An 8-bit chipping sequence is used to encode the data transmissions from the lander and the astronaut, causing the bandwidth to increase from 1.2 MHz to 9.6 MHz.

The three communication links are performed on different frequencies: RFID tag interrogation is centered at 2.4 GHz, astronaut to lander communication is centered on 2.45 GHz, and lander to astronaut communication is centered on 2.5 GHz, as shown in the figure below.

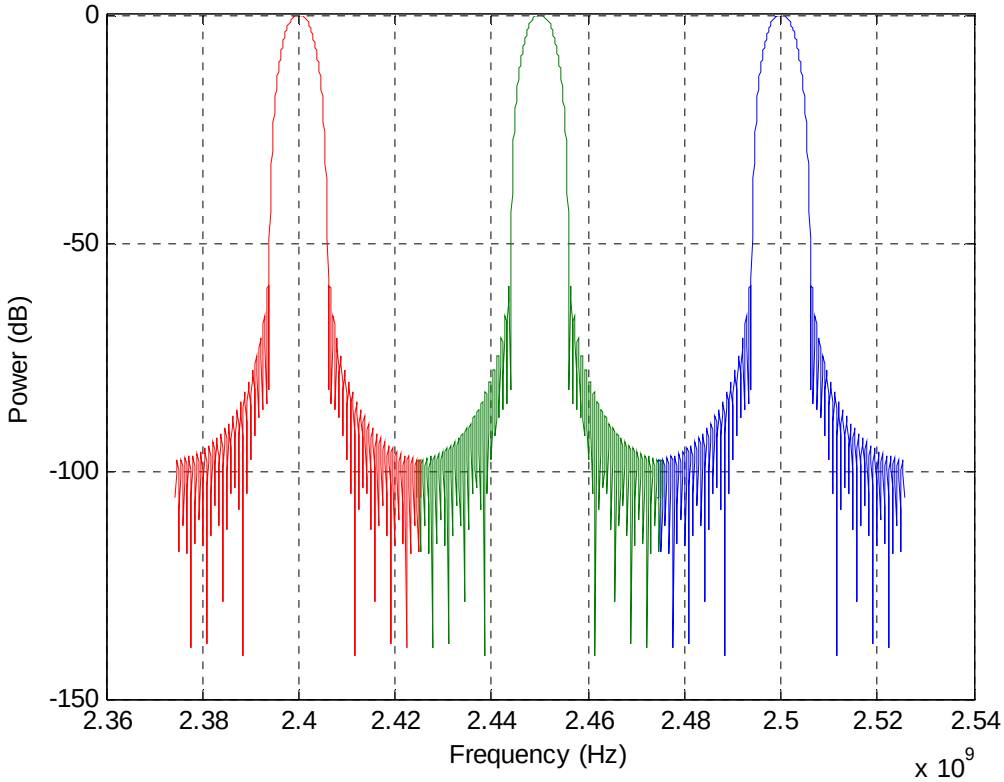

Figure 13: Frequency Allocation for lunar communication. Lander to Astronaut communication is centered around 2.5 GHz, Astronaut to Lander Communication is centered around 2.45 GHz, and RFID tag interrogation is centered at 2.4 GHz

Based on the spectral components of a raised cosine pulse with 0.9 rolloff and a bandwidth of 9.6 MHz, none of the unique communication links interfere with each other. The chirp and communication information are multiplied together, adding interference to the Signal to Noise Plus Interference Ratio (SNIR). The interference noise is compensated for by the increase in SNIR from the DSSS by adding back in the eight chips per bit.

5.2 RFID Interrogation

The RFID tag uses Pulse Interval Encoded (PIE) modulation to transmit its data. The data is merely a unique index identifier. The tags are dropped in sequential numerical order, allowing the lander computer to plot the path of the astronaut in a "connect the dots" manner.

The Radar antenna sends a brief "chirp" to excite the RFID tag. The width of this chirp determines the resolution of the radar, as described in [6]. It is given according to the bandwidth by PW = ½ P_B. The bandwidth of this link is 10 kHz, so the pulse width is 0.1 mm.

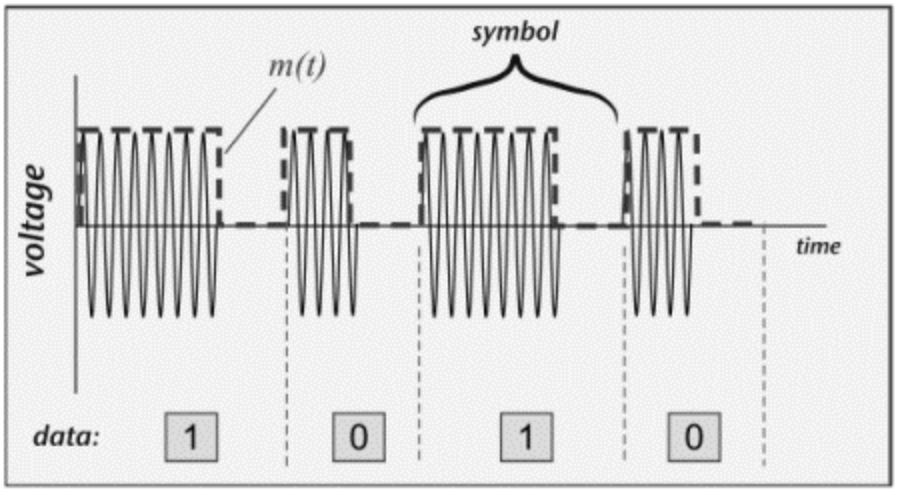

Figure 14: Pulse Interval Encoded (PIE) Modulation for RFID tags

6 Link Budgets

6.1 Fundamental Design

6.1.1 Lunar Link Budgets

All link budgets for the lunar surface are derived with the same assumptions. The three major physical factors contributing to loss in a lunar link budget are the free-space path loss, multipath loss, and shadowing loss. Both the multipath and the shadowing losses depend heavily on the topology of the landscape of the lunar surface, for which there is no model.

Multipath losses are caused by constructive and destructive interference created by the radio signal bouncing off of the lunar surface, which is similar enough to a terrestrial application that the same modeling can be used. As shown in [8], the Multipath losses follow a Rayleigh distribution and a statistical model may be applied to estimate the losses to a high accuracy. For many approximations, the Multipath loss standard deviation is 7.5 dB with a log-normal distribution.

There is no terrestrial analog to Lunar shadowing, but a worst case comparison can certainly be drawn between lunar terrain and a down-town, urban environment [2]. Consequently, the lunar surface will exhibit "slow fading" nulls created by shadowing losses modeled with a log-normal distribution [8]. Standard deviations for urban environments are estimated between 4 and 14 dB.

6.1.2 Erceg Path Loss Model

The Erceg path loss model for suburban environments [10] is used to determine path losses for the lunar environment over the range of distances from adjacent to the Altair to 2000 m away from it. The Erceg model accounts for multipath and shadowing modeled as log-normal distributions. This model was chosen over other models such as the Hata

model because of its' improved resolution over longer distances and because the model accounts for height of the transmitter. Given the requirement to maintain communications at 2000 m and the availability of the Altair for mounting the transmit antenna at a 10 m height, these were useful components to improve model accuracy.

The Erceg model for path loss is given by:

$$PL = [A + 10\gamma\log_{10}(d/d_o)] + [10x\sigma_\gamma\log_{10}(d/d_o) + y\mu_\sigma + yz\sigma_{\sigma]}; d \geq d_o, dB$$

where the first bracketed term is median path loss at distance d and the second term is the random variation about that median. The path loss exponent, $\gamma = (a - bh_b + c/h_b)$, takes into account base station height, h_b, in meters and improves (decreases) with height. For a base station on the top of the Altair at 10 m, the path loss exponent is $\gamma = 4.05$. The parameters a, b, and c vary with terrain, and are given in [10]. The variables x, y, and z are independent Gaussian variables of unit standard deviation. Given Erceg's Terrain model parameters and likening the lunar surface to the "Flat/Light Tree Density" terrain category, the path loss increases with distances as shown below:

