Design of a Small Satellite TT&C Subsystem

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The aim of this project was to design and analyse a Telemetry, Tracking and Command Subsystem (TT&C) for a Microgravity Experiment Recovery Satellite (MERS) with multiple experiment payloads to operate at a variety of Low Earth Orbits (LEO) and inclinations. This subsystem is an integral part of any satellite system as it performs three vital functions; monitoring satellite health, tracking satellite position, and processing received and transmitted data. The project was divided into three parts; the literature review and background research, the design, and the analysis. As a result of the design process, two different configurations were proposed; Configuration A, which utilises VHF and UHF Bands is the ideal configuration; and Configuration B, which introduces an S-Band component to allow for the ability to support higher data rates. Analysis was conducted for altitudes of 400, 600, and 800 km for inclinations of 47^{o} and 98^{o}. It was determined that Configuration A satisfied all the requirements derived for the MERS Communication system, whereas Configuration B failed to meet the requirement to operate at a variety of LEOs. Overall, Configuration A proved to have a greater daily data downlink capacity compared to Configuration B, which was due to a combination of poor link margin performance and access time for the Configuration B system.

Contents

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Nomenclature

AFSK	=	Audio Frequency Shift Keying	*LEO*	=	Low Earth Orbit
BER	=	Bit Error Rate [%]	*MERS*	=	Microgravity Experiment Recovery Satellite
BPSK	=	Binary Phase Shift Keying	*RF*	=	Radio Frequency
C'	=	Received Carrier Power Density [dB]	RX	=	Receiver
C/N_0	=	Carrier to Noise Density Ratio [dB]	*S/N*	=	Signal to Noise Ratio [dB]
C/N	=	Carrier to Noise Ratio [dB]	*S-Band*	=	S Frequency Band
COTS	=	Commercial-Off-The-Shelf	*TT&C*	=	Telemetry, Tracking and Command
ε	=	Elevation [º]	TX	=	Transmission
E_b/N_0	=	Bit Energy to Noise Density Ratio [dB]	*UHF*	=	Ultra High Frequency Band
EIRP	=	Effective Isotropic Radiated Power[dB]	*VHF*	=	Very High Frequency Band
EPS	=	Electronic Power System			

I. Introduction

This project forms part of a larger project known as SplashSat, which involves the design and construction of a Microgravity Experiment Recovery Satellite (MERS). The MERS will assist to expand areas of material science, biology, and engineering by increasing the availability of long duration microgravity experimentation. The proposed MERS design details a satellite, weighing less than 50kg, which must operate in Low Earth Orbit (LEO) for a certain period, following which it must re-enter the Earth's atmosphere and be recovered – intact.

This project will cover the detailed design and analysis for the MERS Telemetry, Tracking and Command (TT&C) subsystem, which will be referred to as the MERS communication system in this report. The MERS Communication system encompasses the TT&C, the antenna and the transceivers, which together ensure the establishment of a link between MERS and a ground station. The MERS mission philosophy, to 'maintain flexibility to enhance viability', resulted in a vast design space. The communication system will be required to accommodate a wide variety of experimental payloads and should be able to be launched and operated in a number of orbits, which has been captured by a number of derived requirements that are contained in this report.

II. Project Outline

A. Project Aim

The aim of the project is to design and analyse the simplest possible communication system with COTS components to meet the requirements for a satellite operating at a LEO carrying multiple experiment payloads.

B. Project Goals

Four goals can be considered to satisfy the aim of this project:

1. Define key parameters such as the operating frequencies, supported data volumes, link budget, and ground station requirements.
2. Design a simple communication system utilising COTS components.
3. Conduct analysis on the communication system for MERS operating on a number of LEOs; and supporting multiple experiment payloads.

C. Methodology

The project can be divided into three parts; the literature review, the design and the analysis. A breakdown on the steps followed for each process of the project have been included in §4.

The literature review was conducted to obtain a comprehensive overview of the appropriate theory required to conduct the design and analysis processes of the project. A summary of this literature was produced for the initial project report and will accompany the final deliverable submission.

The design of the communication system was conducted to satisfy the project aim for a simple system built with COTS components. The design process drew upon the literature review to understand the componentry involved with the design of a communication system. The componentry was selected based on the requirements established for the project, which include an operating frequency of VHF, UHF and/or S-Band. The requirements for the design will be covered in §4.A.

The analysis of the project design was perhaps the most important and time critical aspect of the project. Based on the finds from the literature review, a process for the analysis was developed. The analysis utilised software programs such as Systems Took Kit (STK) for simulations and physical modelling, and MATLAB for all calculations and mathematical modelling. In general the MERS orbital data was collected from STK to be used in the mathematical analysis in MATLAB.

III. Background

This is a shortened version of the literature review for this project, and will cover the important theory that will be required to understand the design and analysis presented in this report.

A. The TT&C Subsystem—the MERS Communication System

The Communication system is an integral component of a satellite system and is required by all satellites regardless of their application[1]. The TT&C subsystem performs three major tasks to ensure the successful operation of all satellite applications. The first is to monitor the health and status of the satellite through the collection, processing, and transmission of data from the various spacecraft subsystems. This task is generally coupled with the transmission of payload data. The second is the determination of the satellite's exact location through the reception, processing, and transmitting of ranging signals. The third is the proper control of satellite through the reception, processing, and implementation of commands transmitted from a ground station[1].

