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Analysis of the MESA ISS Pallet Experiment as a Standalone Satellite

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by

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Table of Contents

Dedication:

This project is dedicated to my parents and to Team A; without the support of either, this would not have been possible.

Abstract

The MDT Experiments and Systems Analysis (MESA) mission is an International Space Station (ISS) external pallet experiment to test the in-space performance of MEMS Digital Thrusters (MDTs), which are micro-electromechanical systems (MEMS's) comprised of printed microthrusters. Designs for MESA are currently being developed by different teams of the University of Alabama in Huntsville's Integrated Product Team (IPT) class. The purpose of this project is to examine the effects on the command and data handling subsystem if Team A's design for the MESA ISS pallet experiment design was a standalone satellite, instead of utilizing the ISS's communications relay. This includes analyzing data transfer to the ground via different communications protocols, communications windows to the ground and relay satellites, bandwidth requirements, and necessary updates to the command and data handling subsystem. By examining these parameters, the viability of Team A's design could be evaluated.

For the satellite, the daily transmission time on days without tests would range from 345.6 seconds to 0.864 seconds, and, on days with a test, it would range from 1458.44 seconds to 3.646 seconds, assuming ideal conditions and depending on the communications protocol. If the satellite had limited ground transmissions, it could store up to 3.624 weeks of data, and, to send three weeks of data to the ground station, the communication window would range from 10,596.133 seconds to 26.490 seconds. If the satellite was limited to a communications window of 480 seconds, it would need a bandwidth of 220.753 megabits per second. If the satellite transferred data daily via relay satellites, the window would range from 146.441 seconds to 2.880 seconds on days without tests, and from 617.985 seconds to 12.154 seconds on days with a test. Finally, since Team A's design did not require a significant overhaul of the command and data handling strategy, it would be possible to modify the subsystem for a standalone satellite.

Introduction

The University of Alabama in Huntsville's Integrated Product Team (IPT) class is a senior design capstone course developing designs for an external pallet experiment for the International Space Station (ISS) for the Northrop Grumman Corporation and the Missile Defense Agency. The goal of this mission, titled MDT Experiments and Systems Analysis (MESA), is to determine the in-space performance of MEMS Digital Thrusters (MDTs), where MEMSs are micro-electromechanical systems. The MDTs are printed microthrusters, which produce close to one newton of thrust and have a burn time of approximately four milliseconds. The MDTs are printed in panels, with sixteen thrusters per panel. These thrusters could have significant benefits because they have no moving parts, are extremely small, and have very few components. However, they also have a low technology readiness level due to their novelty. The IPT class was split into four different teams to conceptualize different designs for this mission while meeting its objectives and constraints, and this paper will focus on the design developed by the IPT's Team A. The mission has a variety of different science objectives, constraints, threshold measurements, which are those necessary to the mission, and objective measurements, which are secondary measurements that are not essential but would be beneficial to the mission. There are four different science objectives with test that will be performed over the twelve to eighteen-month duration of the mission; the first is to determine the performance of individual MDTs when commanded to fire, which will occur every two weeks, and two panels will be dedicated to this objective. The second objective is to fire multiple MDTs at once to determine if the panel's integrity holds, occurring every three months, with five boards dedicated to this goal. The third objective is to determine if firing an MDT affects others around it by firing four MDTs every month, with three panels dedicated to this objective. Finally, the fourth objective is to determine the performance of an entire panel by firing all sixteen thrusters at once, with this test being conducted upon starting the experiment operations, six months into the mission, and twelve months into the mission. All four of these objectives require a total of thirteen panels, but Team A's design has incorporated an extra three panels as backup, for a total of sixteen panels. The project's constraints are as follows: the maximum volume for the experiment is thirty centimeters long, by thirty centimeters wide, by sixty centimeters tall, the total mass of the experiment must not exceed 30 kilograms, the power draw for the experiment must not exceed 60 Watts, and the total cost of the experiment must not exceed $200,000. The threshold measurements are as follows: the thrust generated by each MDT firing, high-speed, visible evidence of a firing, and the temperature inside and outside the experiment enclosure throughout the lifetime of the experiment. The threshold measurements are thrust misalignment, high-speed infrared (IR) evidence of a firing, and the radiation inside and outside the experiment enclosure throughout the lifetime of the experiment. Team A's design meets all of these objectives and requirements. Currently, this design is part of an ISS external pallet experiment, which is a pallet of several experiments, of which MESA is one, and will attach to the outside of the ISS, which will provide the power of 60 Watts, and a downlink bandwidth of 10 megabits per second (Mbps) to transfer data to the ground. The goal of this project is to determine the impact on communications and command and data handling of Team A's design if MESA were a standalone satellite, including the transfer times of different communications protocols, necessary bandwidth to transmit data to ground stations, communications times to relay satellites, and essential changes to the command and data handling strategies of the design to accommodate these communications differences.

