DISCO – Develop Inertial Spin Created On-orbit: A Magnetic Spin-Rate Controller for STARSHINE 4

Jonathan A. Lovseth
Rockwell Collins Advanced Technology Center
MS 137-117, 855 35th Street NE, Cedar Rapids, IA 52498-0001; (319) 295-7319
jalovset@rockwellcollins.com

Richard R. Schultz
University of North Dakota, Department of Electrical Engineering
Upson Hall II Room 160, 243 Centennial Drive Stop 7165, Grand Forks, ND 58202-7165; (701) 777-4429
RichardSchultz@mail.und.edu

Gil Moore
STARSHINE Project Director, Monument, CO
GilMoore12@aol.com

Chris McCormick, Brian Giesinger
Broad Reach Engineering, Golden, CO, and Tempe, AZ
ccmcc@broadreachengineering.com, brian@broadreachengineering.com

Warren J. Wambsganss, Nicholas E. Hulst
Rockwell Collins, Cedar Rapids, IA
wjwambsg@rockwellcollins.com, nehulst@rockwellcollins.com

ABSTRACT: The “Develop Inertial Spin Created On-orbit (DISCO)” magnetic spin-rate controller was designed to maintain a 5°/second spin-rate for the three-year mission of the STARSHINE 4 microsatellite. This subsystem was designed, built, and tested by University of North Dakota electrical engineering students, with support from Broad Reach Engineering, an aerospace hardware development firm. The primary mission of STARSHINE, or the Student Tracked Atmospheric Research Satellite for Heuristic International Networking Experiment, is to learn about orbit degradation caused by atmospheric response to solar extreme ultraviolet radiation. This is accomplished by tracking orbit times using a highly-visible satellite that has a known ballistic coefficient. On deployment, the satellite is placed into a spinning motion, which allows sunlight to be reflected to Earth from any of the 1,000 high-polished mirrors placed on its spherical surface. In this manner, the blinking satellite can be tracked with the naked eye by space enthusiasts from around the world. Unfortunately, STARSHINE satellites 1, 2, and 3 each stopped blinking after approximately three months in orbit once the spin-rate was depleted through a combination of atmospheric drag and satellite hysteresis, which thereby limited satellite tracking to radar or laser systems. For the next STARSHINE mission, an active controller consisting of three spin-rate sensors, a magnetometer, and three torque rods will maintain spin throughout the mission life, from deployment to reentry. Once each day, the system will wake up to measure the satellite’s spin-rate and to increase it, if necessary. The DISCO system will increase the useful lifespan of the STARSHINE 4/5 mission by making STARSHINE 4 visible to the naked eye throughout its three-year mission. The design of electronic, software, and mechanical subsystems is described, along with the development of ground test equipment for the verification of requirements. DISCO hardware was delivered to the system integrator in mid-2005, and it is anticipated that STARSHINE 4/5, with the custom spin-rate controller installed in STARSHINE 4, will be launched sometime in 2007 or 2008.

INTRODUCTION & BACKGROUND

The Student Tracked Atmospheric Research Satellite for Heuristic International Networking Experiment, or STARSHINE, is a K-12, university, industry, and government laboratory collaborative effort that began in the late 1990s. The program has two primary objectives. The first of these goals is to study the effect of solar activity on the Earth’s upper atmosphere[1], and consequently, the degradation of low Earth orbits (LEOs) of satellites. The second major goal is the inspiration of young people to study math and science through their direct involvement in a meaningful space experiment.

Each STARSHINE satellite is a mirrored spherical microsatellite designed to be observable from the Earth's surface under twilight conditions. Similar to a mirrored disco ball, light from the sun strikes the surface of the satellite and is reflected to the Earth, where it is easily observed traveling across the night sky with the naked eye. By timing visual observations of the location of this spherical mirrored satellite, its orbit can be determined. STARSHINE 1 is shown in Figure 1, and STARSHINE versions 2 through 4 are very similar in appearance.

Figure 1. STARSHINE 1, covered with nearly 900 polished circular aluminum discs.[2]

At the dawn of the space-age, Operation Moonwatch utilized volunteers to observe satellites through small telescopes and to record their meridian crossing times. The collected data was provided to the Smithsonian Astrophysical Observatory, which would then calculate the orbits of these bodies. Professor Gil Moore, STARSHINE Project Director, was among those collecting data for Operation Moonwatch[3]. As a natural evolution of this relatively low-tech tracking method, the STARSHINE project also relies on volunteers to directly observe satellites in the interest of orbital science.

Thus far, three STARSHINE satellites have been designed, built, and launched. STARSHINE 1 was launched on May 27, 1999, and it orbited for almost one complete year, decaying from LEO on February 18, 2000. It had a mass of 39 kg and was launched from the Space Shuttle Discovery during STS-96. The face of STARSHINE 1 was covered with 878 polished aluminum mirrors. STARSHINE 2 was launched on December 5, 2001, onboard the Space Shuttle Endeavor during STS-108 as part of NASA's Hitchhiker program for educational satellites[2]. STARSHINE 2 was similar to version 1, consisting of a 38 kg sphere with a diameter of 48 cm. It was covered with 854 mirrors. Its LEO orbit decayed on April 26, 2002. Most recently, STARSHINE 3 was launched on an Athena 1 rocket on September 30, 2001. STARSHINE 3 was twice the size of its two previous sister satellites at 90 kg and 1 m in diameter, and it carried 1,500 mirrors. STARSHINE 3 ended its 16-month mission upon orbit decay on January 21, 2003.

STARSHINE satellites are observable by using a passive reflective system of polished aluminum mirrors to reflect light from the sun onto the surface of the Earth, effectively causing a blinking effect across the night sky to a viewer on our planet's surface. Other satellites behave in similar ways. The Department of Defense Iridium constellation, originally developed by Motorola for worldwide wireless communications, consists of 66 LEO satellites. These communication satellites have very large antennae covered with silverized Teflon tape, which often cause what are called "Iridium flares," flashes of reflected sunlight visible from Earth. Being much smaller than the antennae of the Iridium constellation, a STARSHINE satellite increases the visibility of this reflected light by using over 800 polished aluminum circular discs covering nearly its entire surface. Each disc, shown in Figure 2, is 2 cm in diameter and is attached directly to the face of the spherical satellite surface.