B. Satellite Propagation Theory

1. Frequency Bands

The frequency band denotes a portion of frequency spectrum for the entire range of frequencies. There are a variety of frequency classification standards outlined by organisations such as the ITU, IEEE, and the EU, however the IEEE standard has been used for this project since it is the most commonly used standard to describe satellite communications[2]. Three frequency bands are proposed for the MERS communication system; VHF Band, UHF Band and S-Band. There are benefits and limitations associated with each frequency band, however those important to the project will be covered below. The operating frequency bands for MERS will be based on the spectrum license currently held by UNSW Kensington and can be observed in Table 1.

Table 1: Summary of the MERS Frequency Bands

Band	Frequency Range	MERS Centre Frequency	Bandwidth
Very High Frequency (VHF)	30-300 MHz	145.95 MHz	20 kHz
Ultra High Frequency (UHF)	300-1000 MHz	436.537	25 kHz
S	2000-4000 MHz	2351 MHz	28 MHz

The benefits and limitations of the VHF and UHF Bands are very similar. A benefit of the lower frequency bands is low propagation losses, while the limitations arise from smaller bandwidths that cannot support high data rates. The higher frequency bands, such as S-Band, have much greater bandwidths so they can often support large data rates, however the higher frequencies are also subject to higher propagation losses which deteriorates the quality and performance of the system.

2. Important Terminology

There are a variety of terms that needs to be understood when the analysis of a satellite to ground station link is conducted. A diagram which shows the marked geometry between a satellite and a ground station is shown in Fig. 1. Understanding the terminology used in Fig.1. is crucial in understanding how altering the parameters affects the geometry between the satellite and the ground station. The most pertinent terms for the analysis are the elevation denoted ε, the slant range, *r*, and the altitude of the satellite, *h*.

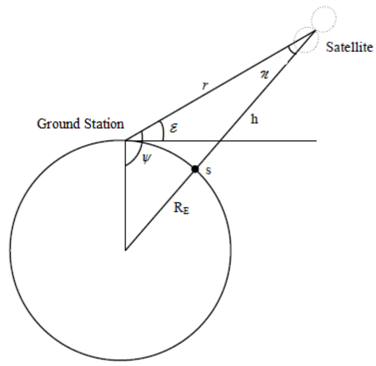

Figure 1. Geometry between a satellite and a ground station[2].

C. System Analysis

1. Link Budget

The link budget analysis is the most complex aspect of the analysis and is the most critical step in describing a realistic link between a satellite and a ground station[1]. The link budget analysis encompasses all aspects of the link from when the signal is prepared for transmission, until the signal has been received and processed. Primarily, the link budget asses the losses and noise incurred to the signal through the various stages from the transmitter to the receiver.

The most important parameters in the link budget analysis are the Effective Isotropic Radiated Power (EIRP), the Received Carrier Power Density (C'), the Carrier to Noise Density Ratio (C/N_0) and the Bit Energy to Noise Density ratio (E_b/N_0). When a link budget analysis is conducted, these parameters describe the performance of the link and indicate how the performance of the satellite or ground station can be improved to optimize the link.

2. *System Loss*

The system loss is a combination of many factors that the signal is subject to during propagation. A realistic value of loss is important as this will ensure that the result of the link budget analysis will accurately describe the performance of the system.

Some loss is reliant on particular parameters such as the altitude, elevation or frequency, while other loss is constant[3]. It is observed in Fig. 2 that the largest contributor to loss is the FSL, which is dependent on the operating frequency and the distance between the satellite and the ground station. Increasing the operating frequency increases the FSL, however increasing the elevation angle decreases the FSL, because the distance between the satellite and the ground station decreases.

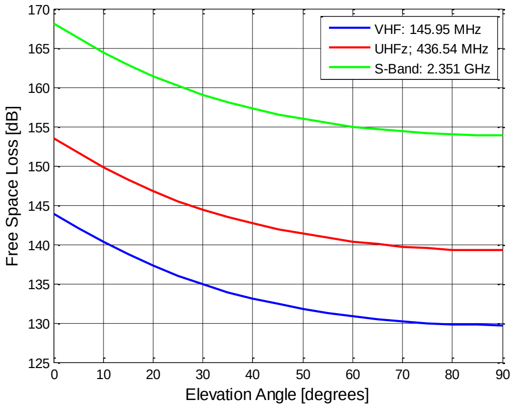

Figure 2. A relationship between the Frequency, Free Space Loss and the elevation angle for an altitude of 500 km[4].

3. *Noise Floor*

It is important that a realistic noise floor is established in the link budget analysis[3]. The analysis of the noise in a system assists in determining the effect of noise on the signal power delivered to the antenna. The system noise is divided into two parts; composite noise, which is noise internal to the system, and antenna noise, which is noise external to the system. When calculating composite noise the internal componentry of the communication system, which includes the LNA, cabling and the transceiver are analysed.

The antenna noise is determined by considering three terms; the noise contribution due to the main lobe, due to the side lobe, and due to the back lobe[3]. The antenna noise is dependent on the operating frequency of the system, and also the antenna's operating environment. The operating environment produces particular values of sky brightness temperature, which is a function of frequency, and ground brightness temperature, which is dependent on the geographic location. The addition of the composite temperature and the antenna noise temperature yields the system noise temperature, which is considered the noise floor of the system[3].

4. *C/N_0 and E_b/N_0*

The C/N_0 describes the ratio of the carrier power to the noise power density at the antenna receiver. It is related to the Carrier to Noise ratio (C/N) by multiplying the value of C/N_0 by the bandwidth of the system. The C/N is related to the Signal to Noise ratio (S/N), where the C/N describes the modulated signal and S/N the unmodulated signal. The most important parameter resulting from the link budget analysis is the Eb/N_0, which describes the bit energy associated with noise power in a 1Hz bandwidth[5]. The value is effectively the normalized C/N or S/N and is useful in comparing the bit error probability performance of different digital modulation schemes without taking bandwidth into account. Eb/N_0 is related to the C/N by multiplying by the ratio of the channel data rate to the channel bandwidth[5].