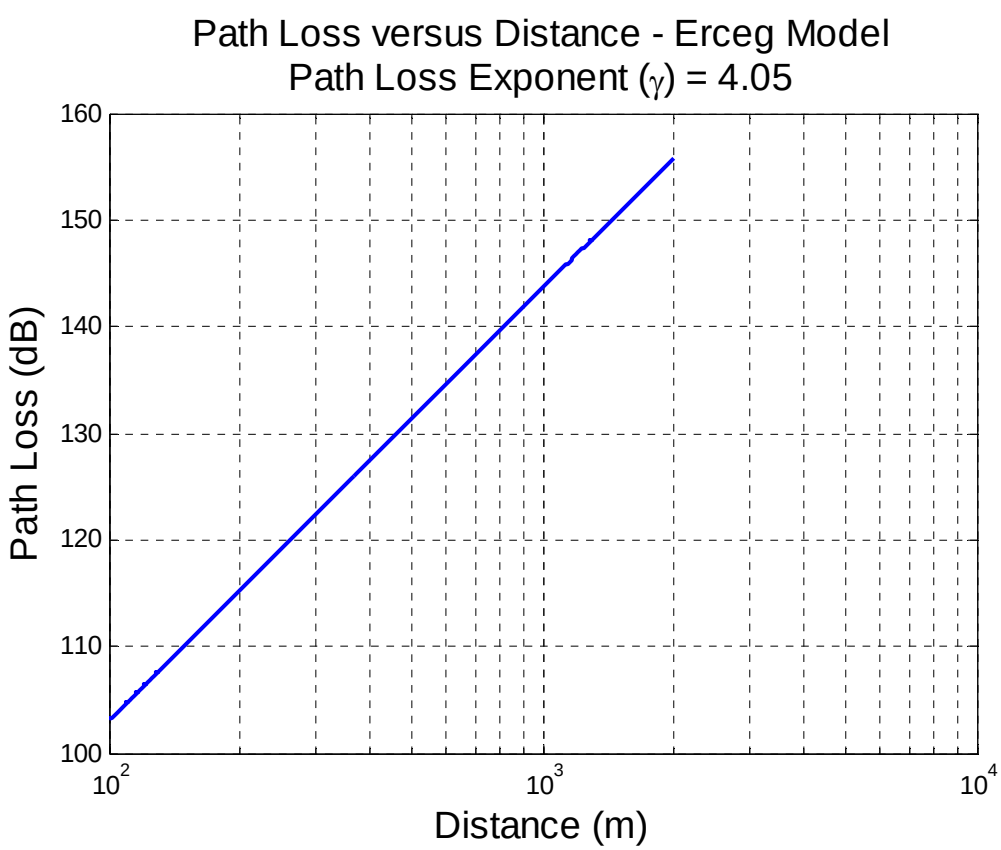

Figure 15: Path Loss given by Erceg Propagation Model

6.1.3 Noise Temperature

For noise temperature calculations, the two components most responsible for system noise are physical noise of the environment and the device noise of the Low Noise Amplifier, the first major component in a standard Superheterodyne receiver [13]. Very little information is available about the noise temperature of lunar surface communications because very little RF communication has been attempted on the moon; for our purposes, we assume a worst-case "room temperature" value of 270 K. In [12], Kuo describes a Low-Noise Amplifier with a noise figure of 2.78 dB and points to other LNAs with similar NFs varying from 1.36 to 3.3 dB.

Reference	f [GHz]	NF [dB]	S_{21} [dB]	P_{diss} [mW]	IIP_3 [dBm]	SiGe HBT peak f_T [GHz]	FOM_1 [dB/mW]	FOM_2 [1/mW]
This work	9.5	2.78 mean	11.0	2.5	-9.1	180	4.40	1.58
[8]	10.0	1.36 mean	19.5	15.0	0.8	200	1.30	1.71
[10]	10.0	1.68	24.2	33.6	-6.7	120	0.72	1.02
[11]	8.2	1.6	22.0	14.4	-	70	1.53	1.96
[12]	10.5	2.0	26.3	26.6	-	80	0.99	1.33
[13]	10.0	3.3	15.0	43.2	-6.8	50	0.35	0.11

Figure 16: Comparative Noise Temperatures for Low Noise Amplifiers (LNAs) [12]

A NF of 2.78 dB taken at room temperature translates roughly to a noise temperature of 270 K. This total is doubled (1000 K per link) to ensure margin on the signal-to-noise (SNR) calculations below. The total noise power is -137.8 dBW.

6.1.4 BER Calculations

To calculate Bit Error Rate, the Carrier to Noise ratio (CNR) at the receiver must be calculated. BER for QPSK is given by BER = Q[(SINR) ^ ½] for linear SINR. Given the constant SINR of 60 dB, the BER is negligible.

6.2 Individual Communication Links

6.2.1 Lander to Astronaut Link Budget

Because the lander and astronaut will have to communicate in a range from 10 to 2000 m, the power transmission on the lander antenna will have to be varied with distance to avoid saturating the LNA on the astronaut's backpack. Much like a terrestrial cell phone network, the lander antenna will begin with as little power as possible to maintain acceptable communications and increase as the astronaut moves farther away. With this in mind, the link budget is designed for the worst case scenario when an astronaut is communicating with the lander at 2000 m. The variable transmit power was not included in these calculations, instead always assuming the maximum transmit power of 10 W. Communication is performed at 2.5 GHz.

Lander to Astronaut Characteristics

Modulation	QPSK	
Quantization	8	bits
Comms Frequency	2.5	GHz
DSSS Chips per Bit	8	Chips

Lander to Astronaut Link Budget

	Description	linear	exp	log	
PT	Tranmit Power	10.00	1	10.00	dBW
GTR	Transmitter Antenna Gain	1005.73	1	30.02	dB
Gr	Receiver Antenna Gain	7.94	1	9.00	dB
lambda	Wavelength	0.12	2	-18.24	dB
4pi	constant	12.57	-2	-21.98	dB
r	Distance	2000.00	-2	-66.02	dB
Le	Erceg Path Loss	0.01	-1	-19.50	dB
PR	**Antenna Received Power**	**2.13E-08**	**W**	**-76.72**	**dBW**

NOISE POWER CALCULATION

k	Boltzman's constant		1	-228.60	dBW/K/Hz
Ts	System noise temperature	1000.00	1	30.00	dBK
Bn	Noise bandwidth	1.20E+06	1	60.79	dBHz
N	**Receiver noise power**	**1.66E-14**	**W**	**-137.81**	**dBW**

Signal to Noise Ratio

SNR	**PR(dB) - N(dB)**	**61.09**	**dB**

Signal to Noise Ratio (with Turbo Code Gains)

SNR	**SNRq + (PR(dB) - N(dB))**	**109.09**	**dB**

Signal to Interference + Noise Ratio (with DSSS Gains)

SINR	**Q*M*Pr / Pn+(Pr/2)**	**60.04**	**dB**

Figure 17: Lander to Astronaut Communication Link Budget

Received signal strength in the link budget varies with distance. The Erceg model uses a fixed offset A, taken as the free space path loss at do = 100 m, as the intercept of the path loss model, for which distances less than 100 m are not accurately predicted by this model. Since the link budget is designed with the worst case at 2000 m, the received power will never be less than this for distances closer than 100 m. The backpack received power from 100 to 2000 m is given below.

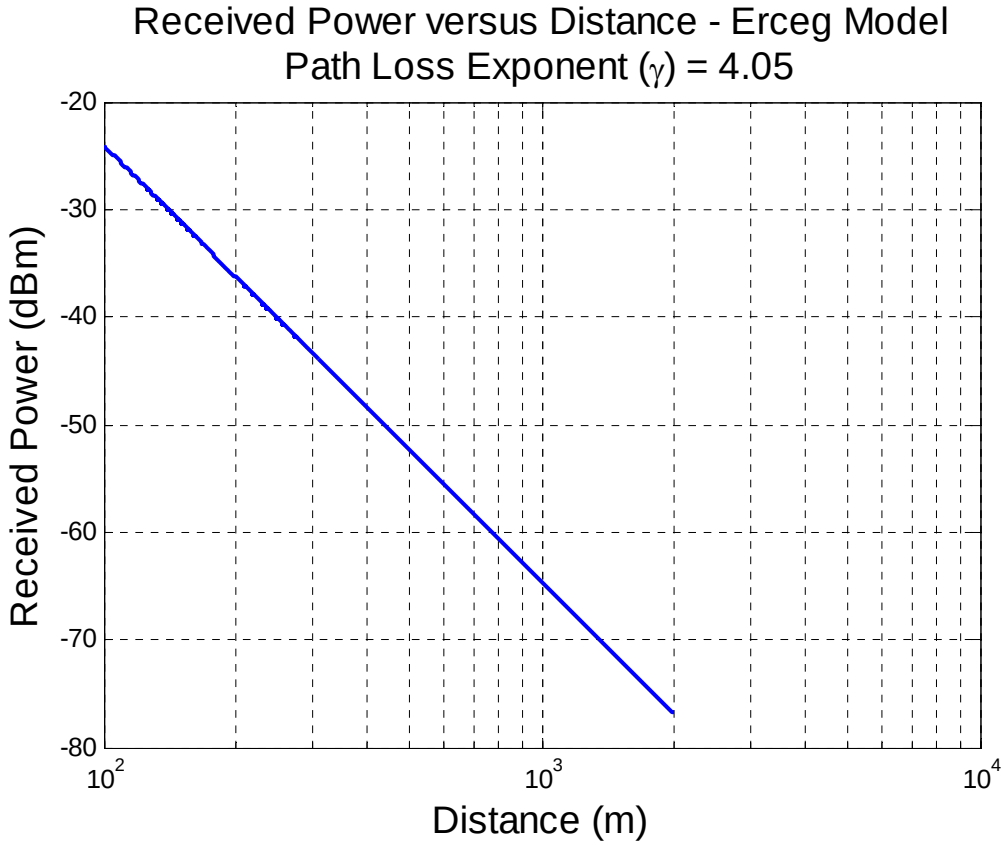

Figure 18: Lander to Astronaut Received Power versus Distance

Received power is calculated to be at least 10 nW, even at 2000 m. Because of the narrow bandwidth required for this communication, an SNR of 60 dB is achievable with Turbo Coding, allowing substantial margin for unexpected losses. This also allows the transmit antenna to run the closed loop pointing control algorithm which sweeps from side to side. Communication with the backpack is still possible even when the radar is pointed several degrees off maximum from the astronaut.

It is interesting to note that, since the received power varies logarithmically with distance and the interference power is taken to be half of this power, the SINR is constant for all values of transmit power and receiver distance. The SINR of the system for all communication between the lander and the astronaut is 60 dB, a healthy SINR which provides adequate margin to accommodate unforeseen losses.