Figure 2. Polished aluminum mirror prior to mounting on STARSHINE satellite.[2]

The human eye is responsive to blinking light. At the same time, however, the human visual system has trouble recognizing flashes if they are too short. It will perceive blinking light of equal magnitude flashes if the duration of each flash is greater than 0.1 seconds. Flashes of shorter duration cause this light to be attenuated[4]. To take advantage of this visual responsiveness, it is desired that the STARSHINE satellite continuously and slowly spin while on orbit. When spinning, the satellite appears to twinkle as it travels across the night sky. The light can be quite bright, as shown in Figure 3. A launch vehicle can start the satellite spinning at 5°/second when the satellite is deployed.[2] Two factors, however, cause de-spin to take place over time: atmospheric drag and satellite hysteresis.

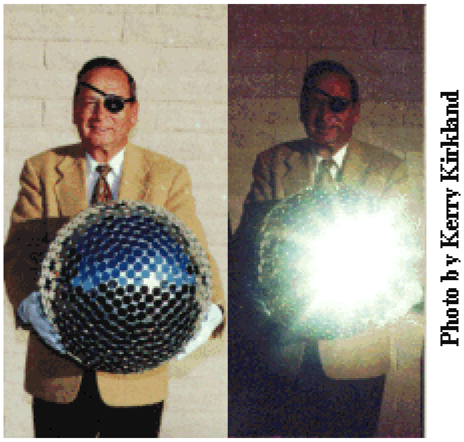

Figure 3. Professor Gil Moore, STARSHINE Project Director, holding STARSHINE 1.[2]

The STARSHINE satellites are launched into LEO at an altitude of approximately 450 km. *Space Mission Analysis & Design, Third Edition* predicts that a satellite with a ballistic coefficient of 200 kg/m^2 and launched to an altitude of 450 km will remain in orbit for 724 to 1,497 days.[5] The variation in this orbit life is due to solar activity maximum and minimum, respectively. As solar energy reaches Earth's atmosphere, a portion is absorbed and the atmosphere reacts. An increase in the atmospheric density leads to increased drag and consequently, less time in orbit. As the orbit altitude reduces in size, the effect is magnified because satellite velocity increases.[5] One goal of the STARSHINE project is to learn more about the effects of solar activity on orbit degradation by studying satellite orbit perturbations.

In LEO, atmospheric pressure is near vacuum. Atmospheric density varies from 2.47 x 10^{-13} to 3.61 x 10^{-12} kg/m^3 at an altitude of 450 km.[5] This atmospheric density, albeit extremely low, causes drag to act upon a body in motion. The energy reduction due to drag causes an orbit to become smaller, leading to further increases in drag. Eventually, the altitude of the orbit becomes so small that the satellite reenters the atmosphere and burns up. This deceleration due to drag is represented as

$$\alpha_D = -\frac{\rho C_D A V^2}{2M}, \tag{1}$$

where ρ is defined as atmospheric density, A is the satellite's cross-sectional area, M is the satellite's mass, V is the satellite's velocity, and C_D is the drag coefficient.[6]

The spinning STARSHINE satellite will be traveling through a fluid, the extremely low-density atmosphere. Friction on the surface of the sphere can slow the rotation as well as degrade the orbit.

Additionally, satellite hysteresis can absorb kinetic rotational energy. As a ferromagnetic material travels through a magnetic field, it is magnetized in one direction. When the magnetic field is removed, the material will not return to a zero magnetized state. The orbiting body will retain some magnetization, thus causing an opposing force if a field in the opposite direction is then applied. This is experienced for a rotating body traveling through Earth's magnetic field during orbit.[7]

Over time, these two factors deplete the spin-rate of the satellite, although it is difficult to predict which effect is dominant. When not spinning, the effect of blinking is reduced, which therefore reduces the ability of a person to view the STARSHINE satellite without the use of a telescope or other tracking equipment. STARSHINE 1, 2, and 3 each ceased to spin after two-to-three months in orbit.[2] It then became impossible to track the satellite from the surface of the Earth with the naked eye. To greatly extend the useful life of the project, STARSHINE 4 will incorporate an active electronic system capable of maintaining spin for the duration of the mission.

Inspiring Young Scientists, Engineers, and Mathematicians

Children and young adults in the elementary and secondary education systems contribute to the STARSHINE project in several ways. Younger students in selected classrooms around the United States and throughout the world are asked to prepare flight hardware by polishing the mirrors mounted to the surface of the sphere. After a presentation from a member of the STARSHINE team, classrooms are provided a free kit containing three aluminum plates, grinding slurry, and polishing pastes used to prepare the metal to reflect sunlight. Students take turns polishing each mirror's surface for two hours. The best two disks are sent back to the STARSHINE team, where the team members select the better of the two mirrors to be mounted on the actual satellite. The third mirror is kept for the classroom as a memento of their involvement in the project. Over 120,000 students from 43 countries (one elementary school classroom is shown in Figure 4) have been involved in the various STARSHINE projects.[3]

Figure 4. Professor Gil Moore and a group of elementary school children polishing STARSHINE mirrors.[2]

Since STARSHINE does not produce light of its own, it is only visible some of the time. Satellites are only visible when sunlight strikes them and the observer on the Earth is already in darkness. These conditions are met only when the sun is below an observer's horizon, but not so far as to cast the Earth's shadow upon the satellite. The best times for satellite viewing, therefore, occur a few hours after sunset and right before sunrise. In the middle of the night, the sun is simply too far below the horizon to light the STARSHINE mirrors. In summer months, areas of high latitude can experience better satellite viewing opportunities, when the tilt of the Earth allows the sun's rays to light a satellite but not the ground where the observer is located.