5. *Link Margin*

The link margin is the final value calculated from the link budget analysis. Essentially, the link margin describes two things; the strength of the connection between the satellite and a ground station, and the margin in the signal that could account for unforeseen or unaccounted for attenuations in the signal. An effective link margin is considered when the link margin ≥ 0 dB, however for digital satellite communications the ideal link margin is ≥ 3 dB[6]. For instance, if a system is designed and found to have a link margin of 4 dB, this would be considered a signal with a strength of 4 dB, but also indicates that the system has a redundancy of 4 dB to account for any unforeseen losses that may inflict further loss or noise to the system up to 4 dB.

6. *Error Probability*

The value of E_b/N_o provides a measurement for a required error probability. Ideally, the bit error probability for digital communications systems is 10^{-6}, which is the probability that one bit error will occur for every 10^6 bits transmitted[6]. The proposed modulation schemes implemented by the transceivers of both configurations are Audio Frequency Shift Keying (AFSK) for the uplink and Binary Phase Shift Keying (BPSK) for the downlink. The AFSK and BPSK modulation techniques are popular schemes, which provide a simple yet effective form of modulation and demodulation[7]. Lower order modulation schemes also require less power than the higher order modulation techniques, and are more suited to the lower frequency bands such as VHF and UHF[7].

7. Access Time

The access time describes the duration of an established link or connection between the satellite and a ground station. Access time is critical to any mission as the downlink of data cannot occur until a connection has been established. The access time is often limited by the link margin performance of the communication system across different elevation angles.

8. Communication Protocol

The Amateur Protocol AX.25 is a popular amateur communication protocol that is implemented in a majority of microsatellite and CubeSats[8] and will be utilised for MERS. It is popular due to its simplicity and minimal overhead in a transmission. AX.25 transmission is executed by organising information into blocks of data, denoted as frames. The maximum size for a MERS data packet is 1520 bits, where the AX.25 tail, header and flag occupy 160 bits. This is an overhead of approximately 10%. The overhead represents the bits of a data packet that contains information on the data packet, rather than the experiment or housekeeping data.

IV. Detailed Design and Analysis

A. Communication System Requirements

To conduct the design and analysis for the communication system, a number of requirements were proposed for MERS by the project team. MERS has been designed to be a flexible system, though some initial values were derived to ensure that the design could be quantitatively analysed to support the conclusions made from a qualitative analysis. The necessary requirements for the communication system have been listed below;

1. MERS will operate in a Low Earth Orbit at an altitude ranging from 400 – 800 km;
2. MERS will operate at an inclination of 47^0 and 98^0 (sun synchronous);
3. MERS will operate with a single Canberra ground station with the possibility of multiple global stations;
4. MERS will operate on a VHF and UHF band with the possibility of an S-Band option; and
5. MERS will have the ability to establish a link with ground station and downlink experimental payload data when the connection has been established.

B. MERS Payload Scenario

The current concept for MERS supports four experiment payload modules that will be utilised by external parties to conduct microgravity experiments. The MERS mission life has been divided into five stages; the launch stage, calibration and test stage, experiment stage, excess data downlink stage, and re-entry stage. The primary focus of this project will be the experiment stage, because this stage will be the longest in duration, but will also require that the MERS communication system is operating at full capacity.

While the design of the experiment payload data acquisition system will not be covered in this project, a proposed scenario has been developed, which can be observed in Table 2, in order to conduct quantitative analysis for typical experiment configurations potentially offered by MERS. The standard format for the payload experiment consists of three 8 bit sensors that have varying sample rates, and a camera that takes high quality photos at set intervals. The housekeeping data, which is a combination of the engineering data collected from the subsystems of the spacecraft and often contains telemetry, tracking and health information for the spacecraft, was also included in the payload scenario. A summary of the payload scenario is shown in Table 2.

Table 2: Summary of the MERS Payload Scenario

Payload Classification	Duration		Experiment Classification	Frequency of Data Acquisition		Total Data Acquired for Experiment
	Classification	Value		Sensor	Photo	
P1	1 Orbit	93 mins	Short	/ms	/orbit	135Mbit
P2	1 Day	24 hrs	Medium-Short	/s	/hour	50Mbit
P3	1 Week	7 days	Medium-Long	/min	/day	28Mbit
P4	1 month	30 days	Long	/hour	/day	60Mbit
Housekeeping	2 month	60 days	N/A	/2min	N/A	17Mbit
Average Experimental Data Acquired by MERS per day						**4.55Mbit**

C. The Communication System

The design of the MERS communication system was the most crucial aspect of the design process. It was desirable that the system operates on VHF/ UHF, however a configuration that utilises S-Band has been considered. For a proposed configuration, the relevant COTS components were chosen in order to conduct a realistic link budget analysis.

1. Configuration A

Configuration A, the VHF/ UHF system, shown in Fig. 3 was designed as the ideal configuration for MERS based on the original requirement. The performance of the propagation VHF signal versus the UHF signal is very similar as shown in Table 3, hence it makes little difference whether VHF or UHF is utilized by the uplink or downlink. For the sake of analysis, VHF was chosen for uplink and UHF for downlink.