The backscattered received power from the backpack follows the radar equation [1] and is given below:

Lander Backscatter Characteristics

Modulation	QPSK	
Quantization	8	bits
Comms Frequency	2.5	GHz
DSSS Chips per Bit	8	Chips

Lander Backscatter Link Budget

	Description	linear	exp	log	
PT	Tranmit Power	10.00	1	10.00	dBW
GTR	Transmitter Antenna Gain	1458.31	2	31.64	dB
Gr	Receiver Antenna Gain	7.94	2	9.00	dB
lambda	Wavelength	0.12	4	-36.48	dB
4pi	constant	12.57	-4	-43.97	dB
r	Distance	2000.00	-4	-132.04	dB
Le	Erceg Path Loss	0.01	-1	-19.50	dB
PR	**Antenna Received Power**	**7.32E-19**	**W**	**-181.35**	**dBW**

NOISE POWER CALCULATION

k	Boltzman's constant		1	-228.60	dBW/K/Hz
Ts	System noise temperature	1000.00	1	30.00	dBK
Bn	Noise bandwidth	1.20E+06	1	60.79	dBHz
N	**Receiver noise power**	**1.66E-14**	**W**	**-137.81**	**dBW**

Signal to Noise Ratio

SNR	**PR(dB) - N(dB)**	**-43.54**	**dB**

Signal to Noise Ratio (with Turbo Code Gains)

SNR	**SNRq + (PR(dB) - N(dB))**	**4.46**	**dB**

Signal to Interference + Noise Ratio (with DSSS Gains)

SNR	**M*Pr / Pn+(Pr/2)**	**13.49**	**dB**

Figure 19: Lander Received Backscatter Power Link Budget

Even with a roundtrip path, enough power comes through the backscattered power from the radar antenna to maintain an SNR of 13.5 dB, enough SNR to fully recover the signal.

6.2.2 Astronaut to Lander Link Budget

The astronaut to lander link budget is very similar to the lander to astronaut budget, except that the lander backpack is far more power limited. The backpack is capable of a continuous power output of 1 W to the antenna. Because this is an omni-directional antenna, power is radiated equally in all radial directions but is limited in the vertical direction to roughly perpendicular to the antenna.

Astronaut to Lander Characteristics

Modulation	QPSK	
Quantization	8	bits
Comms Frequency	2.5	GHz
DSSS Chips per Bit	8	Chips

Astronaut to Lander Link Budget

	Description	linear	exp	log	
PT	Tranmit Power	1.00	1	0.00	dBW
GTR	Transmitter Antenna Gain	1005.73	1	30.02	dB
Gr	Receiver Antenna Gain	7.94	1	9.00	dB
lambda	Wavelength	0.12	2	-18.24	dB
4pi	constant	12.57	-2	-21.98	dB
r	Distance	2000.00	-2	-66.02	dB
Le	Erceg Path Loss	0.01	-1	-19.50	dB
PR	**Antenna Received Power**	**2.13E-09**	**W**	**-86.72**	**dBW**

NOISE POWER CALCULATION

k	Boltzman's constant		1	-228.60	dBW/K/Hz
Ts	System noise temperature	1000.00	1	30.00	dBK
Bn	Noise bandwidth	9.60E+06	1	69.82	dBHz
N	**Receiver noise power**	**1.33E-13**	**W**	**-128.78**	**dBW**

Signal to Noise Ratio

SNR	**PR(dB) - N(dB)**	**42.06**	**dB**

Signal to Noise Ratio (with Turbo Code Gains)

SNR	**SNRq + (PR(dB) - N(dB))**	**90.06**	**dB**

Signal to Interference + Noise Ratio (with DSSS Gains)

SINR	**M*Pr / Pn+(Pr/2)**	**60.04**	**dB**

Figure 20: Astronaut to Lander Communication Link Budget

Again, notice the SINR is 60 dB, despite the change in transmit power.

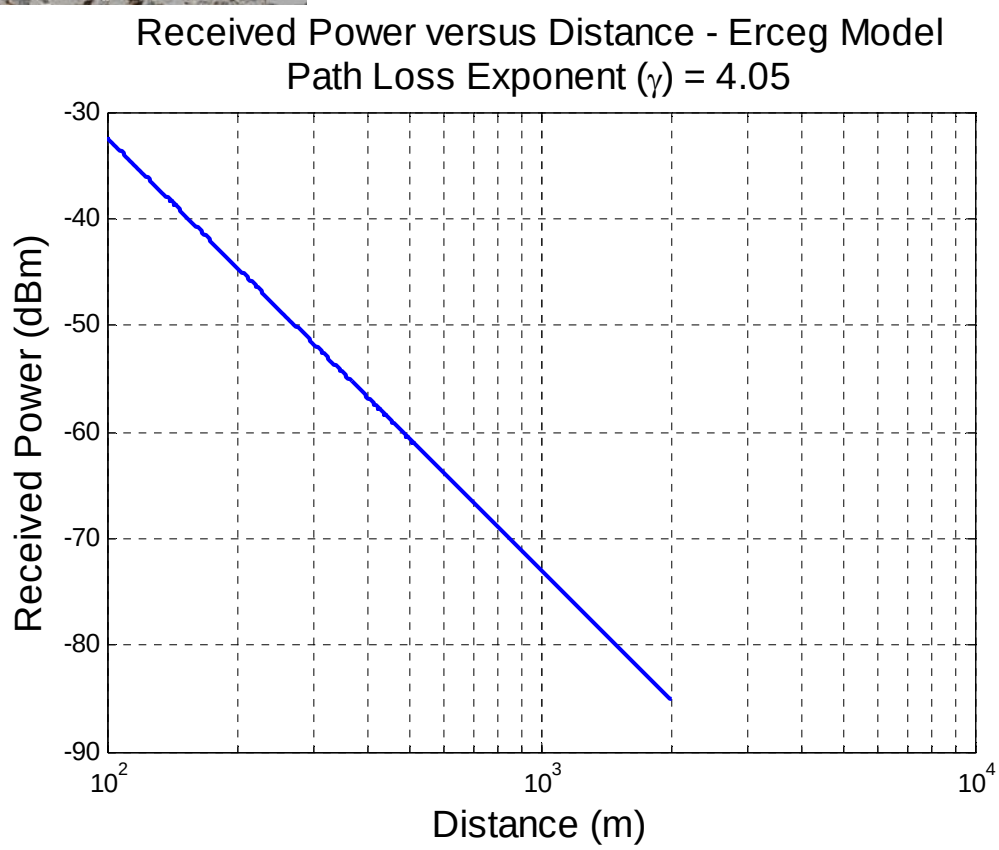

Figure 21: Astronaut to Lander Received Power versus Distance

6.2.3 Astronaut to RFID Tag Link Budget

Communication between the astronaut and the RFID tags is performed with the two interrogator antennas with 9 dBi gain and the RFID tags with 0 dBi gain. The RFID tag must receive adequate radiated power to power-up the onboard IC enough to respond with a transmission of its unique identifier index. The interrogator message is a long burst of power at 2.4 GHz. The link budget for monostatic backscatter for communication with an RFID tag proposed in [4] is used as the propagation model:

$$P_R = \frac{P_T G_{TR}^2 G_t^2 \lambda^4 X^2 M}{(4\pi r)^4 \Theta^2 B^2 F_2}$$

where P_R is the received power at the reader, P_T is the transmit power, G_{TR} is the gain of the interrogator/receiver, G_t is the gain of the RFID tag, λ is the wavelength, X is polarization mismatch, M is the modulation factor, Θ is the on-object gain factor, B is the path blockage, and F is the backscatter fade margin. This model is more appropriate for the link between the RFID tag and the astronaut because it is more accurate over short distances than the Erceg model. It takes into account factors that are specific to RFID tag communication which the Erceg model does not incorporate. Based on this model, the RFID tag will receive enough power from an interrogator with a power of 1 W at a maximum distance of 4.5 m. The power received by the RFID tag must be at least -20 dBm in order to ensure enough power to relay the tags information

Power Received at RFID Tag

	Description	linear	exp	log	
PT	Tranmit Power	1.00	1	0.00	dBW
GTR	Receiver/Transmitter Antenna Gain	7.94	1	9.00	dB
Gr	RFID Antenna Gain	1.00	1	0.00	dB
lambda	Wavelength	0.13	2	-18.06	dB
X	Polarization mismatch	0.50	1	-3.01	dB
M	Modulation factor	0.25	1	0.00	dB
4pi	constant	12.57	-2	-21.98	dB
r	Distance	4.50	-2	-13.06	dB
omega	On-object gain penalty (acrylic)	1.29	-1	-1.10	dB
B	Path blockage	1.50	-1	-1.76	dB
F2	(Mono) backscatter fade margin	1.00	-1	0.00	dB
PR	**Antenna Received Power**	**1.00E-05**	**W**	**-49.98**	**dBW**
				-19.98	**dBm**

Figure 22: RFID tag Received Power from Backpack Link Budget

The total backscattered radiation back to the backpack is given by the equation in [4] as

Backscatter Power Received at Backpack Tag

	Description	linear	exp	log	
PT	Tranmit Power	1.00	1	0.00	dBW
GTR	Receiver/Transmitter Antenna Gain	7.94	2	9.00	dB
Gr	RFID Antenna Gain	1.00	2	0.00	dB
lambda	Wavelength	0.13	4	-36.12	dB
X	Polarization mismatch	0.50	2	-6.02	dB
M	Modulation factor	0.25	1	-6.02	dB
4pi	constant	12.57	-4	-43.97	dB
r	Distance	4.50	-4	-26.13	dB
omega	On-object gain penalty (acrylic)	1.29	-2	-2.20	dB
B	Path blockage	1.50	-2	-3.52	dB
F2	(Mono) backscatter fade margin	1.00	-1	0.00	dB
PR	**Antenna Received Power**	**3.17E-12**	**W**	**-114.98**	**dBW**
				-84.98	**dBm**

Figure 23: Backpack Received Backscattered Power Link Budget

With a noise power of -158.6 dBW (with System Temperature at 1000 K and bandwidth of 10 kHz), the SNR of the backscattered communication received by the backpack antenna is 43.62 dBW.

