The Icarus Student Satellite - A Fully Autonomous Student Built Small Satellite for NASA

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Abstract

University of Michigan students, with the mentoring support of engineers from NASA, Michigan, and elsewhere, have developed a small endmass satellite—dubbed Icarus—for NASA's ProSEDS (Propulsive Small Expendable Deployer System) electrodynamic-tether propulsion mission. The ProSEDS experiment will be launched in late 2002 as a secondary payload attached to the second stage of a Delta–II launch vehicle. Following the completion of the Delta–II primary mission, the second stage will initiate a series of burns to place ProSEDS into a 360-km, near-circular orbit at an inclination of 35°. The Icarus endmass satellite will be cast off from the Delta–II second stage and be deployed in the zenith direction. The endmass will remain connected to the Delta–II via a combination space tether consisting of 5-km aluminum conducting tether nearest the Delta–II attached to 10-km nonconducting Spectra fiber, connected to the endmass.

Throughout tether deployment, and for the duration of the ProSEDS mission, Icarus will collect and transmit data on tether deployment and dynamics. The endmass is responsible for providing tether-endbody location information (using a GPS receiver) and endbody attitude dynamics (using an aspect magnetometer). The data from these instruments will be stored and transmitted to ground telemetry stations. Power to the endmass will be provided by rechargable batteries and solar cells; an onboard command and data handling system will provide control functions. The endmass will continue to record and transmit data as ProSEDS lowers its altitude. Icarus also serves as a backup for mission location information to the main ProSEDS GPS receiver located on the Delta-II second stage.

Introduction

The Icarus student satellite is part of the Propulsive Small Expendable Deployer System (ProSEDS), an electrodynamic tether propulsion mission developed by NASA's Marshall Space Flight Center in Huntsville, Alabama (Gilchrist et.al. 2001, Johnson et.al. 1993). ProSEDS is a low-cost experiment to demonstrate the use of an electrodynamic tether for propellantless propulsion, magnetic breaking in this case, - a technology that has the potential to drastically reduce the cost of space transport.

Electrodynamic tether propulsion takes advantage of the well known phenomenon that when a wire moves through a magnetic field, an electrical potential is produced that can drive current as seen in Figure 1 using the Earth's ionosphere to return the current from one end to the other to "close" the circuit. The current interacts with the magnetic field inducing a force on the wire (the so-called Lorentz force).

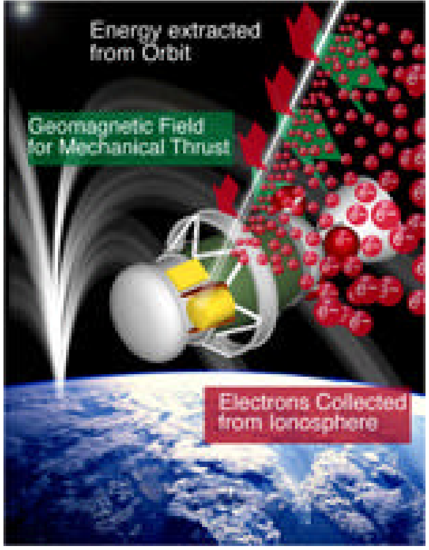

Figure 1 – Electrodynamic tether science

This force on the tether, when connected to a spacecraft, serves to lower the orbit of the satellite. ProSEDS will use a particular form of electrodynamic tether called a bare tether where the electrical current is collected along the tether conductor (Sanmartin, 1993). A mass is connected to the opposite end to gravity-gradient stabilize the entire tether system. This primarily fosters the deployment of the tether and prevents the tether from being pulled from vertical due to the Lorentz force generated by the tether current.