Design and Science Concept of Operations

In order to meet the measurement requirements, Team A has developed two different test platforms that are easily scalable and exchangeable. The first platform, shown in components view in Figure 1, features a force sensor that measures in three dimensions to determine both the thrust generated and the thrust misalignment. Team A plans to employ this platform on three of the panels, with two for the panels to determine individual MDT performance and one for a reserve panel. The second test platform, also shown in Figure 1, will be utilized for the rest of the panels, and it includes a force sensor that only measures in one dimension to measure the thrust generated. These two different test platforms are necessary not only to ensure that there is a large margin between the cost of the design and the budget, but also since the thrust misalignment measurements would not be applicable to tests where multiple thrusters are fired simultaneously, especially for the panels being used to determine integrity and proximity effects. These force sensors will measure for one second during each test. Additionally, to measure the radiation and temperature throughout the mission, two of each of these sensors will be utilized, with one of each on the inside and outside of the enclosure. These sensors will be employed for six seconds during each MDT test, in addition to every thirty minutes throughout the lifetime of the mission. Since all of these instruments are analog sensors, they will be connected to 12-bit analog-to-digital converters (ADC), with one ADC dedicated to the radiation and temperature sensors, and two dedicated to the force sensors. Finally, the design employs two cameras, one camera for observation that will record for sixty seconds during each test, and one high-speed camera with an IR filter for optical evidence of a firing, which will operate for one second during each test. Currently, for storage, Team A's design utilizes two, 64 gigabit memory modules, which is equivalent to 64,000 megabits (Mbs). The overall design of the experiment, without its enclosure, is shown in Figure 2 and a components view of the design is shown in Figure 3.