7 Power

7.1 Solar Cells

The power for *THESEUS'* STRING will come exclusively from solar cells. For the lander, portions of the upper deck of the lander can be covered with solar cells. For the astronaut, the upper half of the astronaut's backpack can be covered with solar cells. The

solar cells selected for this mission are the E6M+ BlackPower solar cells made by Ersol and have power efficiency between 17-15% [14]. They are 15.6 cm x 15.6 cm (~ 6" x 6"). The cells provide a maximum of 4 W of peak power output. A total of 3 cells can be mounted to the pack, allowing a peak power of 12 W. For the lander, a total of approximate 1000 cells can be mounted on the top surface of the lander, allowing a total power budget of 4000 W. *THESEUS* assumes this power is required for all station keeping operations and requires a small percentage of this power to operate. A maximal estimate of 20 W is required to power the lander operations of *THESEUS*.

7.2 Backpack Power Unit

A peak power tracker, voltage conditioning unit, and Lithium-Ion batteries will be included in the backpack. The peak power tracker will regulate the output of the solar cells and monitor the health of the batteries. The voltage conditioning unit will provide low voltage to the digital electronics and 28 V to the antennas. Only one antenna can be transmitting at any given time, and the power unit controls when the interrogator antennas or the lander antenna can transmit. The batteries are made by Saft and provide 15 years of operation with only 80% Depth of Discharge [15]. Solar cell health and battery health is relayed to the lander as telemetry.

7.3 Lifetime

The only limitation for system operational time is the position of the sun to power the solar arrays. Battery backup is minimal to reduce mass of the backpack and can only power the system for approximately 2 hours after sunset. All materials used are radiation qualified, high reliability producing a total system mean time between failure of 100,000 years. *THESEUS'* STRING may be used on multiple sorties per lunar mission.

8 Instructions for the Astronaut

The cheap and expendable nature of the RFID tags allows a purely mass-limited number of RFID tags to be carried and dropped by the astronaut. The astronaut is encouraged to drop an RFID tag roughly every 5 meters so as to provide a clear trail back to the lunar lander. It is also recommended that for every turn in the astronauts' path, a tag is dropped, helping to clarify the resultant lunar map and ease return to lander operations. RFID tags should be placed in elevated locations where possible, in order to facilitate communication with the lander. Placing a tag in a shadow or depression should be avoided.

The RFID tags must be carried in a conductive, easy to access pouch on the astronauts' person in order to shield them from excitation by the backpack antenna until deployed. A cluster of RFID tags would cause interference in the channel.

9 Schedule

Schedule is given in Appendix A. Schedule assumes funding in the new year, and begins work on January 11, 2010. A single prototype unit and a single flight unit are built. All work concludes in Q1 of 2013, for total project duration of 3 years. A 120 day reserve is maintained to cushion schedule slip.

10 Costing

Costing includes company overhead. A 25% reserve is maintained to account for cost growth. This is separate from a fully funded 120 day schedule reserve. All work will be performed onsite. Per task costing is provided in Appendix B. All material, equipment, and supply costs are encapsulated under "Hardware Procurement." Miscellaneous extraordinary costs will come out of the reserve budget. Costing accounts for overhead costs

Position	Cost
Management	$1,590k
Engineering	$4,995k
Technician	$240k
Hardware Procurement	$1,213k
Subtotal	**$8,0374k**
Reserve (25% of Subtotal)	$2,010k
TOTAL	**$10,050k**

Milestones include individual design reviews, a Mission Preliminary Design Review (PDR) and a Mission Critical Design Review (CDR). Flight hardware fabrication will not begin until Mission CDR is passed.

11 Conclusions

THESEUS STRING allows astronauts on the moon the opportunity to explore the lunar surface unhampered by the concern of having to navigate for themselves. *THESEUS'* STRING is a light weight, low power system, yet is still designed with reliability in mind. The initial development cost is affordable and the three year time to market allows the STRING to be fully developed well before human return to the moon. Man's return to the moon is the next step in the never ending saga of man's discovery of the universe. We are ready to take this next step in space exploration and *THESEUS'* STRING will help get us there.

CITATIONS:

[1] "Radar." *Wikipedia*. Web. <http://en.wikipedia.org/wiki/Radar>.

[2] "Team FREDNET." *Forums: Rover/Lander Link Budget*. 28 Jul 2010. phpBB, Web. 7 Dec 2009. <http://forum.teamfrednet.org/viewtopic.php?f=4&t=577&p=4987&hilit=multipath#p4987>.

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[4] Griffin, Joshua D., and Gregory D. Durgin. "Complete Link Budgets for Backscatter-Radio and RFID Systems." *IEEE Antennas and Propagation Magazine*. 51.2 (2009): 11-25. Print.

[5] Hsiong, W., S. Huntzicker, et al. (2009). Performance and area tradeoffs in space-qualified FPGA-based time-of-flight systems. Electronic Measurement & Instruments, 2009. ICEMI '09. 9th International Conference on.

[6] "Introduction to Naval Weapons Engineering COURSE SYLLABUS." *Federation of American Scientists*. 20 Jan 1998. US. Navy, Web. 7 Dec 2009. <http://www.fas.org/man/dod-101/navy/docs/es310/syllabus.htm>.

[7] Trotter, Matthew, Joshua Griffin, and Gregory Durgin. "Power-Optimized Waveforms for Improving the Range and Reliability of RFID Systems." *IEEE Int'l RFID Conference*. (2009): Print.

[8] Goldsmith, Andrea. *Design and Performance of High-Speed Communication Systems over Time-Varying Radio Channels.* 1st ed. Berkeley, CA: University of California Berkeley, 1994. Print.

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[10] Vinko Erceg, "An Empirically Based Path Loss Model for Wireless Channels in Suburban Environments"

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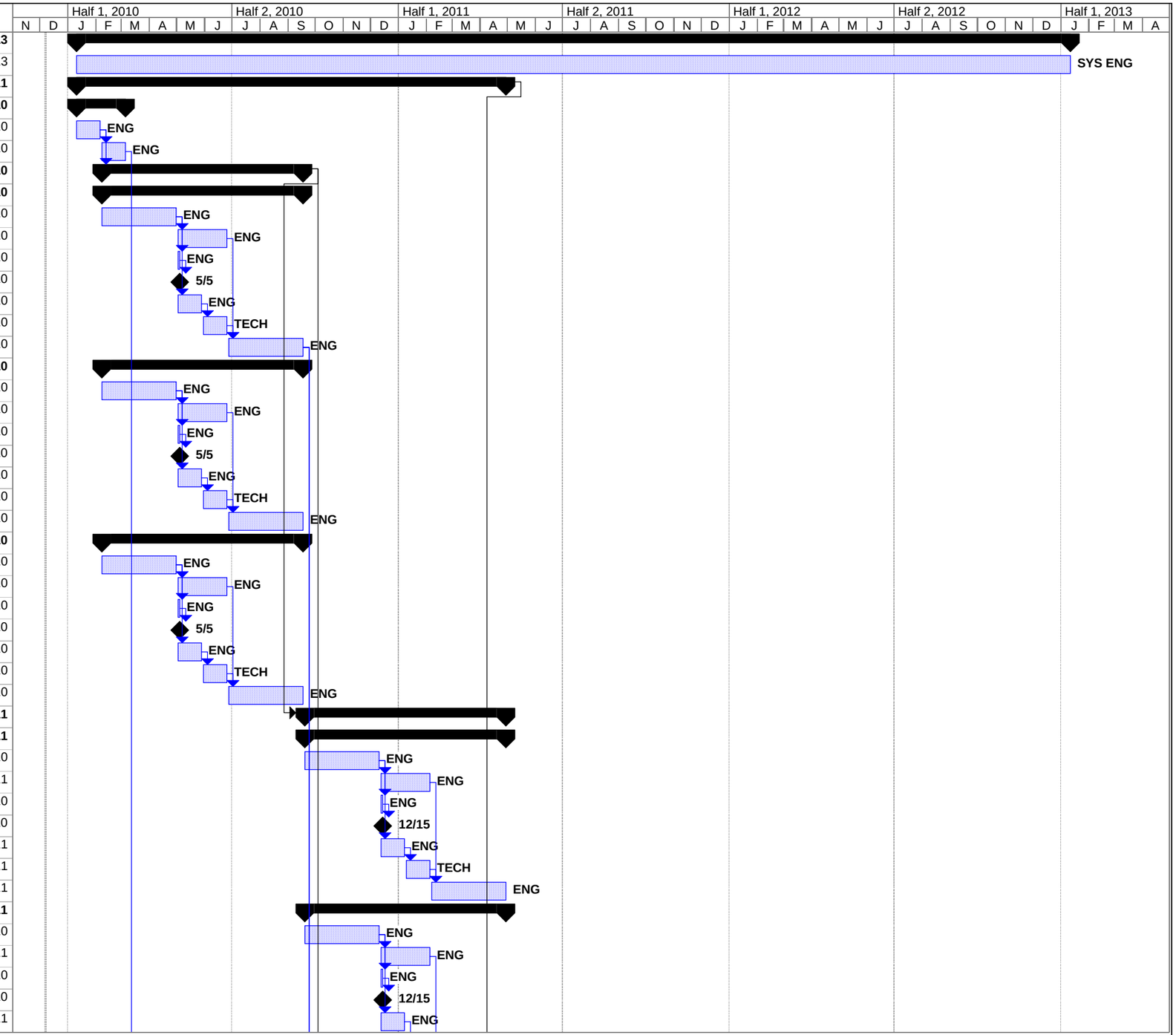
[13] Pratt, Timothy et.al. Satellite Communications. Chichester: John Wiley & Sons, 2003.