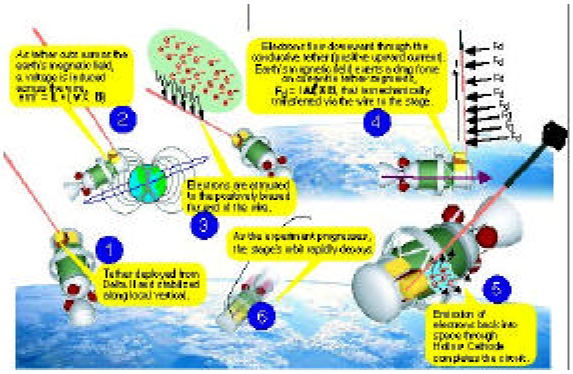

Figure 2- ProSEDS Operation

Mission Objectives

There are three main mission objectives driving the Icarus Student Satellite project. First, the Icarus Endmass will serve as a stabilizing anchor for the ProSEDS tether system. Second, Icarus will collect and transmit data on tether deployment and dynamics as well as Endmass attitude using the on board aspect magnetometer and GPS receiver. The Endmass GPS data acts as back-up for ProSEDS position tracking. Lastly, the mission serves as a test bed for University of Michigan's Student Space System Fabrication Laboratory (S3FL) ability to design, built, test, and operate a fully autonomous satellite, while providing an unmatched educational opportunity.

Mission Timeline

The Icarus endmass is deployed from the Delta-II via a spring-loaded ejection system. The ejection system consists of a Payload Attachment Adapter (PAA) mounted by a Clamp Band to the Payload Attach Fitting (PAF). At approximately 2 hours following launch, two pyrotechnic bolt cutters are fired by the Delta-II avionics releasing the Clamp. Ejection springs push the Endmass/PAA assembly away from the Delta-II. The ProSEDS tether is attached to Icarus and is pulled from the ProSEDS deployer by the force of the ejected endmass. Other than the mechanical non-electrical tether connection, there are no electrical or functional connections with the rest of the ProSEDS experiment.

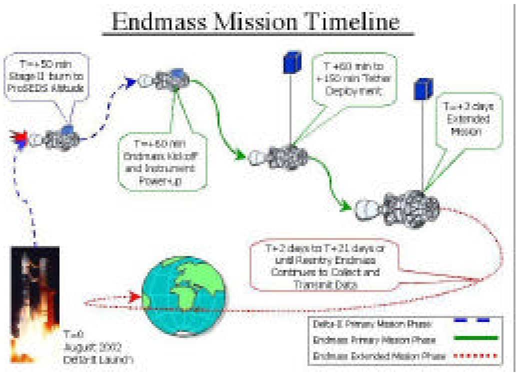

Figure 3- Endmass Mission Timeline

The Icarus Endmass continuously transmits data during the first four orbits after its deployment from the Delta-II. After the first four orbits, the transmitter is cycled on only over ground station locations determined by GPS data. After 21 days on orbit, hardware timers inhibit data transmission due to NTIA frequency licensing. In the event of extended loss of valid GPS data, the transmitter is put into a contingency mode turning on for one entire orbit, and off for two orbits in order to minimize the loss of data collection.

Icarus is a fully autonomous satellite and there are no uplink capabilities during the mission lifetime. Mission operations consist solely of data collection and analysis. A data analysis center has been arranged at Marshal Space Flight Center in Huntsville, AL. The ProSEDS project is using a mix of ground stations from the Deep Space Network (DSN), the Air Force Space Command Network (AFSCN), and two other NASA ground stations. The DSN stations are located in Goldstone, California, Canberra, Australia, and Madrid, Spain. The Air Force stations are located in Hawaii, Guam, and Vandenberg AFB, CA. In addition ground stations in Santiago, Chile, and Wallops Island, Virginia will be used.

System Specifications

The design of the Icarus satellite was broken down into five subsystems - Structures, Payload, Power/Electrical, Command and Data Handling

(C&DH), and Telemetry. A block diagram of the interface between subsystems is shown in Figure 4.