Middle and high school students are asked to track STARSHINE satellite orbit times. A Web site maintained by Chris Peat can be used to predict the approximate time that the orbiting STARSHINE satellite will be viewable over a listed geographic area.[2] The Heavens Above Web site at http://www.heavens-above.com is hosted by the Deutsches Zentrum für Luft- und Raumfahrt e.V. (i.e., the German Aerospace Center) at the German Space Operations Center. Students are instructed to track the amount of time for the satellite to travel from one reference point to another.

For instance, a student living in Logan, Utah, may be asked to find the satellite just above the northwestern horizon at 5:51 AM. Ursa Major and Venatici indicate the starting line for the student to begin timing the satellite's speed using a stopwatch. When the satellite reaches a reference line formed by Mercury and Mars, the stopwatch should be stopped. Theoretically, it should take from 5:51:17 AM to 5:57:10 AM for the satellite to travel this distance. If it takes less than five minutes and 53 seconds, the satellite velocity has increased, indicating a greater degradation of orbit than expected.

User coordinates can either be selected from a large list or entered manually. For example, Grand Forks International Airport (KGFK) is located at 47°56'57.3180" N / 097°10'34.0000" W and at 845' above sea level. To use this data on the Heavens Above Web site, one would enter the decimal representation of these coordinates: Latitude = 047.949255, Longitude = -097.176111, Elevation = 257.556 m. A host of satellite orbits are stored in the database at this Web site along with their predicted pass times, maximum altitude, and projected visual magnitude for the given location. By selecting a date on the list, a star map, similar to that shown in Figure 5, is generated to aid the viewer in locating the orbiting body of interest. The stars and planets on this chart can be used to help a viewer in locating the satellite as it travels across the night sky. The map may appear to have West and East juxtaposed, but it is designed to be held overhead and will therefore match the appropriate directions when used in this manner.[8]

The experimental data collected by students and space enthusiasts is then passed to scientists at the Naval Research Laboratory through the project STARSHINE Web site. Analytical Graphics, Inc., has modified Satellite Tool Kit (STK) to generate the orbit propagation data based on the satellite orbit times in order to provide an immediate response to new data. With data received from observations of the STARSHINE satellites, orbit perturbations and degradation can be correlated with activity taking place on the sun.

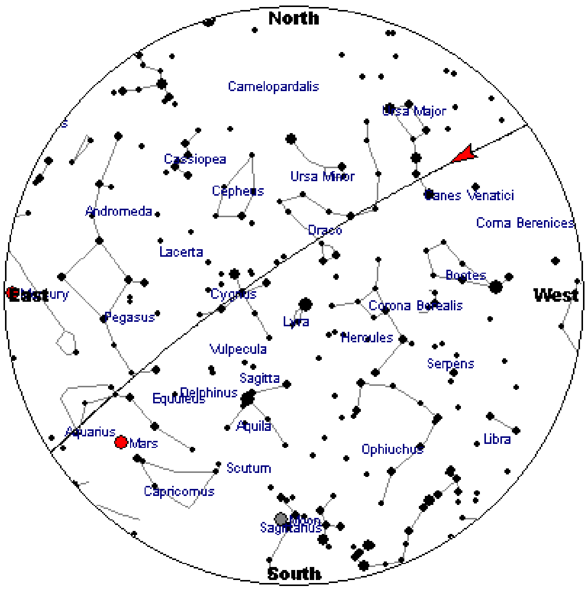

Figure 5. Star map from Heavens Above Web site, www.heavens-above.com.[8]

STARSHINE 4/5

The current iteration of STARSHINE consists of two satellites. STARSHINE 4 will be equipped with the "Develop Inertial Spin Created On-orbit (DISCO)" magnetic spin system, designed and built by the University of North Dakota and Broad Reach Engineering. STARSHINE 5 is a smaller satellite initially housed inside STARSHINE 4. Sixty seconds after separation from the launch vehicle, timers onboard STARSHINE 4 will activate an ejection system to release STARSHINE 5 into an adjacent orbit. This satellite has a different ballistic coefficient and therefore a different drag coefficient.[6]

Scientists, space enthusiasts, and K-12 students will be able to track STARSHINE 4 by sight without the aid of a telescope. At the same time, STARSHINE 4 will be radar tracked by the Air Force Space Command and laser tracked by the International Satellite Laser Ranging Network. Data from the student visual network and the highly accurate radar and laser networks will be compared, with error information fed back to the individual volunteer trackers for refinement of their observational techniques.

STARSHINE 5, at a diameter of 10 cm, is too small to carry external mirrors and will therefore be tracked exclusively by the Air Force Space Command and the International Satellite Laser Ranging Network.

Table 1 lists STARSHINE mission information.

Table 1. STARSHINE satellite specifications. STARSHINE 4 and STARSHINE 5 will be launched together, and STARSHINE 5 will deploy on orbit. The STARSHINE 4/5 launch date and altitude are expected values.

SATELLITE NAME	DIAMETER	MASS	NUMBER OF MIRRORS	INITIAL ALTITUDE	LAUNCH	END-OF-MISSION
STARSHINE 1	48 cm	39 kg	878	385 km	05/27/1999	02/18/2000
STARSHINE 2	48 cm	38 kg	858	370 km	12/05/2001	05/01/2002
STARSHINE 3	94 cm	90 kg	1,500	475 km	09/29/2001	01/21/2003
STARSHINE 4	48 cm	45 kg	1,000	500 km	TBD 2008	---
STARSHINE 5	10 cm	TBD	0	500 km	TBD 2008	---

DISCO SYSTEMS ENGINEERING

The DISCO magnetic spin-rate controller consists of battery-powered electronics, an ultra-low power microcontroller, spin-rate sensors, a magnetometer, and three torque rods. A block diagram of the hardware architecture is shown in Figure 6, with the implemented system shown in Figure 7. DISCO development was funded by Broad Reach Engineering, and it was designed by students at the University of North Dakota (Grand Forks, North Dakota) and engineers at Broad Reach (Tempe, AZ).

