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Results from the Advance Power Technology Experiment on the Starshine 3 Satellite

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Abstract. The Starshine 3 satellite was put into orbit on September 30, 2001 as part of the Kodiak Star mission. Starshine 3's primary mission is to measure the atmospheric density of the thermosphere and serve as a learning outreach tool for primary and secondary school age children. Starshine 3 also carries a power technology experiment. Starshine 3 has a small, 1 Watt power system using state-of-the-art components. Eight small clusters of solar cells are distributed across the surface. Each cluster consists of a 6-cell string of 2 cm x 2 cm, GaInP/GaAs/Ge, triple-junction solar cells. These cells have twice the power-to-area ratio as traditional silicon solar cells and 25% more power than GaAs cells. Starshine 3 also carries novel integrated microelectronic power supplies (IMPS). The idea behind an IMPS unit is to allow greater flexibility in circuit design with a power source not tied to a central bus. Each IPS is used to provide 50 microwatts of continuous power throughout the mission. Early results show that this design can be used to provide continuous power under very adverse operating conditions.

Introduction

The Starshine 3 satellite was put into a circular orbit of 472 km and a 67° inclination, on September 30, 2001. Starshine 3 is a 36″ diameter spherical satellite covered with 1500 1″-diameter mirrors slowly rotating to produce a visible flash when viewed at twilight. The Starshine 3 satellite presented both an interesting challenge and opportunity in nearly all phases of the spacecraft life cycle. In the summer of 2000, an opportunity arose from NASA to launch the third in a series of satellites known as Project Starshine. The spacecraft had to be ready to launch in 10 months and there was little direct funding to build the spacecraft. Using donated services and hardware from scores of institutions and companies, Project Starshine was able to design, build and test a 3-foot diameter satellite with a complete power and telemetry system. Over 1000 schools participated in the educational outreach portion of Starshine 3.

Additionally, all of the systems were designed from scratch. Virtually no system on board had any significant flight heritage. Even the mechanical design had to be altered from the Starshine 1 and 2 designs as they were 19˝ diameter spheres and carried no instruments. As one might expect, with the limited resources at hand, the traditional design cycle with an engineering model, qualification, and flight hardware could not be adhered to. Starshine 3 took a "protoflight" approach where a single level of hardware was built, tested, refurbished and then used as flight hardware. This is a very high-risk strategy for building a spacecraft. Given the time constraints however, it was the only viable method of doing so. Fortunately, the threshold for mission success of Starshine 3 is relatively low in that it need only to deploy into orbit in one piece. Its primary mission is a passive one; observe it's orbital decay using radar, lidar and visual sightings.[1]

To improve the reliability and compatibility of the power technology experiment (PTE) with other spacecraft systems, the design was kept simple and had redundant measurements. Once in orbit, amateur radio operators sporadically collected data by listening for a radio beacon transmitting a set of measurements every two minutes.[2] The experiment therefore, could not depend on timely or continuous data collection.

The PTE contains three separate experiments. They are: Integrated micro power supplies (IMPS), a power system consisting of triple junction GaInP/GaAs/Ge 24% efficient solar cells and lithium ion batteries, and a test of optical transmission of silicone adhesives used for solar concentrator lenses. Details of the hardware can be found in reference 3. The spin rate was of particular interest in that it helped characterized the lightband separation mechanism used to deploy Starshine.[4] Measurements of the solar array current were used to calculate the spin rate.

Experiment Design

Eight strings of solar cells used to power the spacecraft were distributed more or less evenly over the surface of Starshine 3. The strings appear as clusters on the spacecraft. Figure 1 shows a string mounted on the spacecraft. The six outer solar cells in figure 1 provide power for the electronics and transmitter. The center coupon is one of the IMPS devices. This pattern was repeated for six of the eight strings.