[14] "Solar Cell BlackPower", Ersoft E6M Solar Cell Datasheet, July 2007.

[15] "Rechargeable Lithium-Ion Battery; VL 48E – High Energy Space Cell", Saft Datasheet, September 2007.

Appendix A

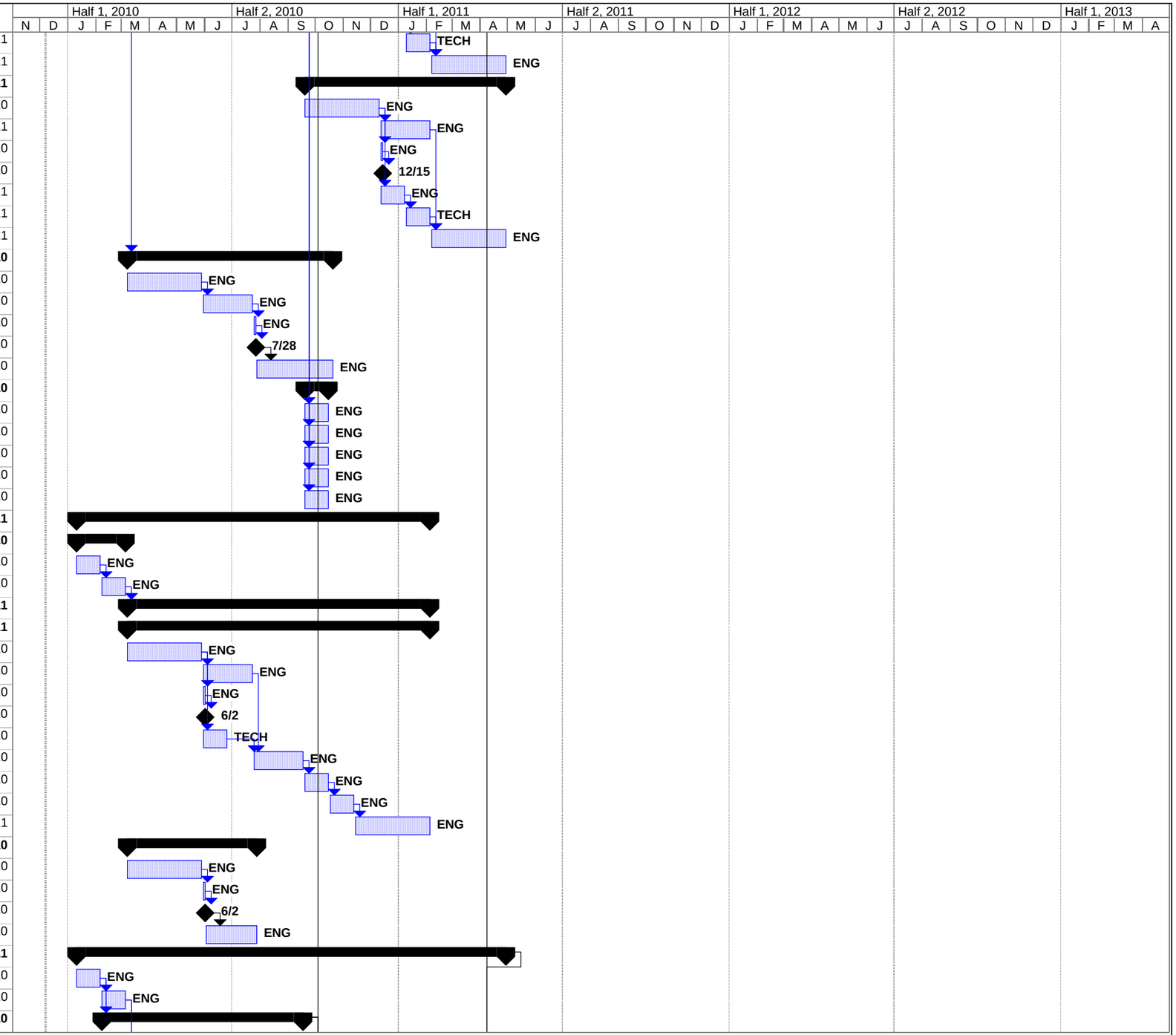
ID	Task Name	Work	Duration	Start	Finish
1	**System Design**	**6,280 hrs**	**785 days**	**Mon 1/11/10**	**Fri 1/11/13**
2	System Specification	6,280 hrs	785 days	Mon 1/11/10	Fri 1/11/13
3	**Base Station Design**	**12,112 hrs**	**340 days?**	**Mon 1/11/10**	**Fri 4/29/11**
4	**Base Station Specificatic**	**320 hrs**	**40 days**	**Mon 1/11/10**	**Fri 3/5/10**
5	Base Station Hardwar	160 hrs	20 days	Mon 1/11/10	Fri 2/5/10
6	Base Station Software	160 hrs	20 days	Mon 2/8/10	Fri 3/5/10
7	**Base Station Hardware E**	**4,848 hrs**	**160 days?**	**Mon 2/8/10**	**Fri 9/17/10**
8	**CPU Board**	**1,616 hrs**	**160 days?**	**Mon 2/8/10**	**Fri 9/17/10**
9	CPU Schematic I	480 hrs	60 days	Mon 2/8/10	Fri 4/30/10
10	CPU FPGA Desi	320 hrs	40 days	Mon 5/3/10	Fri 6/25/10
11	CPU Board Desi	16 hrs	2 days	Mon 5/3/10	Tue 5/4/10
12	Pass Board Desi	0 hrs	1 day?	Wed 5/5/10	Wed 5/5/10
13	CPU Layout	160 hrs	20 days	Mon 5/3/10	Fri 5/28/10
14	CPU Fabrication	160 hrs	20 days	Mon 5/31/10	Fri 6/25/10
15	CPU Testing	480 hrs	60 days	Mon 6/28/10	Fri 9/17/10
16	**Power Board**	**1,616 hrs**	**160 days?**	**Mon 2/8/10**	**Fri 9/17/10**
17	Power Schematic	480 hrs	60 days	Mon 2/8/10	Fri 4/30/10
18	Power FPGA Des	320 hrs	40 days	Mon 5/3/10	Fri 6/25/10
19	Power Board Des	16 hrs	2 days	Mon 5/3/10	Tue 5/4/10
20	Pass Board Desi	0 hrs	1 day?	Wed 5/5/10	Wed 5/5/10
21	Power Layout	160 hrs	20 days	Mon 5/3/10	Fri 5/28/10
22	Power Fabricatio	160 hrs	20 days	Mon 5/31/10	Fri 6/25/10
23	Power Testing	480 hrs	60 days	Mon 6/28/10	Fri 9/17/10
24	**RF Board**	**1,616 hrs**	**160 days?**	**Mon 2/8/10**	**Fri 9/17/10**
25	RF Schematic De	480 hrs	60 days	Mon 2/8/10	Fri 4/30/10
26	RF FPGA Desigr	320 hrs	40 days	Mon 5/3/10	Fri 6/25/10
27	RF Board Design	16 hrs	2 days	Mon 5/3/10	Tue 5/4/10
28	Pass Board Desi	0 hrs	1 day?	Wed 5/5/10	Wed 5/5/10
29	RF Layout	160 hrs	20 days	Mon 5/3/10	Fri 5/28/10
30	RF Fabrication	160 hrs	20 days	Mon 5/31/10	Fri 6/25/10
31	RF Testing	480 hrs	60 days	Mon 6/28/10	Fri 9/17/10
32	**Base Station Hardwar FM**	**4,848 hrs**	**160 days?**	**Mon 9/20/10**	**Fri 4/29/11**
33	**CPU Board**	**1,616 hrs**	**160 days?**	**Mon 9/20/10**	**Fri 4/29/11**
34	CPU Schematic I	480 hrs	60 days	Mon 9/20/10	Fri 12/10/10
35	CPU FPGA Upda	320 hrs	40 days	Mon 12/13/10	Fri 2/4/11
36	CPU Board Desi	16 hrs	2 days	Mon 12/13/10	Tue 12/14/10
37	Pass Board Desi	0 hrs	1 day?	Wed 12/15/10	Wed 12/15/10
38	CPU FM Layout	160 hrs	20 days	Mon 12/13/10	Fri 1/7/11
39	CPU FM Fabricat	160 hrs	20 days	Mon 1/10/11	Fri 2/4/11
40	CPU FM Testing	480 hrs	60 days	Mon 2/7/11	Fri 4/29/11
41	**Power Board**	**1,616 hrs**	**160 days?**	**Mon 9/20/10**	**Fri 4/29/11**
42	Power Schematic	480 hrs	60 days	Mon 9/20/10	Fri 12/10/10
43	Power FPGA Up	320 hrs	40 days	Mon 12/13/10	Fri 2/4/11
44	Power Board Des	16 hrs	2 days	Mon 12/13/10	Tue 12/14/10
45	Pass Board Desi	0 hrs	1 day?	Wed 12/15/10	Wed 12/15/10
46	Power FM Layou	160 hrs	20 days	Mon 12/13/10	Fri 1/7/11