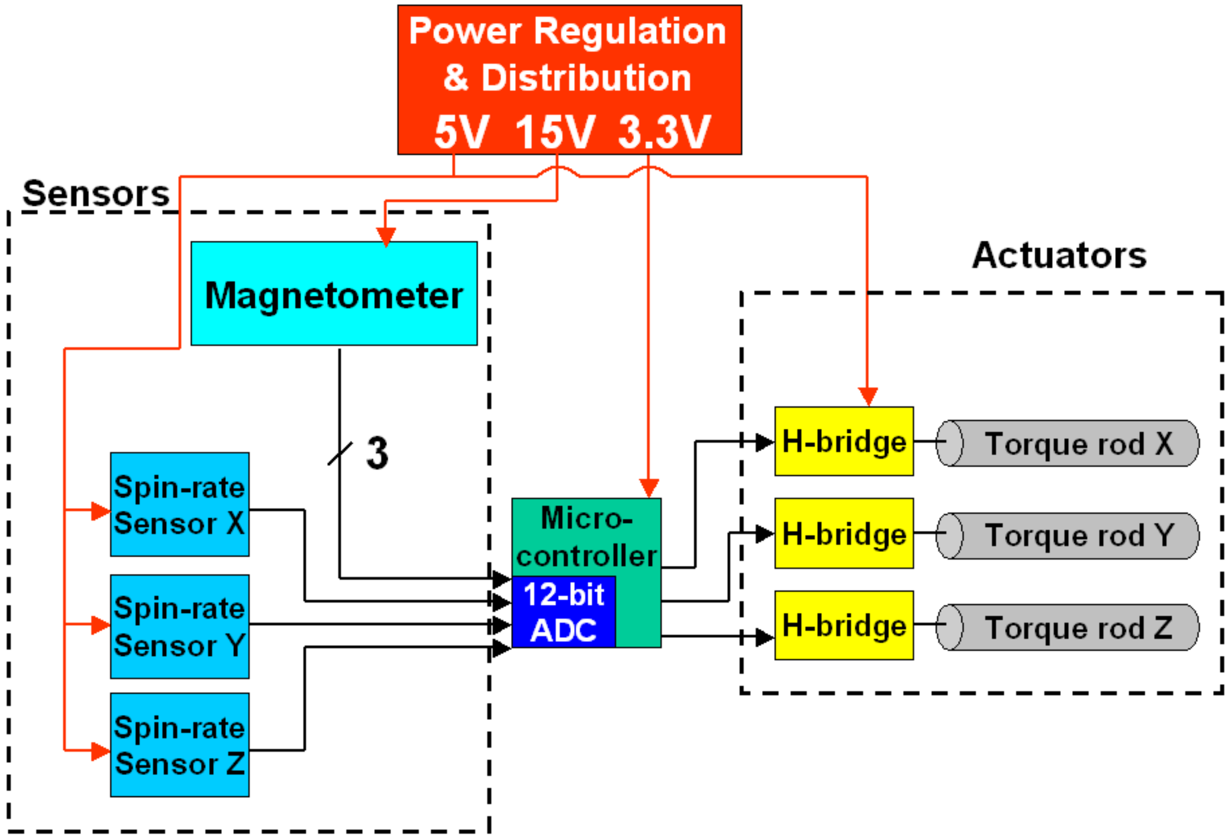

Figure 6. DISCO magnetic spin-rate controller system hardware component block diagram.

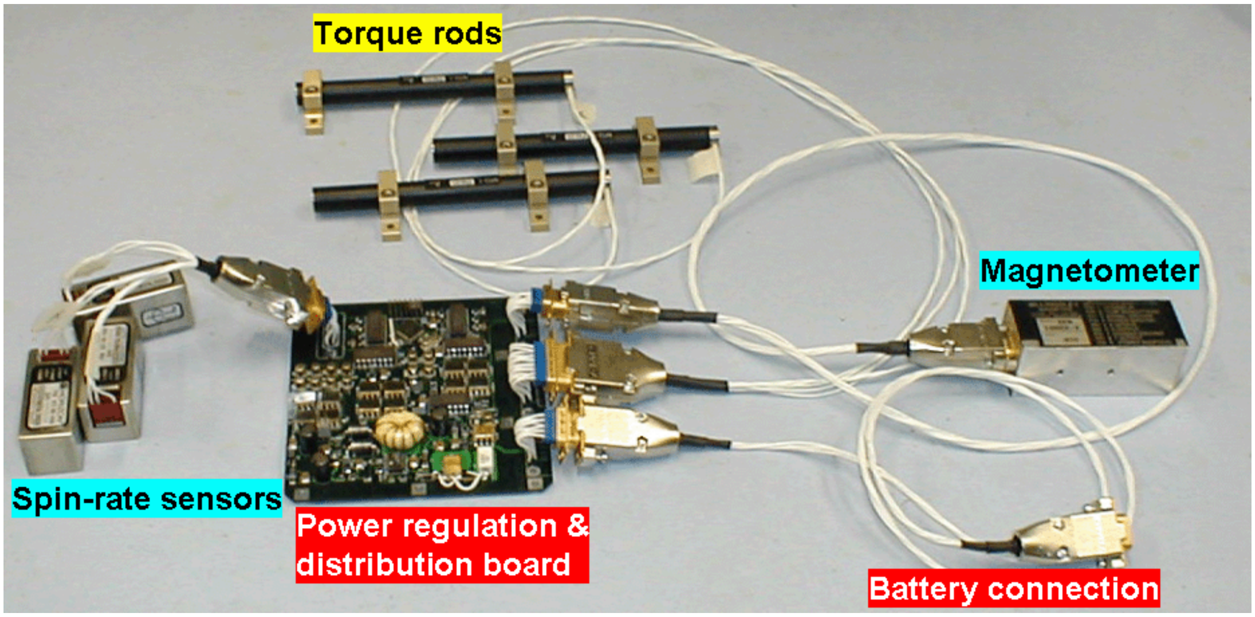

Figure 7. Complete DISCO system, including spin-rate sensors, torque rods, magnetometer, custom power regulation and distribution board populated with electronic components, and battery connection.