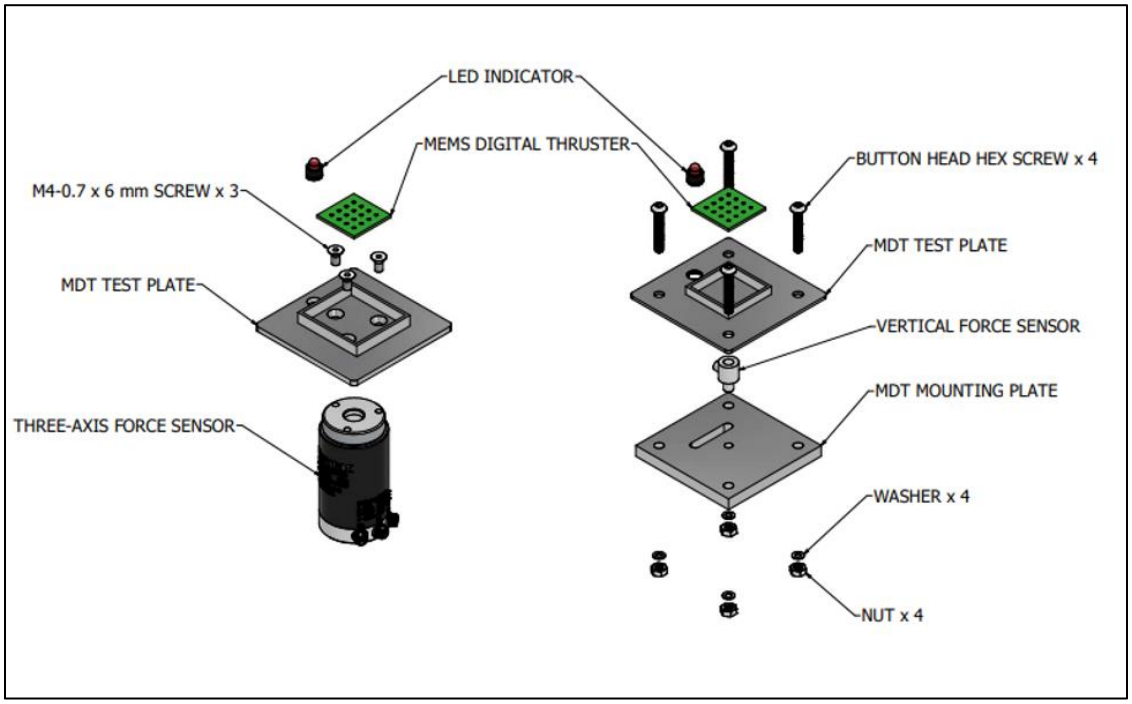

Figure 1: Three-Dimensional Test Platform (Left) and One-Dimensional Platform

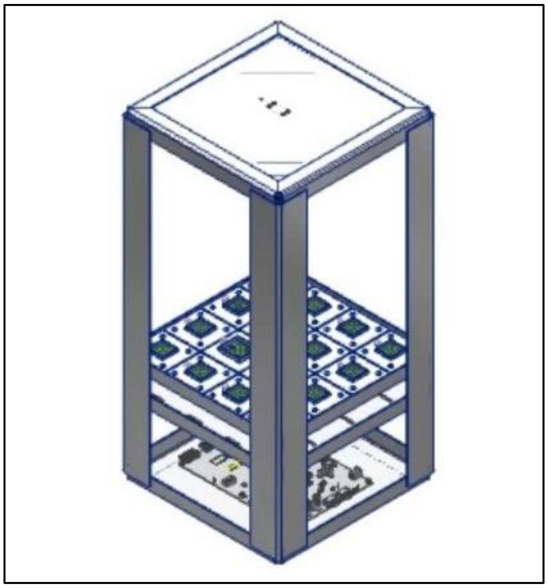

Figure 2: Experiment Design

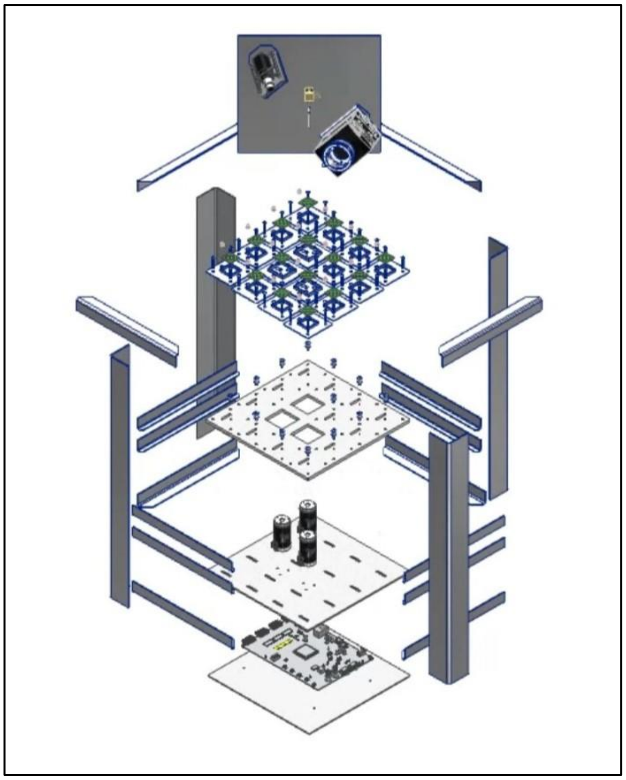

Figure 3: Experiment Design Components View

Data Generated

The ADC that is utilized in Team A's design has a sampling rate of up to one million samples per second (Msps), and a resolution of twelve bits (STMicroelectronics 1). Therefore, when operating, the ADCs will generate up to 12 Mbps, as shown in Equation 1. Since the temperature and radiation sensors are all on one ADC, and operate for six seconds, they will generate up to 72 Mbs each time they operate, shown in Equation 2. Similarly, the force sensors operate for one second every test, so they will generate 12 Mbs. The observation camera has a 2.2 Megapixel camera sensor, with a depth of 10 bits, and a frame rate of 5 frames per second (FPS), and, since it will operate for 60 seconds each test, it will generate 6,600 Mbs per test, demonstrated in Equation 3 (SCS Space 1). Finally, the high-speed camera, at a frame rate of

1,250 FPS, and a resolution of 800 pixels by 600 pixels, generates 2 gigabytes of data in 3.6 seconds, which results in it generating 4444.44 Mbs per test, as shown in Equation 4 (IX Cameras 2).

$$1\ Msps * \frac{10^6\ samples\ per\ second}{1\ Msps} * 12\ bits * \frac{1\ megabit}{10^6\ bits} = 12\ megabits\ per\ second \quad (1)$$

$$12\ mbps * 6\ seconds = 72\ megabits \quad (2)$$

$$2.2\ Megapixels * \frac{10^6\ pixels}{1\ Megapixel} * 10\ bits * \frac{1\ Mbit}{10^6\ bits} * 5\ fps * 60\ seconds = 6{,}600\ Mb \quad (3)$$