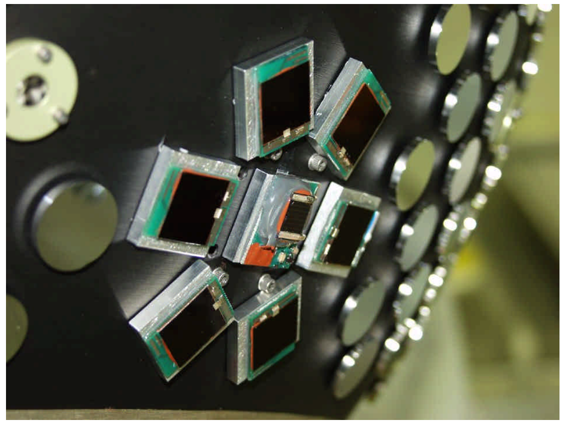

Figure 1) Solar cell string and a IMPS mounted on the Starshine 3.

Two additional strings provided power only. The photograph in figure 2 shows three strings visible on the spacecraft. The instrument package used to characterize the IMPS and power system uses a PIC16F876 micro-controller from Microchip. It has an 8K flash program memory and 368 bytes of RAM plus features such as a 10-bit A/D, three timers, and a watchdog timer. It is operated at 4 MHz as a tradeoff between speed and power. The computer/data acquisition system draws approximately 20 mA from the spacecraft power system.

Figure 2) Starshine 3 is prepared for launch.

The analog signals are digitized using MAX1400 16-bit A/D converters each with a 5-channel input and programmable gain amplifier.

The full-scale range of the A/D is 2.5 volts giving a resolution of 38.1 μV. The programmable gain amplifier can be set to a gain of 1, 2, 4, 8, 16, 32, 64, or 128, and a dc offset can be programmed for each channel. Each MAX1400 A/D converter is configured to read a 16-bit full-scale value and an offset value in addition to the five data channels. Post processing the data values using the A/D offset and full-scale values increases the accuracy. A total of six MAX1400 A/D converters provide 30 channels of data. The voltage reference used with the MAX1400 converters is the MAX6166 operating at 2.5 volts, with ± 2 mV initial accuracy and a temperature coefficient of 5 ppm/degree C. Cynetics Corp. provided the 1.25-Watt, 2-meter ham-band transmitter and receiver. A subset of the AX.25 packet radio protocol is implemented providing a half-duplex communication. A command packet from the ground is picked up by the receiver to tell the program to change the data collection and transmission interval or shut down the transmitter. The data to be transmitted is put into AX.25 UI packets using the APRS format at 9600bps. During the course of the mission no resets of the electronics were detected.

Additional reliability and redundancy was achieved by using 6 independent A/D converters with 5 channels each. If any one of the A/D converters failed there would still be sufficient data channels left to provide meaningful data. Some of the measurements were in themselves redundant. Although we were interested in how a GaInP/GaAs/Ge solar cell string performed in space, we set out to measure the performance of all eight solar cell strings. We were most interested in the operating temperature of the solar cells, and therefore measured the temperature on 3 different cells, including two in nearly identical thermal environments. The performance on five IMPS test coupons (current and voltage) and transparency measurements on two silicone samples and a control cell were also made.

Integration and Operations

The build up of Starshine 3 flight hardware, from a collection of subsystems to a completed spacecraft, took place during a 4-week period about six weeks before the scheduled launch date. The electronics subsystems were never tested in an end-to-end fashion until the spacecraft was built up. In truth, the solder was still cooling when the power system and electronics were integrated together. Once built, it was very difficult to de-bug any problems in the subsystems since the subsystems had irrevocably become part of the whole. As a result of the limited ability to solve problems that occurred during and after integration, Starshine 3 went into orbit with only 25 of the 29 data channels yielding data. The lost channels included one temperature sensor, the current on one solar cell string, and the charging current on two IMPS units. Fortunately, nearly all the scientific value of the experiments was preserved due to a robust and redundant experiment design.