A list of system-level requirements was created based on mission characteristics. They are given as follows:

- The system shall operate as specified herein when supplied from a 12 VDC source.
- The system shall operate continuously for three years, or until discharge of the batteries supplying its power, whichever occurs sooner.
- The system shall be implemented on a printed circuit board with no less than four mounting points for attachment of mounting screws.
- The system shall sense its rotation rate in each of three axes, to a precision of 0.1 revolutions per minute, each day.
- The system shall increase its rotation rate to not less than 5°/second, if such an increase is needed, each day.
- The system shall operate in a low-power "sleep" mode when it is not sensing or increasing its rotation rate.
- The system shall be as small and light as possible while still meeting previously stated requirements.
- The system shall operate on as little power as possible while still meeting previously stated requirements.

It should be mentioned that strict mass, volume, and power requirements were not imposed on the DISCO system design.

Previous STARSHINE satellites have experienced a complete loss of original spin-rate over a period of two to three months. To produce a means of maintaining rotation for the entire life of STARSHINE 4, several options were explored. Thrusters are commonly used on satellites for orbit corrections or maneuvers. Such a system is usually comprised of a tank of pressurized hydrazine and a nozzle specific to the type of thrust required.[5] One drawback to incorporating thrusters is the complicated task of determining orientation to calculate velocity changes. Furthermore, hydrazine tanks eventually become depleted and, consequently, useless.

Reaction wheels are often used to reduce the rotation of a satellite in order to stabilize spin-rate. These devices were considered to increase the rotation rate of STARSHINE 4. By increasing the rotation of a reaction wheel, a satellite experiences a torque in the other direction. A reaction wheel would be able to accomplish the desired rotation, but this approach requires a large mass and volume for the wheel and necessary motor components. Also, if a brake is used to slow the torque wheel, it produces thermal energy that – if not planned for accordingly – can pose serious problems for the system.

The most feasible active system for maintaining the required spin-rate involves the use of magnetic torque rods. Magnetic torque rods are created by coiling lengths of wire around a magnetic core. When a potential is placed across the wire, it passes current through the torque rod generating a magnetic dipole. This dipole creates a torque (in N•m) against the Earth's magnetic field, given as

$$T = DB, \quad (2)$$

where B is the Earth's magnetic field (in Tesla), and D is the generated dipole (in A•m^2).[5]

Three spin-rate sensors are mounted orthogonally and used to measure the spin-rate independently in each direction. The selected device is the Systron BEI GYROCHIP Model HORIZON angular rate sensor.[9] It operates on an input of 8 to 15 VDC with a nominal current draw of less than 20 mA, sensing spin-rate in the range of -90°/second to +90°/second. The sensor has an extremely low noise rating of less than $0.0025°/\text{second}/\sqrt{\text{Hz}}$.

ZARM Technik manufactures very small torque rods with near zero hysteresis.[10] Although they are not yet in mass production, DISCO will use three ZARM MT2-1 torque rods. Each rod has one coil and is able to operate on 500 mW at 5 VDC. These torque rods have a linear dipole moment of 2.0 A•m^2, are only 157.5 mm in length, and have a diameter of 15 mm. Each rod has a mass of only 200 g, with a nominal current draw of 100 mA.

A Billingsley Magnetics TFM100G2-S triaxial fluxgate magnetometer was selected to sense the magnetic field.[11] This is a space-rated magnetometer that operates at 15 VDC, with high accuracy and linearity across a range of –100 μTesla to +100 μTesla. It provides magnetic field data relating to three axes.

A Texas Instruments MSP430F149 microcontroller was selected to control the operation of the spin system. This microcontroller was selected because of its extremely low power consumption. While in sleep mode, the MSP430F149 can operate at 3.3 VDC with a current draw of only 1.6 μA. It also houses a 12-bit analog-to-digital converter, 60 kB of flash memory, and a built-in watchdog timer. Microcontroller development was accomplished using the IAR Systems Embedded Workbench and the C-Spy tool, also developed by IAR Systems.[12]

DISCO Hardware Design

The DISCO hardware was designed to be as small and light as possible and to operate on as little power as possible, while still being extremely reliable. The main functions of the hardware are to supply power to all of the components, obtain magnetic field and spin-rate measurements, and switch the torque rods on and off as dictated by the system software.

Since the sensors and actuators do not all operate on the same voltage levels, a custom power regulation and distribution board was designed and built by Warren J. Wambsganss, a master's-level graduate at the University of North Dakota, now employed by Rockwell Collins in Cedar Rapids, Iowa. The power subsystem supplies three different voltages: 3.3 VDC for the microcontroller, 5 VDC for the torque rods, and 15 VDC for the magnetometer and spin-rate sensors. The board receives power from the battery at 12 VDC, which it then converts and regulates. In order to conserve power, all voltages except the 3.3 VDC line can be turned off by the microcontroller when the system is in sleep mode. A DC/DC flyback converter is used to efficiently step the voltage up from 12 VDC to 15 VDC, and down to supply 3.3 VDC and 5 VDC from this line.

An H-bridge design of optically-coupled field effect transistors (opto-FETs) is used to allow current to be driven in either direction through each of the three magnetic torque rods. This allows each torque rod to produce either a positive or negative torque relative to the present magnetic field when desired.

All power regulation and distribution components, as well as the microcontroller, are soldered to the printed circuit board (PCB). It is an eight-layer board, including separate layers designed specifically for thermal transfer, two power planes, two ground planes, and two signal planes. The populated PCB is shown in Figure 8. The board is made of special space-grade material to prevent off-gassing and to withstand radiation effects.