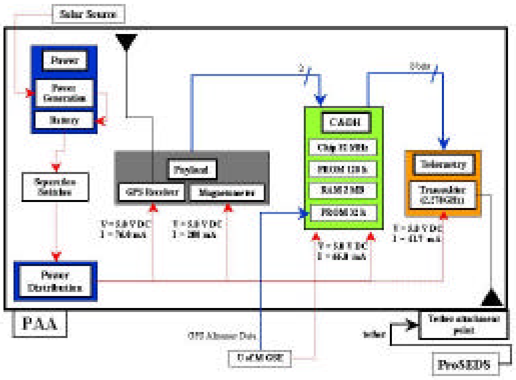

Figure 4 - System Block Diagram

Structure

The Icarus Endmass is a 10.25” x 13.65” x 18.75” structure with a mass of 21.3 kg fully assembled (including PAA). The shell is made of gold plated aluminum panels with Kapton cover. The Endmass is properly balanced such that the center of mass is close to the center of the structure. This reduces the risk of the Endmass tumbling during deployment and becoming wrapped in the tether and provides more stability. Icarus thermal control is provided by a passive thermal switch developed by Starsys Systems, Colorado, USA. In addition a blanket of Multi-Layer Insulation (MLI) is added around all electrical components that require warmer operating temperatures.

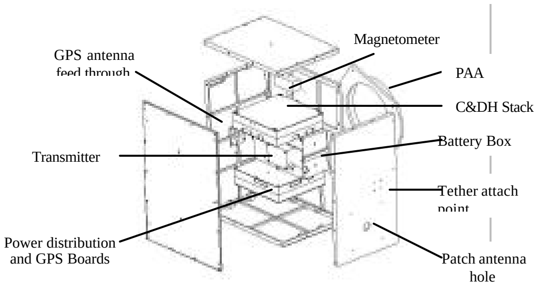

Figure 5 – Structural Layout

Payload

The Icarus satellite is equipped with an aspect magnetometer and GPS receiver for tether dynamics and attitude data. The magnetometer chosen was the Billingsly Model TFM 100G-2 which has a high enough accuracy to provide a ±5° accuracy on the Endmass attitude. While no formal magnetic cleanliness program was instituted, it was necessary to track nearby materials and do a post-fabrication calibration to attempt to calibrate the integrated internal biases.

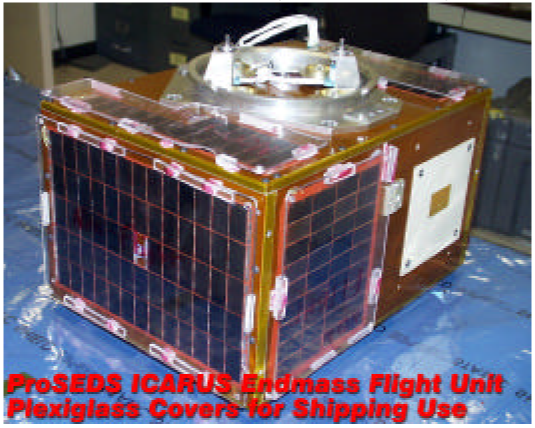

Figure 6 - Endmass View of PAA and Transmitter Antenna with Solar Cell Protective Panels Attached

The Rockwell- Collins MPE-I was chosen for the GPS receiver due to its low power consumption and low cost. The MPE-I has flight heritage on the Orbcomm communications satellite constellation. However, because the ProSEDS spacecrafts must operate fully autonomously, it was necessary to do extensive simulation testing at NASA MSFC to understand how the receiver will operate in space. The MPE-I is also the identical receiver being used by the Delta-II side of ProSEDS.

Power/Electrical

Power to the Endmass is supplied using four parallel strings of rechargeable Energizer NiCd batteries, model E3200D. Average power required by the system is calculated to be 12.5W for the primary mission (100% transmitter duty cycle) and 8.6W for the secondary mission (33% transmitter duty cycle). The batteries contain enough capacity to last for the entire primary mission, but in order to remain operational for the extended mission, Icarus requires solar cells to recharge the batteries on orbit. Twelve strings consisting of 387 Si solar cells (acquired from HelioKinetics) recharge the batteries to extend the lifetime of the mission. In addition to providing extra power, the solar cells also provide a secondary means of Icarus attitude determination. Figure 7 shows a block diagram of the electrical system.