Configuration A can be divided into the Receiver (RX) circuit and the Transmission (TX) circuit. The RX circuit is also referred to as the uplink circuit and the TX circuit is the downlink circuit. The uplink circuit receives the signal from the ground station at the deployable dipole antenna system and passes the signal through the Low Noise Amplifier (LNA), which effectively increases the received signal strength without adding additional noise. The signal will then be processed by the VHF receiver. The role of the downlink circuit is to transmit data from the satellite to a ground station once an effective link has been established. The signal is passed from the transmitter to the power amplifier, which increases the signal strength in preparation for transmission through the antenna system.

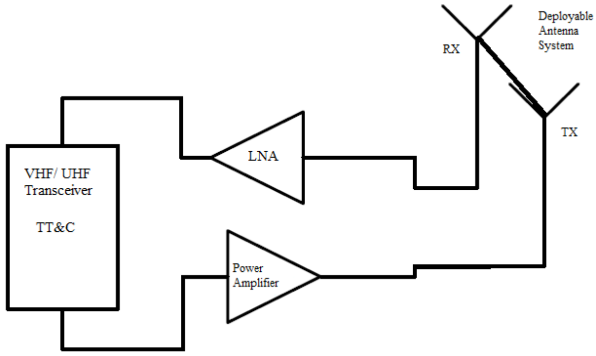

Figure 3. MERS Communication System Configuration A; the VHF/ UHF System[9].

2. Configuration B

Configuration B, the S-Band system, shown in Fig. 4 was designed to allow MERS to support higher data rates, which would allow more data to be collected and transmitted. Configuration B operates similarly to Configuration A with the addition of an S-Band transmitter circuit. Unlike Configuration A, the design for Configuration B can be divided into the RX circuit, the TX Housekeeping, and the TX Payload. The difference between the configurations arises when the transmission of data is considered. The TX Housekeeping circuit transmits all the housekeeping data. On the other hand, the TX Payload circuit transmits all the data acquired through the individual experiment payloads.

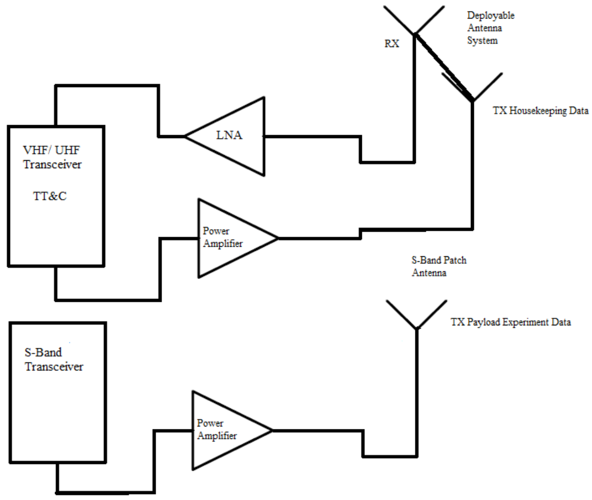

Figure 4. MERS Communication System Configuration B; the S-Band System[9].

The advantage of Configuration B over Configuration A is the use of S-Band allows for the system to support higher data rates as a result of a larger bandwidth, which allows for larger volumes of data to be transmitted in a shorter period of time. Conversely, the disadvantage is the power requirements for the communication system are doubled, which introduces more strain on the MERS Electronic Power System(EPS).

3. Ground Station

To conduct link budget analysis, the use of a ground station was required to facilitate the transmission and receiving of a signal to and from MERS respectively. A COTS ground station configuration was selected, which will also be considered as a likely candidate for a future UNSW Canberra ground station. To conduct analysis of the link between MERS and a ground station it was assumed that the chosen ground station was located at Mt Stromlo, Canberra. In addition, ground station locations were also proposed for Victoria, Canada, and Koforidua, Ghana, as Universities from these locations have expressed interest in MERS involvement.

D. Link Budget Analysis

The Link Budget analysis was conducted to determine whether the communication system design satisfied requirements 1, 4, and 5 shown in §4.A.

1. Uplink and Downlink Analysis

The uplink and downlink analysis was conducted for a scenario to assess the performance of the system under worse case conditions. The scenario had MERS operating at its proposed operating altitude of 500km,

with a minimum ground station elevation of 10^0, which results in greater losses for the signal due to a greater propagation path as seen Fig. 2. A summary of the important parameters for the uplink and downlink analysis can be seen in Table 3. The full tables of the uplink and downlink analysis can be found in Appendix A.

Table 3: Summary of the MERS Uplink and Downlink Budget Analysis

Parameter	**Description**	**Unit**	**VHF**	**UHF**	
Freq	Frequency	MHz	145.95	436.538	
Alt	Altitude	km	500	500	
ε	Elevation	^{0}	10	10	
Uplink Budget Analysis					
EIRP	Effective Isotropic Radiated Power at GS	dBW	28.18	30	
C'_s	Received Carrier Power Density at MERS	dB	-122.96	-129.55	
$C/N_{0\ up}$	Carrier to noise density ratio	dB	77.28	67.45	
$E_b/N_{o\ up}$	Bit Energy Density to Noise Density Ratio	dB	46.49	36.66	
Downlink Budget Analysis					
Parameter	**Description**	**Unit**	**VHF**	**UHF**	**S-Band**
EIRP	Effective Isotropic Radiated Power at MERS	dBW	7.0	6.8	13.2
C'_{gs}	Received Carrier Power Density at GS	dB	-144.14	-152.75	-162.68
$C/N_{0\ down}$	Carrier to noise density ratio	dB	56.90	55.97	51.05
$E_b/N_{o\ down}$	Bit Energy Density to Noise Density Ratio	dB	17.08	16.14	1.05

For the uplink analysis it is observed that there is a high value of E_b/N_o for VHF at 46.49 dB and UHF at 36.66 dB. This is attributed to a high value of EIRP, which is a result of the power and gain capabilities at the ground station. The operating frequencies VHF and UHF have relatively low propagation loss, which results in a good value of C' and C/N_0 when the signal is received by MERS.