Project: STRING
Date: Mon 12/7/09

Task | Split | Progress | Milestone | Summary | Project Summary | External Tasks | External Milestone | Deadline

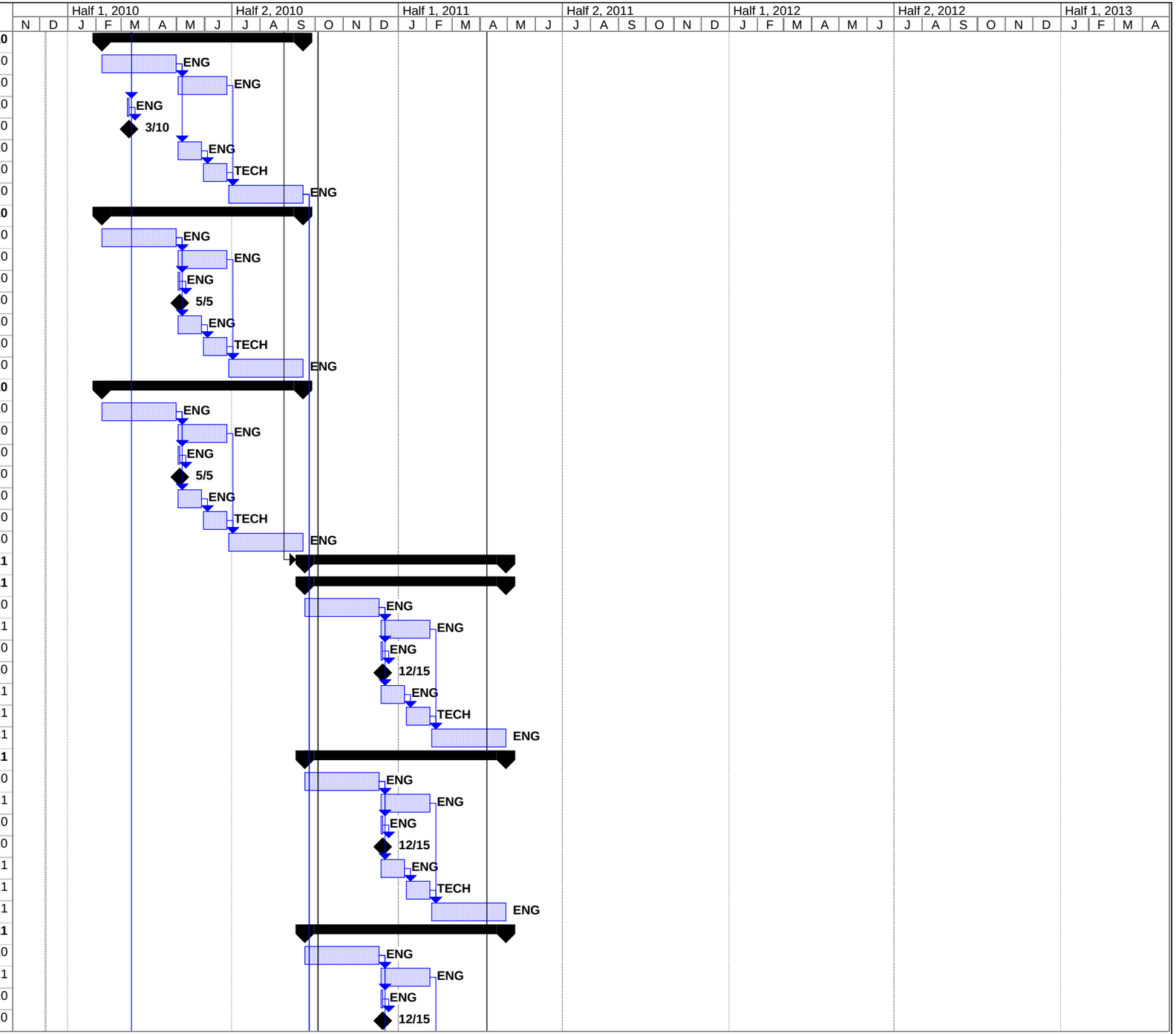
ID	Task Name	Work	Duration	Start	Finish
47	Power FM Fabric	160 hrs	20 days	Mon 1/10/11	Fri 2/4/11
48	Power FM Testin	480 hrs	60 days	Mon 2/7/11	Fri 4/29/11
49	**RF Board**	**1,616 hrs**	**160 days?**	**Mon 9/20/10**	**Fri 4/29/11**
50	RF Schematic Up	480 hrs	60 days	Mon 9/20/10	Fri 12/10/10
51	RF FPGA Update	320 hrs	40 days	Mon 12/13/10	Fri 2/4/11
52	RF Board Design	16 hrs	2 days	Mon 12/13/10	Tue 12/14/10
53	Pass Board Desi	0 hrs	1 day?	Wed 12/15/10	Wed 12/15/10
54	RF FM Layout	160 hrs	20 days	Mon 12/13/10	Fri 1/7/11
55	RF FM Fabricatic	160 hrs	20 days	Mon 1/10/11	Fri 2/4/11
56	RF FM Testing	480 hrs	60 days	Mon 2/7/11	Fri 4/29/11
57	**Base Station Software**	**1,296 hrs**	**163 days?**	**Mon 3/8/10**	**Wed 10/20/10**
58	Software Definition	480 hrs	60 days	Mon 3/8/10	Fri 5/28/10
59	Software Pseudocode	320 hrs	40 days	Mon 5/31/10	Fri 7/23/10
60	Code Review	16 hrs	2 days	Mon 7/26/10	Tue 7/27/10
61	Code Review Comple	0 hrs	1 day?	Wed 7/28/10	Wed 7/28/10
62	Software Prototyping	480 hrs	60 days	Thu 7/29/10	Wed 10/20/10
63	**Analysis**	**800 hrs**	**20 days**	**Mon 9/20/10**	**Fri 10/15/10**
64	Worst Case Timing Ar	160 hrs	20 days	Mon 9/20/10	Fri 10/15/10
65	Worst Case Circuit De	160 hrs	20 days	Mon 9/20/10	Fri 10/15/10
66	Parts Stress Derating	160 hrs	20 days	Mon 9/20/10	Fri 10/15/10
67	Radiation Analysis	160 hrs	20 days	Mon 9/20/10	Fri 10/15/10
68	Thermal Analysis	160 hrs	20 days	Mon 9/20/10	Fri 10/15/10
69	**Communication System Desi**	**3,232 hrs**	**280 days?**	**Mon 1/11/10**	**Fri 2/4/11**
70	**Comm System Specificat**	**320 hrs**	**40 days**	**Mon 1/11/10**	**Fri 3/5/10**
71	Communication Speci	160 hrs	20 days	Mon 1/11/10	Fri 2/5/10
72	Antenna Specification	160 hrs	20 days	Mon 2/8/10	Fri 3/5/10
73	**Comm System Hardware**	**2,912 hrs**	**240 days?**	**Mon 3/8/10**	**Fri 2/4/11**
74	**Antenna Design**	**2,096 hrs**	**240 days?**	**Mon 3/8/10**	**Fri 2/4/11**
75	Antenna Design	480 hrs	60 days	Mon 3/8/10	Fri 5/28/10
76	Antenna Prototyp	320 hrs	40 days	Mon 5/31/10	Fri 7/23/10
77	Antenna Design I	16 hrs	2 days	Mon 5/31/10	Tue 6/1/10
78	Pass Board Desi	0 hrs	1 day?	Wed 6/2/10	Wed 6/2/10
79	Antenna EM Fab	160 hrs	20 days	Mon 5/31/10	Fri 6/25/10
80	Antenna Testing	320 hrs	40 days	Mon 7/26/10	Fri 9/17/10
81	Antenna FM Des	160 hrs	20 days	Mon 9/20/10	Fri 10/15/10
82	Antenna FM Fab	160 hrs	20 days	Mon 10/18/10	Fri 11/12/10
83	Antenna FM Test	480 hrs	60 days	Mon 11/15/10	Fri 2/4/11
84	**Link Budget Design**	**816 hrs**	**103 days?**	**Mon 3/8/10**	**Wed 7/28/10**
85	Link Budget Desi	480 hrs	60 days	Mon 3/8/10	Fri 5/28/10
86	Link Budget Desi	16 hrs	2 days	Mon 5/31/10	Tue 6/1/10
87	Pass Board Desi	0 hrs	1 day?	Wed 6/2/10	Wed 6/2/10
88	Link Budget Test	320 hrs	40 days	Thu 6/3/10	Wed 7/28/10
89	**Backpack Station Design**	**11,952 hrs**	**340 days?**	**Mon 1/11/10**	**Fri 4/29/11**
90	Backpack Hardware Speci	160 hrs	20 days	Mon 1/11/10	Fri 2/5/10
91	Backpack Software Specifi	160 hrs	20 days	Mon 2/8/10	Fri 3/5/10
92	**Backpack Hardware EM I**	**4,848 hrs**	**160 days?**	**Mon 2/8/10**	**Fri 9/17/10**