$$\frac{2\ gigabytes}{3.6\ seconds} * \frac{10^9\ bytes}{1\ gigabyte} * \frac{8\ bits}{1\ byte} * \frac{1\ Mbit}{10^6\ bits} = 4{,}444.44\ Mb \quad (4)$$

During each test, a total of 11,128.44 Mbs of data will be generated, as demonstrated in Equation 5, and during the radiation and temperature measurements that occur every thirty minutes, seventy-two Mb of data will be generated, and additional temperature and radiation measurements are taken during the test. If a single test occurs each week, 35,320.44 Mb of data will be generated per week, as shown in Equation 6. Since Team A’s design utilizes two, 64,000 Mb memory modules for storage, it has a total storage capacity of 128,000 Mb. Therefore, if the design were a standalone satellite, it would run out of storage capacity in approximately 3.624 weeks, as demonstrated in Equation 7. So, the satellite would need to send data to the ground before it reaches this point. Additionally, the data generated on a day with a test is shown in Equation 8, and the data generated on a day without a test is shown in Equation 9.

$$72\ Mb + 12Mb + 6{,}600\ Mb + 4{,}444.44\ Mb = 11{,}128.44\ Mb \quad (5)$$

$$11{,}128.44\ Mb + \frac{72\ Mb}{30\ minutes} * \frac{60\ minutes}{1\ hour} * \frac{24\ hours}{1\ day} * \frac{7\ days}{1\ week} = 35{,}320.44\ Mb/week \quad (6)$$

$$\frac{128{,}000\ Mb}{35{,}320.44\ Mb/week} = 3.624\ weeks \quad (7)$$

$$11{,}128.44\ Mb + \frac{72\ Mb}{30\ minutes} * \frac{60\ minutes}{1\ hour} * \frac{24\ hours}{1\ day} = 14{,}584.44\ Mb/day \quad (8)$$

$$\frac{72\ Mb}{30\ minutes} * \frac{60\ minutes}{1\ hour} * \frac{24\ hours}{1\ day} = 3{,}456\ Mb/day \quad (9)$$