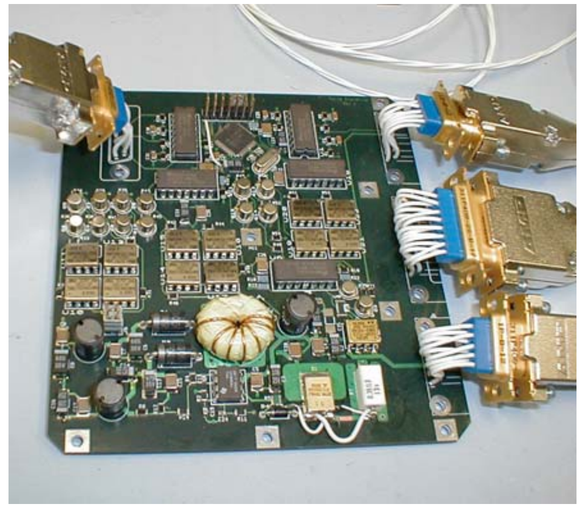

Figure 8. Custom-designed power regulation and distribution board.

DISCO Software Design

Jonathan Lovseth and Nicholas Hulst wrote software for the DISCO system as graduate students at the University of North Dakota. The flowchart used to control the spin-rate system is shown in Figure 9, and it consists of several key steps. First, the microcontroller signals the PCB to power up the sensors and waits for an established period of time for stabilization. Next, the spin-rate sensors are sampled to determine the spin-rate and direction. If STARSHINE 4 is still spinning at 5°/second, the microcontroller powers down the peripherals and will remain inactive for 24 hours. If the satellite's spin-rate has slowed below 5°/second, the magnetometer is sampled as a baseline, and it is resampled one second later to determine the magnitude of the Earth's magnetic field and the orientation of the satellite's spin vector to this magnetic field. The axis that is traveling fastest through the magnetic field is the most efficient one to accelerate when trying to increase to the desired spin-rate. Therefore, this corresponding torque rod is activated, producing a magnetic field that will accelerate the satellite's spin along that axis. After a one-second push, the microcontroller once again checks the spin-rate. The microcontroller will continue to stay in the loop until a desired spin-rate is achieved. It will then power down the sensors and torque rods, waiting 24 hours until it is time to test the spin-rate again.

To further reduce system power consumption, it is desired to fire the torque rods only when it is efficient to do so. After sampling the magnetic field, a magnitude value is calculated. A magnetic field threshold was set to energize the torque rods only when the Earth's magnetic field is significant enough to push against. If the magnetic field measurement is less than 28 μTesla, the microcontroller will enter a short sleep mode of five minutes. These low field regions exist near the Earth's equator.

Since the goal is to pass the mirrored discs across the surface of the Earth at 5°/second in any orientation, a total spin-rate can be calculated from the vector sum of the three separate components. The MSP430F149 CPU does not have a built-in square root function, so values are given extended precision, squared, and then summed. The total is compared to the value of a sensor reading of 5°/second squared.

It is likely that STARSHINE 4 will be spinning faster in one direction compared to the other two axes – this is the component to which the torque should be applied. To ensure that the direction of the applied force is in the fastest spin axis, the X, Y, and Z magnetic field differentials are compared, and only those components constituting 30% or greater of the total sum of magnetic field squares will be used to push against their corresponding fields. This ensures that DISCO will push in the direction that it is already spinning the fastest in order to reduce workload and conserve battery life.

After each torque rod has fired, the microcontroller waits for 0.1 seconds. This is to ensure that the magnetic field has collapsed and that the magnetometer will read the Earth's magnetic field rather than the field produced by the torque rod. This is not necessary if the desired spin-rate has been attained, as the microcontroller will enter "sleep" mode rather than resampling the magnetometer.

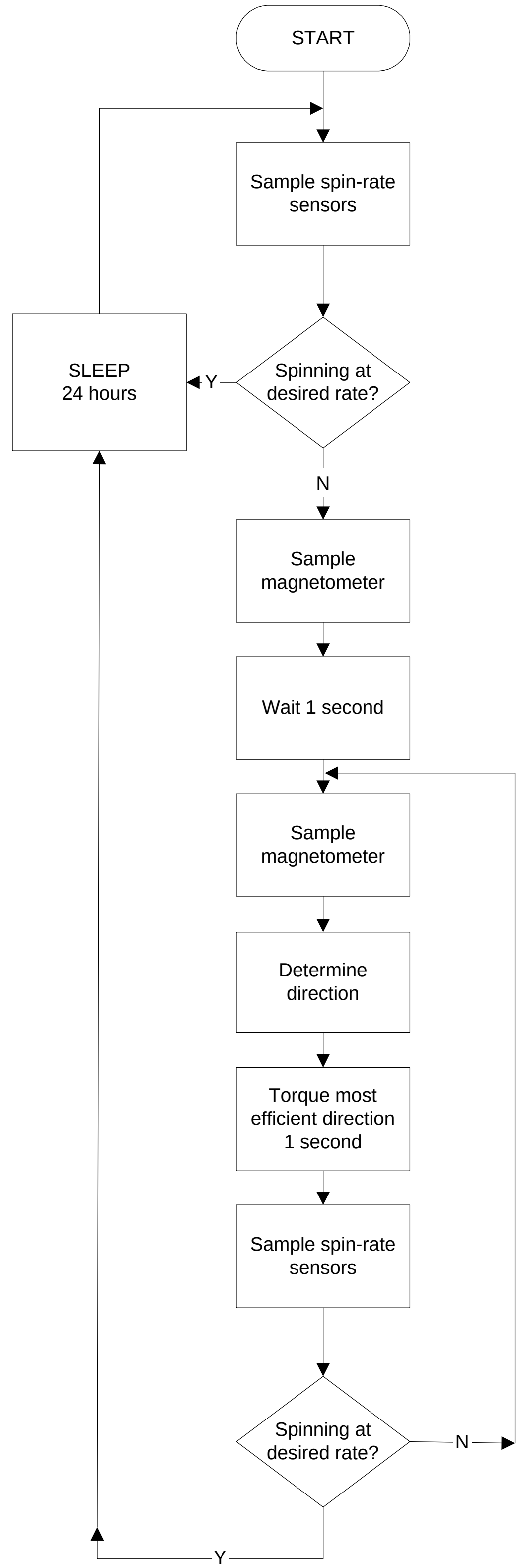

Figure 9. High-level flowchart of the DISCO magnetic spin-rate controller software for STARSHINE 4. Each block represents a module called by the main control routine.