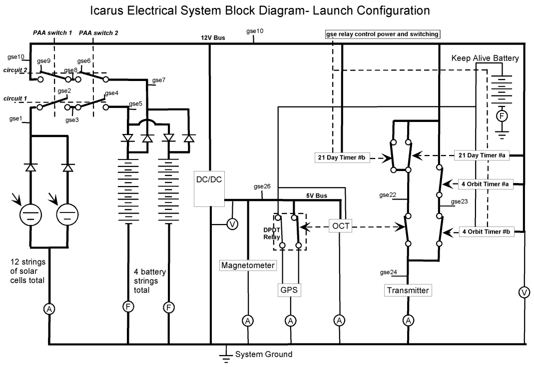

Figure 7 - Electrical Block Diagram

Command and Data Handling

Control functions of the Endmass are provided by an industrial grade CPU, the Octagon Systems 386 processor running MS-DOS 6.22. The Endmass relies on the C&DH subsystem to parse and determine the validity of the GPS data. To supplement the MPE-I's searching capability, an orbital propagator is programmed into the software to approximate position based on a previous known position and time.

Data relating to Endmass attitude is sampled at a 1 Hz rate (this includes the magnetometer data as well as the solar panel voltage data). GPS data is sampled at a 0.5 Hz rate. Health data composed of voltage, current, temperature sensors is sampled once per minute.

The Endmass telemetry frame structure was based off of the SEDS-2 mission data format in compliance with the IRIG standard 106-96. Each major frame consists of one minute of data and is 3248-bytes in length. The major frame is made up of four minor frames (812-bytes each). Each minor frame begins with a 4-byte sync pattern, followed by a 2-byte frame counter, 804-bytes of data, and ending with a 2-byte checksum. The data sections will hold an 8-byte time stamp, 22-bytes of health data, 720-bytes of solar panel data, 2040-bytes of GPS data, 360-bytes of magnetometer data, three 1-byte type ids, and 63-bytes of spare data. In order to balance the number of logical ones and zeros transmitted to keep center frequency, a UART chip internal to the transmitter adds a logical "0" start bit and a logical "1" stop bit to every byte transmitted.

In order to protect the system against Single Event Effects, the Icarus software is equipped with a watchdog timer. If the system is in an off nominal state, the watchdog timer will reset the computer by cycling the power in hopes for a clean restart.

Telemetry

Icarus uses an S-band Southern California Microwave transmitter, model TRX23S to transmit data to ground stations through a linearly polarized microstrip patch antenna. The patch antenna, made at U of M, is approximately 6" x 6" in size and is oriented downward to the earth. Endmass telemetry is not encoded and is transmitted using a PCM FSK (Pulse Code Modulation Frequency Shift Keyed) method. The downlink rate is 115.2 kbits/sec. The entire memory of telemetry, holding three orbits of data is cycled through the transmitter providing redundant copies of frames to minimize the risk of losing corrupted frames and maximizing the reception of data.

Environmental/ Qualification Systems Testing

Since initial Endmass delivery to MSFC in September 2000, Icarus has been through 4 major systems tests - mechanical vibration and shock, thermal cycle, thermal vacuum, and a 48-hour hardware/software verification. In addition, Icarus has undergone long duration software testing as well as a "dental floss" test to recognize possible tether snag hazards.