Communications Protocols and Times

There are several different communication protocols that are used by satellites; some of them are Ultra High Frequency (UHF), S-band, X-Band, and Ka-Band (Small Spacecraft Systems Virtual Institute 244). Each of these different protocols has its own frequency range, shown in Table 1 (IEEE 10). However, the data transmission rate will also depend on the radio used by the satellite. Some examples are as follows: L3Harris' Mars Electra-Lite UHF Transceiver offers a data rate of up to 10 Mbps, Voyager Space's Nanocom S-Band Transceiver offers up to 25 Mbps, µXTx-200 Wide Band, X-band transmitter offers up to 3.5 gigabits per second (Gbps), and their µKaTx-300 Ka-Band Transmitter offers up to 4 Gbps (L3Harris 1; "NANOCOM S-Band" 1; "µXTx-200 WIDE BAND" 1; "NANOCOM Ka-Band" 1). Therefore, assuming that the radio has a constant, maximum data rate and that it transfers data daily, the data transfer time would be 1,458.44 seconds on a day with a test occurrence, or 24.307 minutes, as demonstrated in Equation 10, and the transfer time would be 345.6 seconds on a day without a test, as shown in Equation 11. Repeating these calculations for each communications protocol results in Table 2 below. Nevertheless, these values are assuming ideal conditions and maximum data transfer rate, so in actual applications, these speeds will be lower.

$$14{,}584.44\ mb \div 10\frac{mb}{s} = 1{,}458.444\ seconds * \frac{1\ minute}{60\ seconds} = 24.307\ minutes \tag{10}$$

$$3456\ mb \div 10\frac{mb}{s} = 345.6\ seconds \tag{11}$$

Table 1: Protocol Frequencies (IEEE 10)

Band Designation	Nominal Frequency Range
UHF	300 MHz to 1,000 MHz
S	2 GHz to 4 GHz
X	8 GHz to 12 GHz
Ka	27 GHz to 40 GHz

Table 2: Communications Protocols and Times

	Transfer Time with Test Occurrence (s)	Transfer Time without Test Occurrence (s)
UHF	1458.444	345.600
S-Band	583.378	138.240
X-Band	4.167	0.987
Ka-Band	3.646	0.864

Limited Communications with a Ground Station

If the satellite had limited passes over a single ground station, it would affect the data transmission times, since the satellite would have to store much more data. Since the satellite will run out of storage every 3.624 weeks, it should transmit data to the ground at least every three weeks. If the satellite transfers data every three weeks, and, assuming the mission duration is eighteen months, or 78 weeks, it is necessary for the satellite to pass over the ground station a minimum of 26 times. Therefore, if three weeks of data is transmitted to the ground using the UHF transceiver, it will take 10,596.13 seconds, or 176.602 minutes, as demonstrated in Equation 12. The transmission times for each communications protocol are shown in Table 3.

$$35{,}320.44\,\frac{Mb}{week} * 3\;weeks \div \frac{10Mb}{s} = 10596.133\;s * \frac{1\;minute}{60\;s} = 176.602\;minutes \qquad (12)$$

Table 3: Transmission Times with Limited Contact to Ground

	Transfer Time (s)
UHF	10,596.133
S-Band	4,238.453
X-Band	30.275
Ka-Band	26.490

For a satellite in low-earth orbit (LEO), the average communications window to the ground is 480 seconds (Girardello et al. 378). Since the communication times for UHF and S-Band are much greater than 480 seconds, they would not be viable communications protocols, especially since this is assuming maximum bandwidth. Therefore, if the satellite is limited to the communications window of 480 seconds, it would require a bandwidth of at least 220.753 Mbps, as shown in Equation 13.

$$35{,}320.44\,\frac{Mb}{week} * 3\;weeks \div 480\;seconds = 220.753\;Mbps \qquad (13)$$

Communications with Relay Satellites

Another possible way to transmit data to the ground station is via data relay satellites, which the MESA satellite would send its data to, then the relay satellites would send the data to the ground, with the uplink to the satellite being called a forward link, and the downlink called the return link (Moore 439-455). The National Aeronautics and Space Administration's (NASA) Tracking and Data Relay Satellites (TDRS) are data relay satellites located in geosynchronous orbit and are capable of communicating with satellites for at least 85% of a spacecraft's orbit for LEO (Williams and Bell). For the latest generation of the TDRS, the return data rate is up to 23.6 Mbps for S-band, and, for Ka-band, TDRS has two channels; a 225 MHz channel with a 600 Mbps return data rate, and a 650 MHz channel with a 1200 Mbps return data rate (Zaleski 9). Assuming that data is transferred daily, the necessary communication times for each of these bands are once again calculated using Equations 10 and 11, and are shown in Table 4 for days with and without a test occurring.