DISCO Battery Selection

Power estimation involved both observed and calculated data. The first step involved calculating the satellite's moment of inertia. The moment of inertia of a sphere with a constant mass distribution can be calculated as

$$I = \frac{2}{5}MR^2 = \frac{2}{5}(45.359\ \text{kg})\cdot(0.24448\ \text{m})^2 = 1.0845\ \text{kg}\cdot\text{m}^2\ . \tag{3}$$

The projected rate of spin deceleration was based on previous STARSHINE missions. Past missions experienced a rotation deceleration from 5°/second down to 0°/second over a period of two months.

Magnetic field values were found from a lookup table for a 500 km polar orbit. The average of this field was found to be 3.99 x 10^{-5} T.[14] To calculate how much torque time will be required to maintain spin-rate, a calculation of the average torque generated while the rods are energized must first be calculated:

$$T = DB = \left(2\ \text{A}\cdot\text{m}^2\right)\cdot\left(3.99\times10^{-5}\ \text{T}\right) = 7.98\times10^{-5}\ \text{N}\cdot\text{m}\ . \tag{4}$$

The Earth's magnetic field will only be above the threshold of 2.8 x 10^{-5} T for 70% of the STARSHINE 4 orbit. This results in 66.5 possible minutes of available torque time every orbit, assuming a 95-minute orbit. The average angular acceleration is found by

$$\alpha_{ave} = \frac{T}{I} = \frac{7.98\times10^{-5}\ \text{N}\cdot\text{m}}{0.2647\ \text{kg}\cdot\text{m}^2} = 3.02\times10^{-4}\ \text{rad/sec}^2\ . \tag{5}$$

The amount of spin-up required each day is based on the empirical deceleration rate. This result is given as

$$\alpha_{\text{spin up}} = t_{\text{sleep}}\bar{\alpha}_{\text{decel}} = \left(24\ \text{hours}\right)\ \cdot\left(6.06\times10^{-5}\ \text{rad/sec/hour}\right) = 0.0015\ \text{rad/sec}\ . \tag{6}$$

The total time needed each day to energize the torque rods and increase the spin-rate can then be found as

$$t_{\text{spin up}} = \frac{\alpha_{\text{spin up}}}{\alpha_{\text{ave}}} = \frac{0.0015\ \text{rad/sec}}{3.02\times10^{-4}\ \text{rad/sec}^2} = 4.82\ \text{seconds}\ . \tag{7}$$

Each day, the torque rods are expected to be fired approximately five times. While in sleep mode, the system is found to require 11.3 mW, and while torquing, the system uses 3.388286 W. When the total mission time is applied in sleep and torquing modes, the total power can be found as follows:

$$\begin{aligned} Power_{TOTAL} &= \left(Power_{torquing}\cdot\frac{t_{\text{spinup}}}{\text{t}_{\text{spinup}}+t_{\text{sleep}}}\right)+\left(Power_{sleep}\cdot\frac{t_{\text{sleep}}}{\text{t}_{\text{spinup}}+t_{\text{sleep}}}\right) \\ &= \left(3.388\ \text{W}\cdot\frac{4.82\ \text{sec}}{4.82\ \text{sec}+24\ \text{hours}}\right)+\left(11.3\ \text{mW}\cdot\frac{24\ \text{hours}}{4.82\ \text{sec}+24\ \text{hours}}\right) = 0.01147\ \text{W}\ . \end{aligned} \tag{8}$$

This required torque rod power, in addition to power for the sensors and other electronic components that are always energized, result in a battery requirement of 30.5 Amp-hours. By selecting a 50 Amp-hour battery, a 22% safety factor is built-in to the power budget. The selected 50 Amp-hour Lithium-ion battery will supply 12 VDC to power DISCO. The battery for STARSHINE 4 is still being procured. It may be a Lithium-ion Electrovaya battery, which is manufactured in a gel pack and can be formed into different shapes depending upon the user's specifics before being hardened, making it perfect for a satellite still in its design and development stages. It may also be CR123As in surplus from emergency units for astronaut EVA suits. Battery mass is estimated to be approximately 5 kg.[13]

DISCO Mechanical Structure

Engineers at the Naval Research Laboratory, in collaboration with Microsat Systems, Inc., designed the mechanical structure of STARSHINE 4. The DISCO system will be affixed to a disk-shaped deck in the center of the satellite as shown in Figure 10. Below the deck will be the STARSHINE 5 deployment system, STARSHINE 5, and its launcher. The DISCO custom-designed PCB and spin sensors will be mounted in an enclosure that is attached directly to the deck. The torque rods will be attached to the outside of the enclosure, away from the electronics and orthogonal to one another. The magnetometer will also be attached outside of the enclosure, away from the other electronics to avoid electromagnetic interference effects. Connections for signals used to drive current through the torque rods will be made with gold-plated DB-9 connectors and custom-built cables. The torque rods draw only 100 mA when energized, so DB-9 connectors should be sufficient for connecting both the signal and power lines. An annotated rendering of the proposed component mounting is shown in Figure 11.