Interpreting the data gathered while in orbit was a bit like building a jig saw puzzle one piece and one day at a time. Data was relayed to a web-site one packet at a time from amateur radio operators all over the world. Each data packet was a snapshot of the spacecraft at a particular point in the orbit with a random solar alpha angle but with a predictable solar beta angle.

Integrated Micro Power Supplies Performance

The IMPS consisted of a rechargeable lithium ion battery, a 1 cm x 1 cm solar array and charge control electronics consisting of a voltage regulator and a low voltage cutoff. The IMPS served as a source of 20 micro-amps to a 1000-Ohm platinum RTD. All of the IMPS units were located at either + 45° or – 45° “latitude” on the Starshine sphere. The load is continuous and cannot be turned off while awaiting launch. The storage capacity of each IMPS battery was 45mA-hours, capable of powering the load for 90 days without recharging. When Starshine launched, it had been sixty days since the IMPS units were fully charged and thus they had only one third of their initial charge left. While on orbit, the five independent power supplies experienced very adverse operating conditions: Starshine 3 was deployed in an orbit such that the solar beta angle passed through ±90°.[5] This meant that there were periods when the solar array on an IMPS did not “see” the sun for days at a time. Any charging would have to come from the Earth albedo. Furthermore, when illuminated by just the Earth’s albedo, the operating temperature of the IMPS sank as low as –18°C; only 2 degrees above the battery's operating range. In figure 3 the operating voltage of two IMPS units are shown versus days in orbit. The IMPS marked "+45°" was located 45 degrees above Starshine's equator as defined in by the photograph in figure 2. The IMPS marked "-45°" was located 45° below the equator. When deployed, Starshine 3 had a solar beta angle of –61°. A beta angle of at least –44° is needed for any direct sunlight on the "+45°" IMPS. That meant that the IMPS units in the upper hemisphere would not see the sun at all for the first 18 days. In spite of this condition, the IMPS on the upper hemisphere (+45° data, figure 3) still managed to charge under albedo lighting only. This is evident by the rising voltage during the first 18 days. The net average

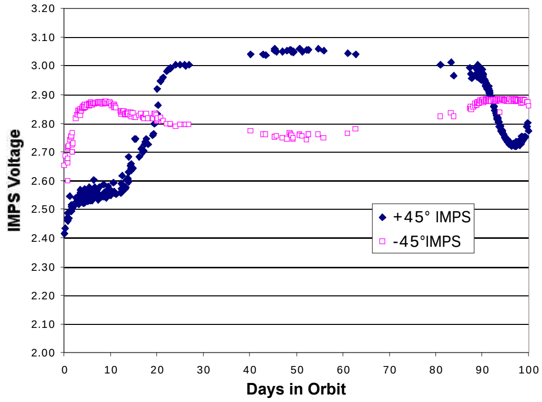

Figure 3) The voltage of two integrated micro power supplies versus days in orbit.

current measured over the first 18 days was +26 micro-amps, enough to account of the rising voltage during albedo illumination. The IMPS in the lower hemisphere (-45° data in figure 3) quickly charged to its maximum voltage of 2.9 Volts. The peak voltages reached by each IMPS are set by the voltage regulators and are not directly comparable. They reflect the set point of each IMPS voltage regulator. During the course of the first 100 days all five IMPS units maintained a voltage greater than 2.5V. The voltage fluctuations seen in figure 3 are attributed to the changing solar exposure due to beta angle and eclipse time.