Project: STRING
Date: Mon 12/7/09

Task | Progress | Summary | External Tasks | Deadline
Split | Milestone | Project Summary | External Milestone

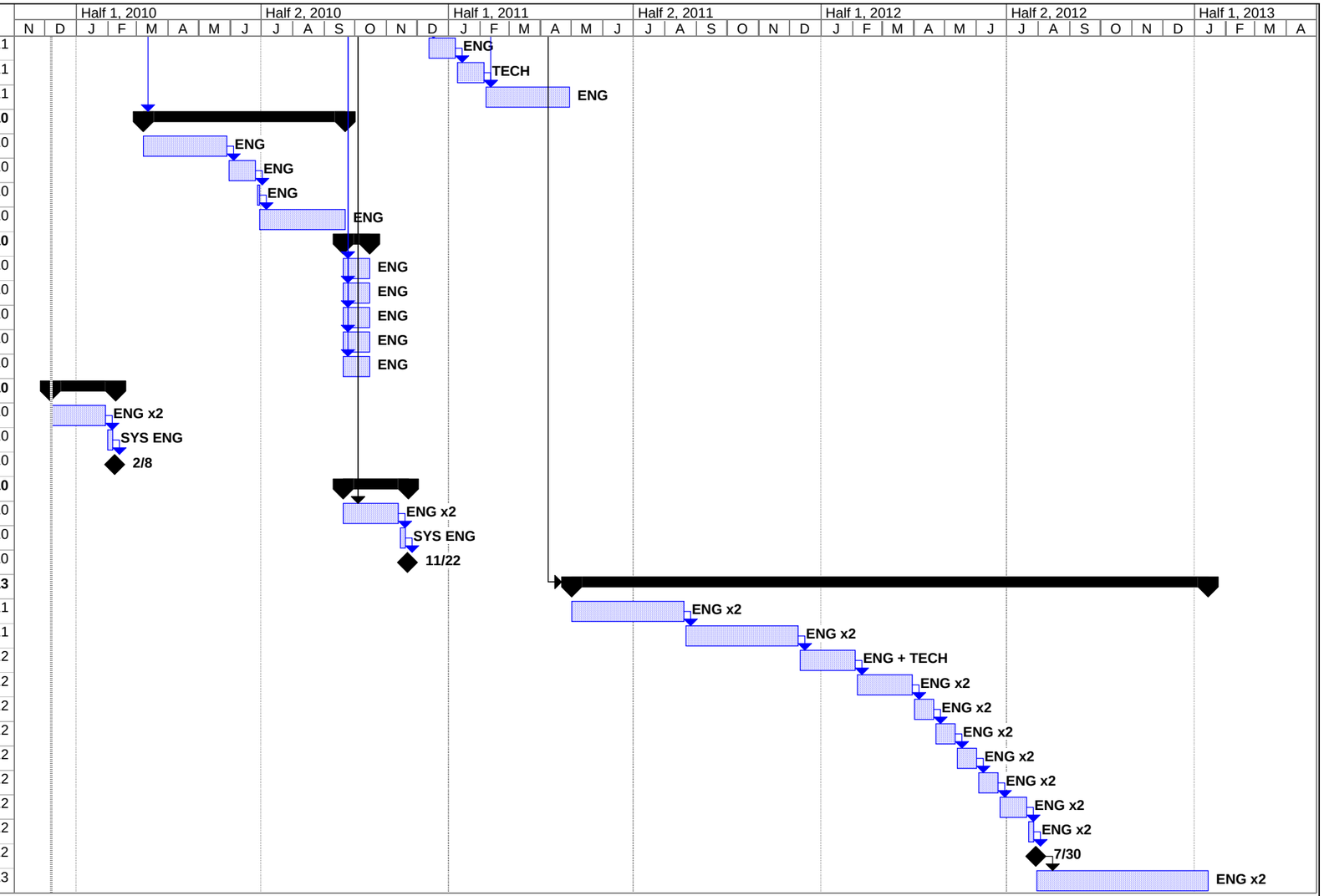
ID	Task Name	Work	Duration	Start	Finish
93	**Backpack CPU Boar**	**1,616 hrs**	**160 days?**	**Mon 2/8/10**	**Fri 9/17/10**
94	Backpack CPU S	480 hrs	60 days	Mon 2/8/10	Fri 4/30/10
95	Backpack CPU F	320 hrs	40 days	Mon 5/3/10	Fri 6/25/10
96	Backpack CPU B	16 hrs	2 days	Mon 3/8/10	Tue 3/9/10
97	Pass Board Desi	0 hrs	1 day?	Wed 3/10/10	Wed 3/10/10
98	Backpack CPU L	160 hrs	20 days	Mon 5/3/10	Fri 5/28/10
99	Backpack CPU F	160 hrs	20 days	Mon 5/31/10	Fri 6/25/10
100	Backpack CPU T	480 hrs	60 days	Mon 6/28/10	Fri 9/17/10
101	**Backpack Power Bo**	**1,616 hrs**	**160 days?**	**Mon 2/8/10**	**Fri 9/17/10**
102	Backpack Power	480 hrs	60 days	Mon 2/8/10	Fri 4/30/10
103	Backpack Power	320 hrs	40 days	Mon 5/3/10	Fri 6/25/10
104	Backpack Power	16 hrs	2 days	Mon 5/3/10	Tue 5/4/10
105	Pass Board Desi	0 hrs	1 day?	Wed 5/5/10	Wed 5/5/10
106	Backpack Power	160 hrs	20 days	Mon 5/3/10	Fri 5/28/10
107	Backpack Power	160 hrs	20 days	Mon 5/31/10	Fri 6/25/10
108	Backpack Power	480 hrs	60 days	Mon 6/28/10	Fri 9/17/10
109	**Backpack RF Board**	**1,616 hrs**	**160 days?**	**Mon 2/8/10**	**Fri 9/17/10**
110	Backpack RF Scl	480 hrs	60 days	Mon 2/8/10	Fri 4/30/10
111	Backpack RF FP	320 hrs	40 days	Mon 5/3/10	Fri 6/25/10
112	Backpack RF Bo	16 hrs	2 days	Mon 5/3/10	Tue 5/4/10
113	Pass Board Desi	0 hrs	1 day?	Wed 5/5/10	Wed 5/5/10
114	Backpack RF Lay	160 hrs	20 days	Mon 5/3/10	Fri 5/28/10
115	Backpack RF Fal	160 hrs	20 days	Mon 5/31/10	Fri 6/25/10
116	Backpack RF Tes	480 hrs	60 days	Mon 6/28/10	Fri 9/17/10
117	**Base Station Hardwar FM**	**4,848 hrs**	**160 days?**	**Mon 9/20/10**	**Fri 4/29/11**
118	**Backpack CPU Boar**	**1,616 hrs**	**160 days?**	**Mon 9/20/10**	**Fri 4/29/11**
119	Backpack CPU S	480 hrs	60 days	Mon 9/20/10	Fri 12/10/10
120	Backpack CPU F	320 hrs	40 days	Mon 12/13/10	Fri 2/4/11
121	Backpack CPU B	16 hrs	2 days	Mon 12/13/10	Tue 12/14/10
122	Pass Board Desi	0 hrs	1 day?	Wed 12/15/10	Wed 12/15/10
123	Backpack CPU F	160 hrs	20 days	Mon 12/13/10	Fri 1/7/11
124	Backpack CPU F	160 hrs	20 days	Mon 1/10/11	Fri 2/4/11
125	Backpack CPU F	480 hrs	60 days	Mon 2/7/11	Fri 4/29/11
126	**Backpack Power Bo**	**1,616 hrs**	**160 days?**	**Mon 9/20/10**	**Fri 4/29/11**
127	Backpack Power	480 hrs	60 days	Mon 9/20/10	Fri 12/10/10
128	Backpack Power	320 hrs	40 days	Mon 12/13/10	Fri 2/4/11
129	Backpack Power	16 hrs	2 days	Mon 12/13/10	Tue 12/14/10
130	Pass Board Desi	0 hrs	1 day?	Wed 12/15/10	Wed 12/15/10
131	Backpack Power	160 hrs	20 days	Mon 12/13/10	Fri 1/7/11
132	Backpack Power	160 hrs	20 days	Mon 1/10/11	Fri 2/4/11
133	Backpack Power	480 hrs	60 days	Mon 2/7/11	Fri 4/29/11
134	**Backpack RF Board**	**1,616 hrs**	**160 days?**	**Mon 9/20/10**	**Fri 4/29/11**
135	Backpack RF Scl	480 hrs	60 days	Mon 9/20/10	Fri 12/10/10
136	Backpack RF FP	320 hrs	40 days	Mon 12/13/10	Fri 2/4/11
137	Backpack RF Bo	16 hrs	2 days	Mon 12/13/10	Tue 12/14/10
138	Pass Board Desi	0 hrs	1 day?	Wed 12/15/10	Wed 12/15/10



Project: STRING
Date: Mon 12/7/09

Task | Progress | Summary | External Tasks | Deadline
Split | Milestone | Project Summary | External Milestone