Table 4: TDRS Communications Protocols and Times

	Transfer Time with Test Occurrence (s)	**Transfer Time without Test Occurrence (s)**
S-Band	617.985	146.441
Ka-Band, 225 MHz	24.307	5.760
Ka-Band, 650 MHz	12.154	2.880

Even though these values are assuming constant, maximum data transmission, utilizing the TDRS system for downlink is a viable option due to its large coverage.

Additionally, commercial relay satellites are a new, but burgeoning market. Addvalue's Inter-satellite Data Relay System (IDRS) provides up to 200 kbps and coverage of up to 99% of orbit for satellites in LEO (IDRS 2). At this rate, it would take at least 72922 seconds, or 20 hours, 15 minutes, and 22 seconds to transfer the data from one test day. Therefore, this currently does not seem like a viable option, due to its low maximum transfer speed.

Updates to the Command and Data Handling Strategy

If Team A's design was a standalone satellite, several updates to the command and data handling strategy would be necessary. However, many of the design considerations for command and data handling as an ISS pallet experiment would still be relevant. All the chosen components have high survival temperature ranges, are at least radiation tolerant, and most have some form of space qualification; these qualities are important for any components that will have to survive the extreme environment of space, so these are also applicable for a satellite design. There are four main components of Team A's command and data handling system: a microcontroller, due to the mission's size and power constraints, an ethernet physical interface, in order to utilize the ISS's data downlink, ADCs, to connect to analog sensors and store their data in digital forms, nonvolatile memory, to store the data, since they have low power consumption and high reliability, and, finally, a custom printed circuit board, to connect the components. For the microcontroller, Microchip Technology's SAMRH71 was chosen due to its low power consumption, small form factor, and embedded error correction code (Microchip 1-2). These characteristics will also be important on a satellite, since space and power will likely still be limited, and error correction coding is still also desirable in any space application to ensure the integrity of the data, so this component could still be employed in a satellite design. The ethernet physical interface was necessary to utilize the data downlink provided by the ISS, however, this would no longer serve a purpose on a satellite, and, therefore, would be removed from the satellite design. For the microcontroller, STMicroelectronics' RHFAD128 was chosen, since it has a high sampling rate of up to one Msps (STMicroelectronics 1). Since the science objectives and concept would remain the same if the mission were a satellite, the sensors would also remain, thus ADCs would still be necessary, so this component would not need to be updated.

Currently, for storage, the design utilizes two of the Data Device Corporation's Radiation Hardened NAND Flash Memory 64 gigabit modules, which were chosen due to their high endurance, support for error correction code, and relatively large capacity for space qualified memory (Power Device Corp. 1). Since the satellite would no longer have access to the ISS's constant data downlink, and the satellite's communications could be limited, it would need the ability to store as much data as possible. Therefore, the memory could be upgraded with 256 gigabit versions of the same model. This would increase the storage capacity by four times, so the satellite would only have to communicate with the ground every 14.496 weeks, instead of every 3.624 weeks, but this would also increase the necessary communication window by four times as well. However, to ensure that no valuable data is lost, one of these should be employed as redundant storage. Utilizing this strategy, the satellite would have to communicate to the ground at least every 7.248 weeks, but the previous data set would also still be stored on the satellite, so the ground station would have ample time to ensure there were no errors. Finally, for the custom printed circuit board, Sierra Circuits was chosen as the manufacturer, since they provided fabrication, assembly, inspection, and testing, along with coating to protect the board from contaminants, moisture, and stress (Sierra Circuits). These characteristics would also be desirable for a satellite, but this would require the circuit board design to be updated to account for the change in components of the satellite design.