Advanced Solar Cells and Batteries

The solar cells used on Starshine 3 to power the electronics and transmitter are GaInP/GaAs/Ge triple-junction cells made by Emcore Corporation. These cells are 24% efficient under air mass zero (AM0) illumination. The Starshine 3 flight marks the first time Emcore triple-junction cells have flown in space. Emcore is currently producing triple-junction cells that are 26% efficient at AM0.[6] The battery used for storage of excess power generated by the solar cells is comprised of three Sony 18650 lithium ion rechargeable cells. The electrical power required to operate the electronics and transmitter is approximately 1/2 Watt averaged over an orbital period. Since Starshine 3 is a rotating sphere and its orientation is not controlled, it was necessary to distribute solar cells over the entire spacecraft in order to insure enough power would be produced regardless of orientation. Eight small strings of solar cells were distributed across the surface of Starshine 3. Each cluster consists of a 6-cell string of 2 cm x 2 cm cells. Three strings are visible in figure 2. Each string has a bypass diode for each cell and a blocking diode on the string to prevent battery discharge through the solar cell string. Figure 4 shows a typical I-V curve for a 6-cell string at 25°C. The nominal operating point for the strings is set at 12.75 Volts. On average, three clusters will be partially illuminated at any one time. Once the battery is charged to 12.45 Volts, charge control circuitry shunts excess power to a resistive load to prevent overcharging. A Starshine 3 Electrical Power System (EPS) performance model was developed to ensure sufficient power was available to support the proposed loads and duty cycles. The model included the solar array strings, blocking diodes, the lithium ion battery. interconnect circuitry and battery voltage control

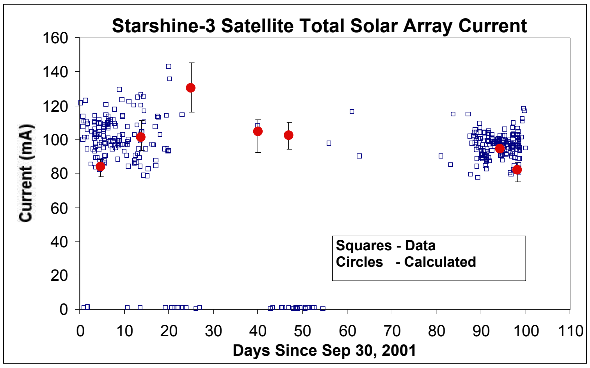

Figure 4) I-V curve from a Starshine 3 solar cell string.

hardware. The EPS design is describe elsewhere.[3] Details of the performance model are found in reference 7. Prior to launch, solar array performance estimates predicted an average current available from the solar arrays of approximately 140mA.[3] In orbit the average solar array current was considerably lower; around 100mA. The original prediction was made prior to a full understanding of the on-orbit conditions. In particular, the baseline predictions were made using uniformly distributed solar cell strings, a random alpha and beta sun angle orientation, and all the solar cells at approximately the same temperature. As built, the solar cell strings were not uniformly distributed. For much of the first 100 days the beta angle was such that only the lower hemisphere was illuminated with the upper hemisphere facing the Earth. This condition created a thermal imbalance since the lower hemisphere absorbed all of the solar energy. As a consequence the solar cells were significantly hotter than the baseline model. However, once the on-orbit conditions were properly modeled the calculated solar cells performance agreed with orbital data. Figure 5 shows modeled solar array current based on the on-orbit conditions compared to measured data. Details of the on-orbit results are found in reference 7. Despite the lower power available from the solar arrays, there was still more than enough power to meet the demands of the electronics and transmitter.

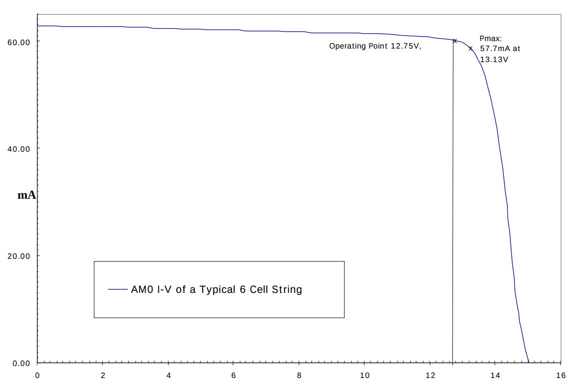

Figure 5) Measured solar array current compared to modeled results.