Vibration and Shock

Icarus underwent vibration and shock testing in May 2000 at MSFC and passed at the following test levels:

Sinusoid Vibration

Maximum Flight Level		**Maximum Flight Level**	
Frequency (Hz)	**Level**	**Frequency (Hz)**	**Level**
Thrust Axis (Delta Vehicle) 5 – 6.2 6.2 – 100	0.5 in. Double Amplitude 1.0 G_0 to p	Thrust Axis (Delta Vehicle) 5 - 7.4 7.4 – 100	0.5 in. Double Amplitude 1.4 G_0 to p
Lateral and Tangential Axes (Delta Vehicle) 5-100	0.7 G_0 to p	Lateral and Tangential Axes (Delta Vehicle) 5 – 6.2 6.2 - 100	0.5 in. Double Amplitude 1.0 G_0 to p
Sweep rate = 4 Octaves/ minute		Sweep rate = 4 Octaves/ minute	

Random Vibration

Frequency (Hz)	**Maximum Flight Level**	**Proto-flight Test Level (Max Flight +3 dB)**
10 – 20	0.001 G^2/Hz	0.002 G^2/Hz
20 – 60	+5.7 dB/Octave	+5.7 dB/Octave
60 – 220	0.008 G^2/Hz	0.016 G^2/Hz
220 – 400	+15.7 dB/Octave	+15.7 dB/Octave
400 – 700	0.18 G^2/Hz	0.36 G^2/Hz
700 – 900	-15.4 dB/Octave	-15.4 dB/Octave
900–1300	0.05 G^2/Hz	0.10 G^2/Hz
1300–1500	+12.4 dB/Octave	+12.4 dB/Octave
1500–2000	0.09 G^2/Hz	0.18 G^2/Hz
Overall G_{rms} =	12.8	18.1
Duration =	30 seconds/axis 3 Axes	60 seconds/axis 3 Axes

Spacecraft Interface Shock Environment

Frequency (Hz)	**Maximum Flight Shock Response Spectrum Level (Q=10)**
100 – 140	50 G
140 – 300	+ 12.7 dB/Octave
300 – 500	250 G
500 – 6000	+ 6.7 dB/Octave
6000 – 7000	4000 G
7000 – 10000	- 1.3 dB/Octave
10000	3700 G
1 Shock/ Axis 3 Mutually Perpendicular Axes	

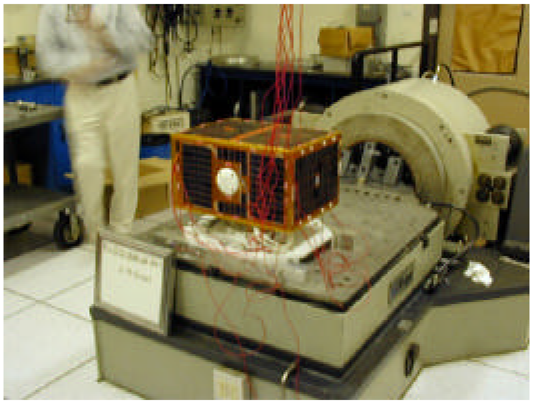

Figure 8 – Icarus During Vibration Testing

Thermal Cycle

The Endmass was thermal cycled in June 2000 at the University of Michigan to evaluate the Endmass response to a dynamic thermal environment. The cycling was performed at ambient pressure with temperatures ranging from +42°C to –16°C.

Thermal Vacuum

Icarus went through a long thermal vacuum test at MSFC in May 2001. The temperature was cycled between +67°C to –45°C for a total of three cycles. Four functional tests were run during the cycling periods, two at a hot cycle soak of +42°C and two at a cold cycle soak of –37°C.

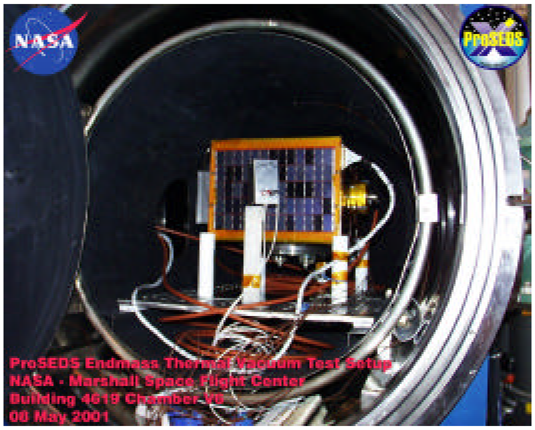

Figure 9 – Icarus in Thermal Vacuum Chamber

48-Hour Test

A full functional test of the flight hardware and software was performed in June 2002 at MSFC. A GPS simulator was used to replicate the satellite on orbit. The test included verifications that the four orbit timers worked nominally, the transmitter turned on over ground stations as located by the GPS, and the GPS kept lock nominally.