It would also be necessary to add several new components to the command and data handling subsystem to function as a satellite. As previously mentioned, the satellite would require a radio, consisting of a transmitter, which transmits the data from the satellite to the ground, and a receiver, which receives the data from the ground, or a transceiver, which is a transmitter and receiver in one (Small Spacecraft Systems Virtual Institute 249). Alternatively, a software defined radio (SDR) could be used, which can implement the radio's function into software, so it is smaller than hardware and allows the use of multiple bands (Small Spacecraft Systems Virtual Institute 249-250). Now, to actually send and receive those signals through space, an antenna would also be necessary (Small Spacecraft Systems Virtual Institute 247). High-gain antennas transmit data at higher rates, but they are extremely directional, and have narrower coverage, while low-gain antennas can be omnidirectional with broader coverage, but have lower data rates, so a high-gain antenna should be used at a higher frequency and as the main form of transferring data, while a low-gain antenna should be used at lower frequency bands to ensure that command over the satellite can be maintained as much as possible (Small Spacecraft Systems Virtual Institute 247). Therefore, for the satellite design, an SDR could be employed at different bands, with a higher frequency to transmit large amounts of data to the ground at a high speed, and a lower frequency band to receive commands, since the commands will not require as high of data rates, and the lower frequency band will provide more coverage. For example, Akash Systems' Ka/S Cubesat Radio is an SDR with a Ka-band transmitter and an S-band receiver, and it has an expected data rate of 2 Gbps (Akash Systems). Assuming that 7 weeks of data will be transferred at a time, since a maximum of 7.248 weeks of data could be stored at once with half of the storage being reserved for redundancy, and, once again, that the data rate is constant at an ideal rate of 2 Gbps, the satellite would need a communications window of at least 123.622 seconds, as demonstrated in Equation 14.

$$7\, weeks * 35{,}320.44 \frac{Mb}{week} \div \left(2Gbps * \frac{1 * 10^3\, Mbps}{Gbps}\right) = 123.622\, seconds \tag{14}$$

So, this strategy seems like a viable option for satellite communications. However, this is assuming ideal conditions, and it would be affected by antenna selection and mission parameters, such as allotted power, mass, and budget, in addition to real-life and environmental factors, like atmospheric attenuation, ground station availability and properties, and even rain (Small Spacecraft Systems Virtual Institute 247). Nevertheless, Team A's design for MESA could be updated from an ISS external pallet experiment to a satellite design without a significant overhaul of the command and data handling subsystem.

Conclusion

If Team A's design for MESA was a standalone satellite, instead of being an external pallet experiment on the ISS, the data transmission times would range from 1458.444 seconds to 3.646 seconds on a day with a test occurrence, or from 345.6 seconds to 0.864 seconds on a day without a test occurrence, depending on the communication protocol and radio utilized, in addition to assuming ideal conditions. If the transmissions of the satellite to the ground station were limited, the satellite could store a maximum of 3.624 weeks of data. If that data was transmitted to the ground every three weeks, the communications window would range from 10,596.133 seconds to 26.490 seconds, once again assuming ideal conditions, and, if the satellite had only the average communications window of 480 seconds, it would need a data transfer rate of 220.753 Mbps. If the satellite were to utilize NASA's data relay satellites to transfer data daily, the necessary communications window would range from 617.985 seconds to 12.154 seconds, on a day with a test occurrence, or, on a day without a test occurrence, from 146.441 seconds to 2.880 seconds, depending on the frequency used. Finally, to update the command and data handling subsystem for a satellite design, an unnecessary component would be removed, the storage capacity would be increased, allowing for redundant storage and the ability to store up to 7.248 weeks of data, and the addition of a radio along with low-gain and high-gain antennas would be necessary, allowing for high transfer rates to the ground, but with limited coverage, and low data rate uplink from the ground, with broader coverage to maintain command of the satellite. Ultimately, due to the availability of multiple different communications protocols, and varying communications methods, along with the command and data handling strategy not requiring significant changes, it would be possible to modify Team A's design for MESA to a viable satellite.

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