The electronics and transmitter require 39mA-hours per orbit to operate. The beacon signal is transmitted every 123 seconds and the power profile is shown in Figure 6. Most of the energy is used by the quiescent current of the system. The peak power of 8.7 Watts required during the transmit portion only accounts for a small percentage of the energy budget due to its short duration. The instantaneous power available from the solar array never exceeds 2 watts and is typically less than 1.5 Watts. So during every beacon cycle the battery must supply some of the power for the transmission

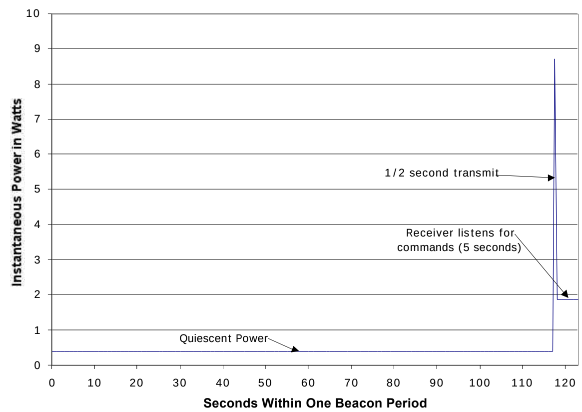

Figure 6) Power profile of the Starshine 3 beacon.

and reception. The anticipated battery discharge should not exceed 15 mA-hours during an orbit. Thus the total depth of discharge compared to the nominal rating of the battery (1.5 Amp-hour) is 1%. The power system is characterized by measuring the solar cell string operating currents, the battery voltage and the charge/discharge current of the battery.

Lessons Learned

The spin rate of Starshine 3 on release from the Athena rocket and the subsequent decay of the spin was of considerable interest to Planetary Systems Corporation, maker of the Lightband separator used to deploy Starshine 3. The Starshine program was also interested in the satellite spin rate. With Starshine 3 slowly rotating its mirrored surface will create a flicking light more easily seen by the human eye than a continuous light. It was possible to calculate the spin rate from the solar cell string current data.

The variation in current of the solar cell strings caused by the spacecraft rotation resembles a half-rectified sine wave. Using both the magnitude and phase relationship of the seven measured solar cell string currents it was possible to model the rotation rate from consecutive packets (i.e. 2 to 4 packets received 123 seconds apart). As luck would have it, we received consecutive packets early in the mission, allowing us to calculate an initial spin rate of approximately 82 seconds per revolution. After 90 days we received more consecutive packets and the spin rate had decayed to 121 seconds per revolution. Although it is difficult to model the spin rate when the data-sampling rate is below the period of rotation, it was possible to do so by putting bounds on the solution. For example, the predicted initial spin rate was approximately 72 seconds per revolution. Higher order harmonics of this frequency can be discarded as non-physical solutions.

Both the IMPS experiment and the advanced GaInP/GaAs/Ge solar cells performed well. Details of the third experiment examining the opacity of silicone rubber samples are found in reference 7 and indicated no significant degradation in the first 100 days of exposure. Additionally, the spin rate calculation helped characterize the first use of a Lightband separator. However, Starshine 3 stopped transmitting after 101 days in orbit.

Piecing together a picture of what caused the failure took some detective work. The sporadic nature of the data collection added to the uncertainty of whether the beacon transmissions had stopped or that no one was listening. Ultimately it was determined that the battery voltage degraded to the point where it could no longer drive the transmitter.

When designing a power system it is important to account for the parasitic losses between the load and the battery. These losses must be accounted for in the energy balance of the design but equally important is the effect they can have on the instantaneous power available. It was originally estimated that the power system would have approximately 0.5 ohms of parasitic resistance between the load (transmitter) and the battery. As the system design evolved, more and more wire, switches, and connectors were placed between the load and the battery. The purpose of the added components was to allow for integration and pre-launch testing of the spacecraft without risking damage to the power and electronics. The resistance of the power bus in the flight configuration was closer to 1 Ohm.