ID		Task Name	Work	Duration	Start	Finish
139		Backpack RF FM	160 hrs	20 days	Mon 12/13/10	Fri 1/7/11
140		Backpack RF FM	160 hrs	20 days	Mon 1/10/11	Fri 2/4/11
141		Backpack RF FM	480 hrs	60 days	Mon 2/7/11	Fri 4/29/11
142		**Base Station Software**	**1,136 hrs**	**142 days**	**Mon 3/8/10**	**Tue 9/21/10**
143		Software Definition	480 hrs	60 days	Mon 3/8/10	Fri 5/28/10
144		Software Pseudocode	160 hrs	20 days	Mon 5/31/10	Fri 6/25/10
145		Code Review	16 hrs	2 days	Mon 6/28/10	Tue 6/29/10
146		Software Prototyping	480 hrs	60 days	Wed 6/30/10	Tue 9/21/10
147		**Analysis**	**800 hrs**	**20 days**	**Mon 9/20/10**	**Fri 10/15/10**
148		Worst Case Timing Ar	160 hrs	20 days	Mon 9/20/10	Fri 10/15/10
149		Worst Case Circuit De	160 hrs	20 days	Mon 9/20/10	Fri 10/15/10
150		Parts Stress Derating	160 hrs	20 days	Mon 9/20/10	Fri 10/15/10
151		Radiation Analysis	160 hrs	20 days	Mon 9/20/10	Fri 10/15/10
152		Thermal Analysis	160 hrs	20 days	Mon 9/20/10	Fri 10/15/10
153		**Preliminary Design Review**	**360 hrs**	**46 days?**	**Mon 12/7/09**	**Mon 2/8/10**
154		PDR Prep	320 hrs	40 days	Mon 12/7/09	Fri 1/29/10
155		PDR	40 hrs	5 days	Mon 2/1/10	Fri 2/5/10
156		PDR Signoff	0 hrs	1 day?	Mon 2/8/10	Mon 2/8/10
157		**Comprehensive Design Revie**	**360 hrs**	**46 days?**	**Mon 9/20/10**	**Mon 11/22/10**
158		CDR Prep	320 hrs	40 days	Mon 9/20/10	Fri 11/12/10
159		CDR	40 hrs	5 days	Mon 11/15/10	Fri 11/19/10
160		CDR Signoff	0 hrs	1 day?	Mon 11/22/10	Mon 11/22/10
161		**Integration and Test**	**3,560 hrs**	**446 days?**	**Mon 5/2/11**	**Mon 1/14/13**
162		Base Station to Backpack	640 hrs	80 days	Mon 5/2/11	Fri 8/19/11
163		Software Integration and T	640 hrs	80 days	Mon 8/22/11	Fri 12/9/11
164		Functional Test	320 hrs	40 days	Mon 12/12/11	Fri 2/3/12
165		Debug	320 hrs	40 days	Mon 2/6/12	Fri 3/30/12
166		Vibration Test (Launch Env	120 hrs	15 days	Mon 4/2/12	Fri 4/20/12
167		Post-Vibe Functional	120 hrs	15 days	Mon 4/23/12	Fri 5/11/12
168		Thermal Vac	120 hrs	15 days	Mon 5/14/12	Fri 6/1/12
169		Post-Thermal Functional	120 hrs	15 days	Mon 6/4/12	Fri 6/22/12
170		Final Functional Test	160 hrs	20 days	Mon 6/25/12	Fri 7/20/12
171		Pre-Ship Review	40 hrs	5 days	Mon 7/23/12	Fri 7/27/12
172		Ship	0 hrs	1 day?	Mon 7/30/12	Mon 7/30/12
173		Schedule Reserve	960 hrs	120 days	Tue 7/31/12	Mon 1/14/13

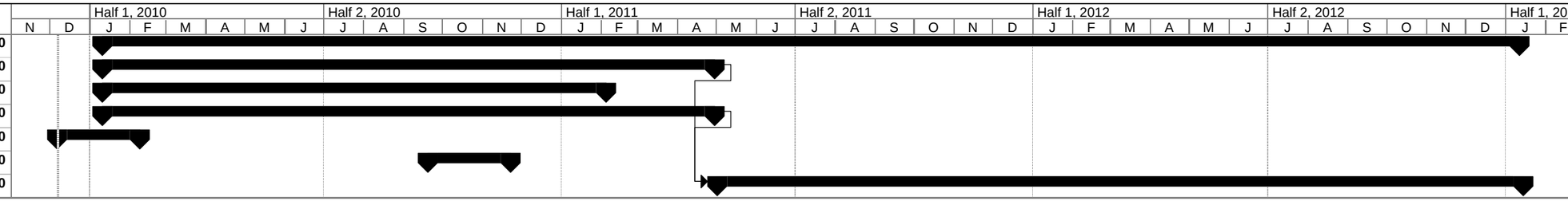


Project: STRING
Date: Mon 12/7/09

Task | Progress | Summary | External Tasks | Deadline
Split | Milestone | Project Summary | External Milestone

Appendix B

ID	Task Name	Total Cost
1	**System Design**	**$1,570,000.00**
3	**Base Station Design**	**$1,768,800.00**
69	**Communication System Desi**	**$476,800.00**
89	**Backpack Station Design**	**$1,744,800.00**
153	**Preliminary Design Review**	**$106,000.00**
157	**Comprehensive Design Revie**	**$106,000.00**
161	**Integration and Test**	**$1,052,000.00**



Project: STRING
Date: Mon 12/7/09

Task | Progress | Summary | External Tasks | Deadline
Split | Milestone | Project Summary | External Milestone

Appendix C

Path Loss, Link Budget, and SNR Matlab Code

```
function [LBwc, SNR] = plotPathLoss()

%Erceg path loss model

% PATH LOSS CALCULATIONS
lambda = 3E8/2450E6;  %wavelength (m)
r = 100:2000;           %distance between tag and antenna

hb = 10;              %base station antenna height
a = 3.6;
b = 0.0050;
c = 20;
x = -1;%1.645;
sigmag = 1.5;
gamma = (a - b*hb + c/hb) + x*sigmag;

z = 2;%1.645;
mus = 8.2;
sigmas = 1.6;
sigma = mus + z*sigmas;

y = 2;%1.645;
s = y*sigma;

do = 100;
A = 20*log10((4*pi()*do)/(lambda));
B = 10*(a - b*hb + c/hb)*log10((r./do));
C = 10*x*sigmag*log10(r./do);
D = y*mus;
E = y*z*sigmas;

PL = A + ...
     B + ...
     C + ...
     D + ...
     E;

 Le = A + D + E;

%PL = 20*log10((4*pi().*r)/lambda)

% LINK BUDGET CALCULATIONS
Pt = 1000;          %TRANSMIT POWER (mW)
Gtr = 31.63848772;            %TRANSMIT ANTENNA GAIN (dBi)
Gt = 9;              %RECEIVER ANTENNA GAIN (dBi)

EIRP = 10*log10(Pt) + Gtr + Gt;

LB = EIRP - PL;

% SNR CALCULATIONS
```

```
%Physical Noise
Bw = 1.2E6;           %BANDWIDTH (Hz)
Tn = 1000;            %NOISE TEMPERATURE (K)
k = 1.38065E-23;     %Boltzman's Constant
Pnphy = Bw*Tn*k;
Nphy = 10*log10(Pnphy);

%Quantization Noise
nbits = 8;            %BITS PER SYMBOL
SNRq = 6*nbits;

%DSSS Gains and Interference
nchips = 8;           %CHIPS PER BIT
SNRss = 10*log10(nchips);

Pr = 10.^(LB./10);
Pntot = (Pr./2) + Pnphy;
Ntot = 10.*log10(Pntot);

SNR = SNRss + SNRq + LB - Ntot;

% semilogx (r, PL, 'LineWidth',2);
% xlabel('Distance (m)', 'FontSize',14)
% ylabel('Path Loss (dB)', 'FontSize',14)
% title(['Path Loss versus Distance - Erceg Model',10,...
%     'Path Loss Exponent (\gamma) = ', num2str(gamma)], 'FontSize',14)
% grid on;

% subplot(2,1,1, 'LineWidth',2)
% plot (r, LB, 'LineWidth',2);
semilogx (r, LB, 'LineWidth',2);

xlabel('Distance (m)', 'FontSize',14)
ylabel('Received Power (dBm)', 'FontSize',14)
title(['Received Power versus Distance - Erceg Model',10,...
    'Path Loss Exponent (\gamma) = ', num2str(gamma)], 'FontSize',14)
grid on;

%semilogx (r, SNR, 'LineWidth',2);

% xlabel('Distance (m)', 'FontSize',14)
% ylabel('Signal to Noise Ratio (dB)', 'FontSize',14)
% title(['SNR versus Distance - Erceg Model',10,...
%     'Path Loss Exponent (\gamma) = ', num2str(gamma)], 'FontSize',14)
% grid on;

% subplot(2,1,2)
% plot (r, 2*(r./3E8));
%
% xlabel('Distance (m)', 'FontSize',14)
% ylabel('Round Trip Time of Flight (s)', 'FontSize',14)
% title('Time of Flight versus Distance', 'FontSize',14)
% grid on;
```

```
LBwc = LB(length(r));    %Power Received (dBm)
```

Appendix D

Artistic Rendering by the Author's Daughter


Isabel 5
Profile