The downlink analysis was extended to include the S-Band. It is observed that the values of E_b/N_o are significantly lower for the downlink analysis across all three frequency bands. This can be explained by firstly analyzing the value of EIRP at the satellite. The value is significantly lower, which is due to the lower power and gain capabilities of MERS. While the propagation losses for VHF and UHF are the same for uplink and downlink, the value of C' is lower due to the lower EIRP. Subsequently, the value of C/N_0 is lower for the downlink in relation to the uplink, which results in a smaller value for E_b/N_o. Though, this is partially due to the fact that the downlink data rate of 9600 baud is far greater than the uplink data rate of 1200 baud. In the case of S-band, a combination of a low EIRP at the satellite, and greater propagation losses due to a higher frequency, the value of C' is lower compared to the VHF and UHF values. Despite the value of C/N_0 being similar for the three frequency bands, the larger data rate supported by the S-Band results in a lower value for E_b/N_o.

E. Link Margin Analysis

The Link Margin analysis was conducted to determine whether the Communication system design satisfied requirements 1, 4, and 5 shown in §4.A.

1. Error Probability

The bit error probability is related to the E_b/N_o in a way that for each modulation scheme there is a required minimum value of E_b/N_o in order meet a particular value of bit error probability. For the uplink signal, that utilises AFSK, to meet the bit error probability requirement of 10^{-6} a minimum E_b/N_o value of approximately 12.5 dB[10]is required. For the downlink signal, that utilises BPSK, a minimum Eb/No value of approximately 9.5 dB[10]is required. The link margin for the uplink and downlink can be calculated by subtracting the required value of E_b/N_o for the modulation technique, from the received uplink or downlink E_b/N_o. The link margin for uplink and downlink is shown in Table 4, which takes the received value of E_b/N_o from Table 3.

Table 4: Summary of the MERS Uplink and Downlink Link Margin Analysis

Uplink Link Margin					
			VHF	**UHF**	
$\mathbf{E_b/N_{o\ up}}$	Bit Energy Density to Noise Density Ratio	dB	46.49	36.66	
$\mathbf{E_b/N_{o\ reqAFSK}}$	Value required for AFSK for BER 10^{-6}	dB	-12.50	-12.50	
LM $_{up}$	Link Margin using AFSK modulation	dB	33.99	24.16	
Downlink Link Margin					
			VHF	**UHF**	**S-Band**
$\mathbf{E_b/N_{o\ down}}$	Bit Energy Density to Noise Density Ratio	dB	17.08	16.14	1.05
$\mathbf{E_b/N_{o\ reqBPSK}}$	Value required for BPSK for BER 10^{-6}	dB	-9.50	-9.50	-9.50
LM $_{down}$	Link Margin using BPSK modulation	dB	7.58	6.64	-8.45

The value of the link margin for the uplink is greater than for the downlink. This indicates that the uplink connection is stronger than the downlink connection. The difference is because of the capability of the ground station versus MERS in terms of power and gain. The link margin for S-Band is negative, which means there is a poor connection between MERS and the ground station when MERS is operating at an altitude of 500km and the ground station antenna is at an elevation of 10°. Therefore, it would not be correct in assuming that this would be the case for other scenarios, which indicates that further analysis for different scenarios was required.

2. Downlink Link Margin Versus Elevation

The downlink link margin analysis was extended to include MERS operating at altitudes of 400, 600 and 800 km against the full range of elevation angles. In reference to Fig. 5, the graph on the left represents the link margin performance for the Configuration A VHF/ UHF system and the graph on the right represents the same for the Configuration B S-Band system. Firstly, it is observed that the link margin for both systems increases as the elevation angle increase, which is a result of the reduction of the distance between MERS and the ground station. As a result of the reduction in distance, the propagating losses are reduced, so a larger link margin is obtained. This observation is also made when comparing the link margin at different altitudes, which shows the higher altitudes yield a lower link margin. When comparing the link margin performance of the VHF/UHF system and the S-Band system it is observed that the S-Band system yields a lower link margin performance. It was shown in Fig. 2 that as the frequency increases the FSL increases. In this case the greater frequency utilised by the S-band system results in greater loss, which produces a lower link margin performance.