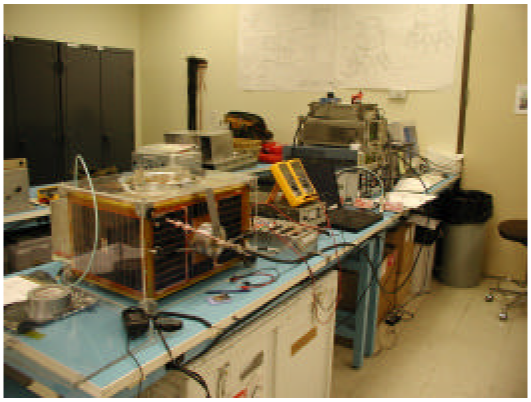

Figure 10 – Icarus Setup for 48-Hour Testing

Student Support

The Icarus Endmass was the basis for a Fall 1998 interdisciplinary design class in the College of Engineering's Master of Engineering in Space Systems program. In January 1999, the Icarus project was reorganized from a class project to a full design team ultimately involving over 100 members. In April of 1999, the team completed

PDR, CDR was completed in September 1999 with fabrication starting shortly thereafter. In May 2000, the Icarus satellite was sent to Marshall Space Flight Center for acceptance and further environmental testing.

Students at both the undergraduate and graduate levels from the fields of Aerospace, Mechanical, Electrical, Chemical, and Computer Engineering have participated on a credit, volunteer, and paid basis.

The students were divided into subsystem teams to cover the major technical areas of the spacecraft- Structures, Power/Electrical, Payload, Command and Data Handling (C&DH), and Telemetry. Each subsystem employed a dedicated, professional cognizant engineer from U of M's Space Physics Research Laboratory (SPRL) to oversee the design and to support the student leaders. The management team consisted of a student Project Manager, Chief Engineer, and Business Manager in conjunction with an engineering Project Manager from SPRL and Project Director from the College's faculty.

Lessons Learned

A number of challenges presented themselves to students during the project. The regular turnover of students as they graduated provided an opportunity for more students to get involved in the project. However, the difficulty in maintaining a consistent output of work and tracking information from semester to semester was a significant challenge. Thus, having undergraduates early in their college career participate became essential as they became the continuity for the project.

As this is principally an educational experience from the University's perspective, student's initial technical inexperience was expected. An important item to identify in this is that close mentoring by professional staff or experienced faculty is needed to keep students on track and avoid design pitfalls before design reviews.

Launch delays are an inevitable consequence of dealing with space science. For a student project, this provides challenges in the personnel turnover as mentioned before, as well as taxing the students' morale and their ability to stretch a typically fixed budget amount.

Finally, the unique environment of a student's life provides challenges to the project management staff. As Icarus involved a majority undergraduate work force working as volunteers, in addition to dedicated graduate students, student project managers had the unenviable task of coordinating a student's project time around their class and exam schedule all the while worrying about their own academic performance. Indeed, this can be accomplished but it requires a student body with enough of a talent pool to draw upon so as not to overtax a few individuals, but good communications and documentation is essential.

Conclusions

As Icarus awaits launch, the student team continues to dwindle due to graduation but new students have been brought in to assist in the ground operations and data analysis phases. The mission data will be published as a final report out of MSFC as well as formal journals.

The project has been an unqualified success from the University's perspective as the Icarus alumni have gained a tremendous educational experience, and been able to parlay this experience into jobs which they may not have been able to gain access to.

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