The design called for a nominal output from the battery of 12.4 Volts. The transmitter required 11.34 Volts to operate, giving us a one-volt margin. What was never firmly established in the design stage was the peak *current* required by the transmitter. As it turned out, the transmitter required 734 mA to generate the 1.25 Watt RF beacon. Combined with the system quiescent current of 36 mA the total current draw was 770 mA. With parasitic resistance, our voltage margin dropped to just 230 mV. Figure 7 plots the days where at least one data packet was obtained versus the net fraction of solar power during an orbit and the battery charging current. The charging current rises and falls with the variation in sunlit fraction of the orbit period. There is a steady decline in the threshold of battery charging current at which signals are lost. The most likely cause of this is that the parasitic resistance of the system is increasing. Some of this parasitic resistance appears between the battery and the point in the circuit where the battery voltage is monitored. This will reduce the maximum voltage to which the battery can charge. The increasing resistance will also limit the ability of the battery to supply current. Unfortunately, the source of this increasing resistance cannot be pinpointed from the on-orbit data. During the month of May 2002, Stashine 3 experienced 10 day of continuous sunlight. No data was received during this interval and the telemetry portion of the mission was declared over.

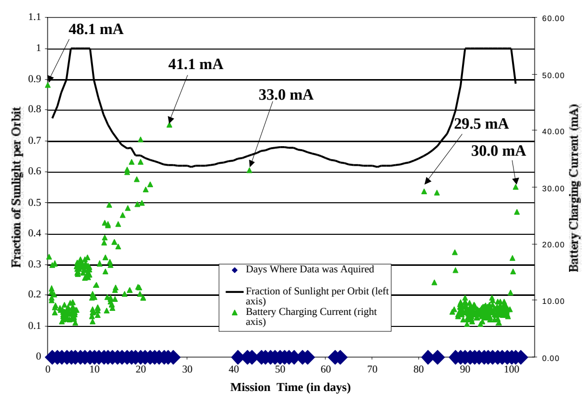

Figure 7) Days when data was acquired versus the fraction of time during an orbit the spacecraft was illuminated and the battery charging current.

Such failures are nearly unavoidable in a program with a compressed timeline and limited resources. Conflicts are usually discovered late in the process and one has less control over their disposition. The best strategy to combat this operating mode is to keep your design simple, minimize single point failure modes, and hope to have enough design margin to account for incompatibilities.

Conclusions

Using donated services and hardware, Starshine 3 went from concept to flight hardware in less than one year. The data collected by amateur radio operators provided enough information to characterize all of the planned experiments. In addition to providing valuable atmospheric density data, and involving thousands of students from all over the world in the construction of a satellite. Starshine 3 demonstrated the concept of Integrated Micro Power Supplies in space. It is also the first satellite to be powered using Emcore triple-junction solar cells.

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[2] The authors wish to express their gratitude to the following amateur radio operators for the data collected from Starshine 3. G0SFJ, G8ATE, G0VRM, JA3TDW, JA1CTU, LW2DTZ, JE9PEL NA1DB, KN4HH, F6AGR, ZS7ANT, ZR1CBC, ZS4AGA, KA7ILU, KB0VBZ, G0VRM, IT9GSV, F5DJL, ON1BKD, KC8SRG, A71EY, KG6GIQ

[3] Advance Power Technology Experiment for the Starshine 3 Satellite", Phillip Jenkins, David Scheiman, David Wilt, Ryne Raffaelle, Robert Button, Mark Smith,Thomas Kerslake, Thomas Miller, proceedings of the 15th Annual Small Satellite Conference, AIAA/Utah State University, August 13-16, 2001.

[4] Ryan L. Perroy, "Automated Separation System Testing," Proceedings of the 36th Aerospace Mechanisms Symposium, held at the NASA Glenn Research Center at Lewis Field, May 15-17, 2002.

[5] For Starshine 3, a beta angle of –90° is equivalent to the sun being parallel to the axis of rotation on the lower hemisphere.

[6] Details of the Emcore GaInP/GaAs/Ge solar cell can be found at: http://www.emcore.com/html _documents/Photovoltaics.htm

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