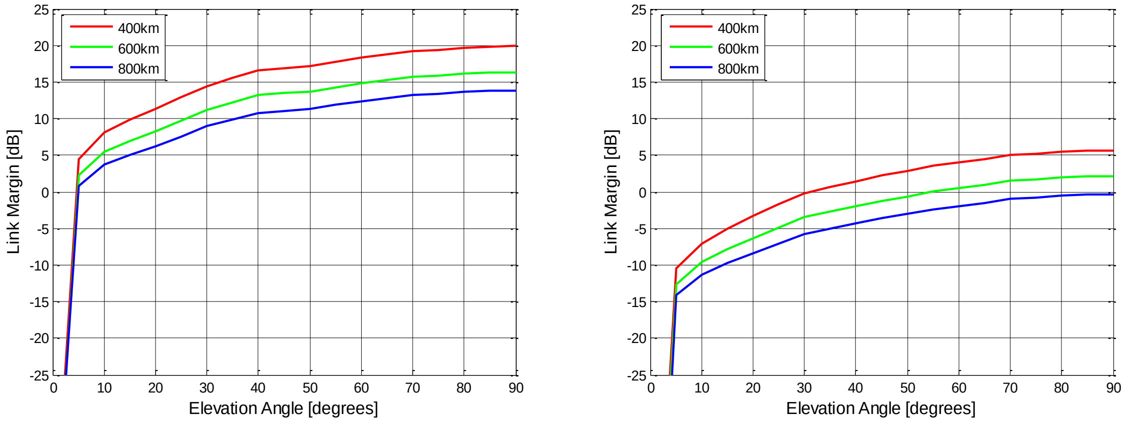

Figure 5. The Link Margin Performance for Configuration A (left) and Configuration B (right) at an altitude of 400, 600, and 800 km for the full range of elevation angles[4].

3. Improve Link Margin Performance

There are a number of ways to improve the link margin performance of a system. Firstly, increasing the EIRP at the satellite would increase the link margin. This could be accomplished by increasing the transmission power or the gain of the antenna and also reducing the passive losses induced in the system. However, increasing transmission power would place strain on the EPS and limit its ability to provide the necessary power to the MERS system, in particular the experiment payloads. Also, the size of the MERS craft places limitations on the number of solar cells that can be used, which limits power generation. Increasing the gain of the antenna is a feasible option that could be explored by designing an antenna specifically for the MERS frequency since the COTS antenna is designed to cater for a larger range of frequencies, which limits performance[3].

Increasing the value of the C/N_0 at the ground station would also increase the link margin. This can be accomplished by increasing the gain of the ground station receiving antenna or by reducing the receiver passive losses or effective noise temperature. The loss and noise is often difficult to improve so the only feasible option would be to increase the antenna gain[3]. Lastly, reducing the data rate will result in a higher link margin, as the decrease in data rate increases the received E_b/N_o, which is related to the link margin by subtracting the required E_b/N_o for the chosen modulation scheme.

F. Access Time Analysis

The Access Time analysis was conducted to determine whether the communication system design satisfied requirements 1, 2, 3, 4, and 5 shown in §4.A.

1. Single Ground Station

The access time analysis was conducted for a single ground station located at Mt Stromlo in Canberra, Australia. The STK was used to simulate MERS at an altitude of 400, 600, and 800 km and at an inclination of 98° and 47°. An inclination of 98° was chosen for it is the most utilised inclination as it allows for a sun synchronous orbit and has greater coverage of the countries in the high latitudes[11]. An inclination of 47° was also chosen to allow for more exposure of the countries with lower latitudes such as Australia.

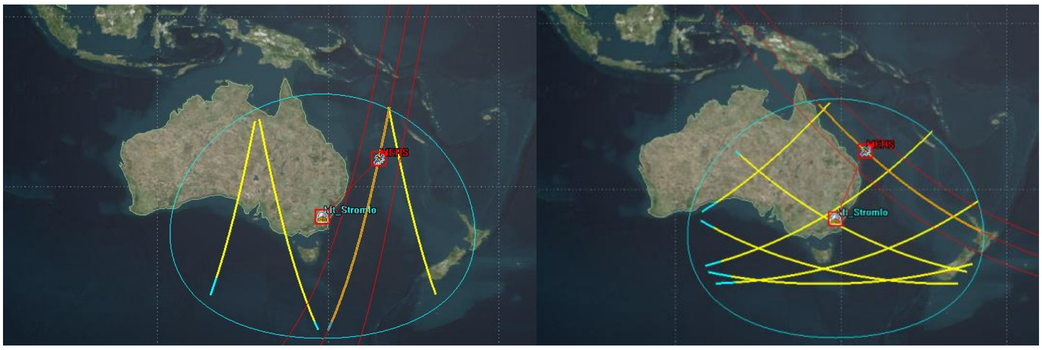

Figure 6. The Ground Trace over the Canberra Ground Station for MERS at an altitude of 400 km and for an inclination of 98° (left) and an inclination of 47° (right)[12].

Figure 6 shows the ground trace of the MERS satellite over the Canberra ground station for an inclination of 98° and an inclination of 47° while at an altitude of 400 km. The red lines represent three separate consecutive MERS orbits, the blue circle indicates Mt Stromlo's line of sight of the sky, and the yellow and blue lines within the circle show the path that MERS took over the ground station. It is observed that there are more exposures between the MERS and the ground station at an inclination of 47° as opposed to an inclination of 98°.

The plots shown in Fig. 7 represent the total daily access time between MERS and the Canberra ground station as measured by the STK simulation at an altitude of 400, 600, and 800 km for the full range of minimum elevation angles. It is observed that as the minimum elevation increases, the access time decreases, because an increasing minimum elevation angle reduces the antennas ability to track the satellite for as long an antenna with a smaller minimum elevation angle. Increasing the altitude also increases the access time, because the satellite travels over the ground station for a longer period than a satellite operating at a lower altitude. When comparing the two plots it is observed that a greater daily access time is obtained at an inclination of 47°. The reason for the greater access time was shown in Fig.6.

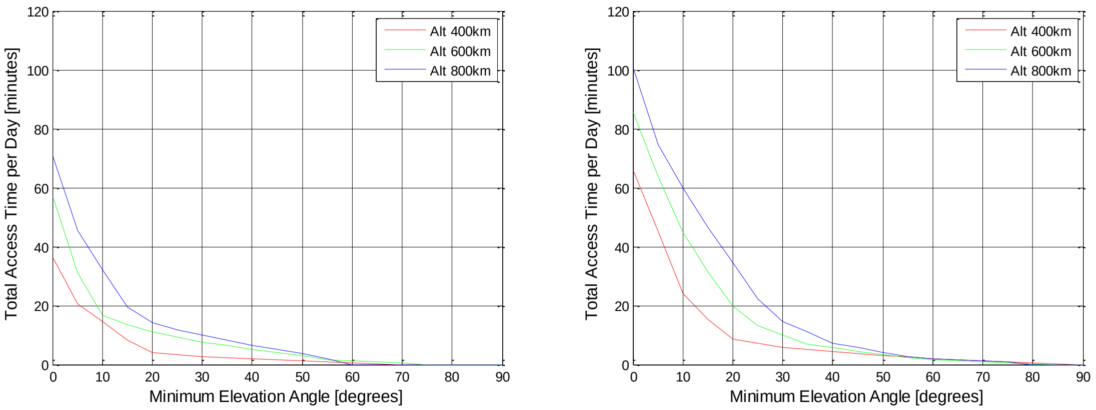

Figure 7. The Total Daily Access Time between MERS and a Canberra Ground Station for an altitude of 400, 600, and 800 km, and an inclination of 98° (left) and an inclination of 47° (right) for the full range of ground station minimum elevation angles[4].

2. Multiple Ground Stations

The access time analysis was extended to include an additional two global ground stations located in Victoria, Canada, and Koforidua, Ghana. From Fig. 8, it is shown that the use of three ground stations produces a far greater daily access time for MERS, which is a result of an increase of exposures between MERS and a ground station. While the goal of the project was to ensure that MERS could operate with one Canberra ground station, the use of multiple ground stations around the world will further enhance the capability of the system.

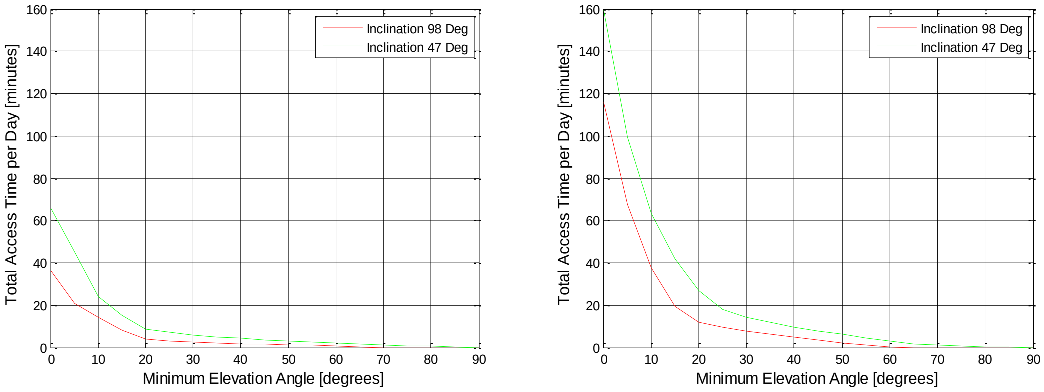

Figure 8. A comparison of the Total Daily Access Time between MERS and a single Ground Station (left) versus MERS and three global Ground Stations (right) for an altitude of 400 km, and an inclination of 98⁰ and an inclination of 47⁰ for the full range of ground station minimum elevation angles[4].

G. Data Downlink Analysis

The Data Downlink analysis was conducted to determine whether the communication system design satisfied requirements 1, 2, 3, 4, and 5 shown in §4.A. The data downlink analysis describes the daily amount of data that can be transmitted by the satellite to a ground station. This analysis combines the results from the link margin and access time analysis conducted for MERS. The important points to draw from the previous analysis is that an effective link margin is described as ≥ 3 dB[6], which is translated to the access time analysis in order to obtain the total daily access time that MERS can establish an effective link between a ground station. Referring to Fig. 5, the minimum elevation angle to establish an effective link for the VHF/ UHF system was observed to be 5⁰, whereas for the S-Band system the elevation angle was 45⁰.

3. Data Downlink Capacity

The data downlink capacity analysis for a single ground station was conducted by referring to the payload scenario in Table 2, the link margin performance of the VHF/ UHF and S-Band system in Fig. 5, and the access time analysis for a single ground station in Fig. 7. A summary of the data downlink analysis for the two configurations with a single ground station is shown in Table 5. The full working can be found in Appendix B. The data downlink analysis was performed by obtaining the total daily access time from Fig. 7 by firstly determining from Fig. 5 the elevation angle that an effective link margin was obtained. The access time was then taken as a function of the minimum elevation angle found for the system. This step was completed for an inclination of 98⁰ and 47⁰. The maximum data transfer per day was then calculated by multiplying the total access time by the data rate. To calculate the effective payload data transfer per day for the VHF/ UHF system, the AX.25 overhead and housekeeping data was subtracted from the maximum data transfer per day. The same calculation was conducted for the S-Band system, however as the housekeeping data is transmitted using the UHF band of the system shown in Fig.4, this value was not subtracted from the maximum data transfer for the S-Band transmission.

There are four conclusions drawn from the data downlink analysis for a single ground station. Firstly, the effective payload data transfer per day is far greater for an inclination of 47⁰ compared to at an inclination on 98⁰. This is a result of the greater access time experienced by MERS at an inclination of 47⁰. Secondly, it is observed that the effective data transfer for the VHF/UHF system is greater compared to that of the S-Band system, despite the S-Band system's higher data rate. This is a result of the greater access time experienced by MERS when it is operating a VHF/ UHF system as opposed to the S-Band system, which is a result of its poor link margin performance as shown in Fig. 5. Thirdly, it is shown that MERS operating either the VHF/ UHF or S-Band system at an altitude of 400 km can support the payload scenario. From Table 2 it is shown that the average payload data generated per day is 4.55Mbits, and it is shown in Table 5, that the effective payload data transfer per day is greater than 4.55 Mbits for each case. The final conclusion, is that the VHF/ UHF system can support the payload scenario for all tested altitudes, while the S-Band system could only support the scenario at an altitude of 400 km. As previously mentioned, Configuration B demonstrated poor link margin performance, an did not achieve an effective link margin ≥ 3dB for an altitude of 600 or 800 km as seen in Fig. 5.

Table 5: The Data Downlink Analysis for Configuration A and Configuration B for a single Ground Station, at an altitude of 400, 600, and 800 km and an inclination of 98° and an inclination of 47°

Parameter	**Units**	**DL 400km**	**DL 600km**	**DL 800km**
VHF/UHF System				
VHF/ UHF System Data Rate	bps	9600	9600	9600
98° Access Time per Day (5° Elevation)	min	20.68	30.90	45.41
Effective Payload Data Transfer per Day at 98°	**Mbits**	**10.44**	**15.73**	**23.26**
47° Access Time per Day (5° Elevation)	min	44.98	63.71	74.63
Effective Payload Data Transfer per Day at 47°	**Mbits**	**23.03**	**32.74**	**38.69**
S-Band System				
S-Band System Data Rate	bps	100000		
98° Access Time per Day (45° Elevation)	min	1.52		
Effective Payload Data Transfer per Day at 98°	**Mbits**	**8.21**		
47° Access Time per Day (45° Elevation)	min	3.57		
Effective Payload Data Transfer per Day at 47°	**Mbits**	**19.28**		

The data downlink analysis was extended to MERS utilising three global ground stations as opposed to a single Canberra station. The results are shown in Table 6. This analysis was conducted for an altitude of 400 km only, for an inclination of 98° and 47°. The first three conclusions drawn from the single ground station analysis can be made for the multiple ground station analysis. However, it was shown that by utilising three ground stations the total daily access time was significantly increased, which resulted in a higher effective payload data transfer per day. While MERS has been designed with the ability to operate with a single ground station, the addition of global ground stations increases the overall performance of the systems.

Table 6: The Data Downlink Analysis for Configuration A and Configuration B for three global Ground Stations, at an altitude of 400 km and an inclination of 98° and an inclination of 47°

Parameter	**Units**	**DL 400km, Incl 98°**	**DL 400km, Incl 47°**
VHF/UHF System			
VHF/ UHF System Data Rate	bps	9600	9600
Access Time per Day (5° Elevation)	min	67.54	99.24
Effective Payload Data Transfer per Day at 98°	**Mbits**	**34.73**	**51.16**
S-Band System			
Access Time per Day (45° Elevation)	min	3.68	7.87
Effective Payload Data Transfer per Day at 47°	**Mbits**	**19.87**	**42.50**

V. Conclusions

The aim of the project was to design the simplest possible communication system with COTS components, for a satellite operating in LEO carrying multiple experiment payloads, and was achieved using the theory acquired from the literature review conducted prior to the design. The design produced two Configurations, A and B; Configuration A is purely a VHF/ UHF system and Configuration B is a VHF/ UHF and S-Band system.

Configuration A and Configuration B were tested against the requirements in §4.A by performing a link budget calculation between MERS and a ground station to determine the link margin performance of each configuration. The link margin performance, combined with the total daily access time between MERS and a ground station, provided an indication of the total daily downlink capacity for the system. A comparison of the two proposed Configurations found that Configuration A satisfied all the system requirements. It demonstrated the best link margin performance, which allowed for a greater access time. As a result of greater access time, Configuration A was able to produce a higher daily data downlink. Configuration B managed to meet all but one of the system requirements, by failing to establish an effective link at an altitude greater than 400 km.

Despite the requirement that MERS should be able to operate with a single Canberra ground station, the analysis concluded that the use of three ground stations significantly enhanced the capability of the MERS communication system. It was also shown from the analysis of both systems that as expected the performance was higher when MERS was operating at an inclination of 47° compared to 98°, though both system were shown to meet the requirements at both inclinations.

In conclusion, the Configuration A communication system is the recommended option for MERS. Configuration B may be a feasible option for the future, but future work will need to be conducted to improve the link margin performance of the system.

VI. Recommendations

It is recommended that subsequent investigations be conducted within the following topics related to this project to further improve the design and analysis of the MERS TT&C subsystem:

1. Improving the Link Margin performance of the S-Band System. The S-Band system is still a feasible option for the MERS communication system, but requires further design and analysis to improve link margin performance. The preliminary process would be to analyse the link budget results and determine the parameters that could be altered to improve the performance. An assessment of a suitable location for the S-Band patch antenna would also be required to maximize visibility, but not take away valuable surface area from the EPS.
2. Purchase components and construct configuration in order to conduct physical testing. Once a communication system for MERS has been decided upon physical testing can occur on the system. Each configuration has been constructed purely from readily available COTS components. The results of th is testing can be compared to the theoretical calculations to further quantify the design.
3. Component Design: Antenna, Transceiver. Further work could be conducted in the area of designing and building the communication system components such as the antenna or the transceiver. By designing a component such as an antenna, it would allow for an increase in the performance since it would be designed for a particular operating frequency on a particular band as opposed to a range of frequencies across a band.

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Appendices (Separate Document)