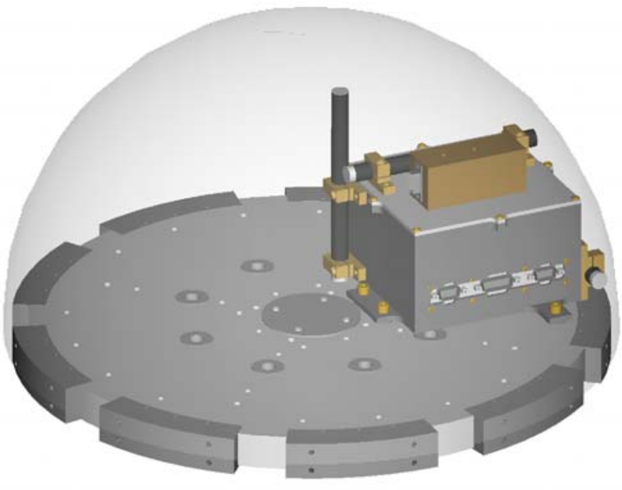

Figure 10. Rendering by Adam Webster, UND post-graduate mechanical engineering research assistant, of the DISCO enclosure mounted to the central deck of STARSHINE 4.

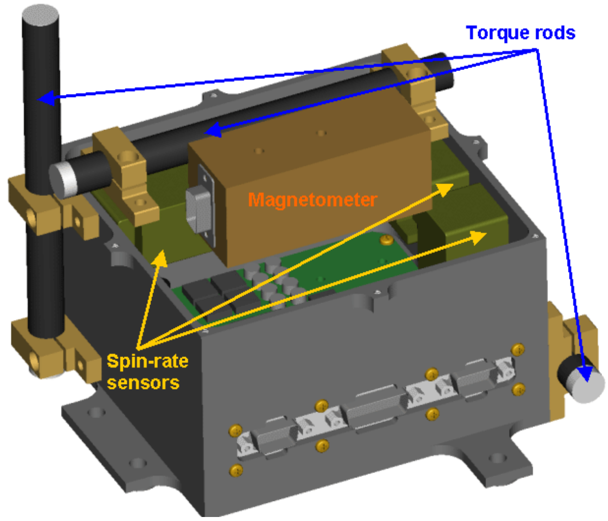

Figure 11. Annotated rendering of the DISCO system, courtesy of Adam Webster.

The DISCO printed circuit board will be mounted to the enclosure using screws. These are thermally conductive fixtures, which act as a thermal and physical interface between the board and the spacecraft chassis. The center deck will be attached to the satellite in such a manner that will avoid damaging the mirrors during launch. The 1,000 mirrors are mounted to the surface of STARSHINE 4 using through-holes as shown in Figure 12.

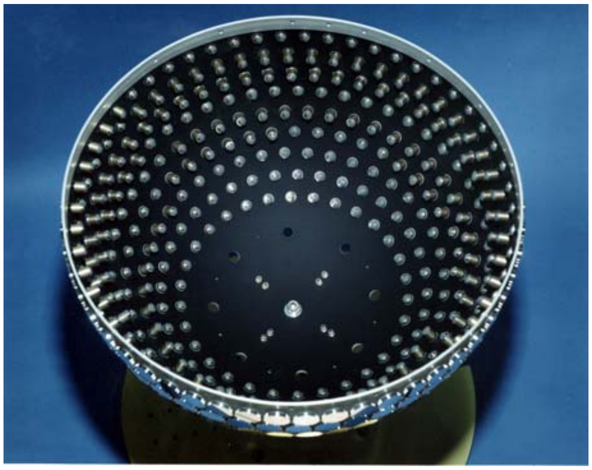

Figure 12. Interior of a STARSHINE satellite, showing the individual mirror mounting.[2]

Prior to installation in the launch vehicle, the system will be counterweighted to bring the center of mass as close as possible to the sphere's center. Separation STARSHINE 4 from the launch vehicle and STARSHINE 4 will involve the use of a 15" Light Band.

DISCO System Integration & Test

Multi-level system integration and test of DISCO first involved testing individual subsystems using laboratory equipment such as multimeters and LabVIEW-based instrumentation. Upon successful subsystem tests, the various DISCO components were integrated into the enclosure and tested as a complete system. To test the spin-rate sensors and actuators, a temporary housing was designed for the DISCO system. Eyehooks on several faces allowed for the unit to be attached to a rafter in the laboratory and thus hang freely in space in different orientations. One eyehook at a time was attached to 10 lb fishing line, which was then hung from a rafter in the laboratory. A Helmholtz coil was built to allow testing in a stronger magnetic field. This was necessary because testing was conducted in atmosphere at 1 G and with significant torque from the support line. The Helmholtz coil is a piece of custom ground support equipment built by Warren J. Wambsganss, and it can produce up to two times the Earth's magnetic field. The test apparatus is depicted in Figure 13.

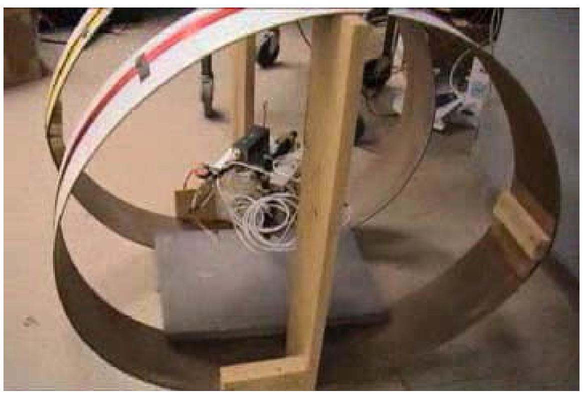

Figure 13. DISCO system suspended by fishing line, undergoing a test in the Helmholtz coil electromagnetic field.

A JTAG header was built into the PCB for DISCO, allowing for programming of the microcontroller without having to remove it from the system. This would be nearly impossible during the development stage, as careful soldering was performed to hold each of the 64 legs of the microcontroller in place, and software changes were necessary due to knowledge gained from testing. Figure 14 shows the microcontroller and the JTAG header used for reprogramming.

Figure 14. Texas Instruments MSP430F149 chip installed on the DISCO PCB.

Challenges

Although development of the DISCO spin-rate controller system is based upon a fairly simple concept, it did present some significant design challenges. One challenge involved reducing power as much as possible. The DISCO magnetic spin system and the STARSHINE 5 deployment system are the only active systems onboard STARSHINE 4. Because there is no attitude control, communications, or science payloads on board, solar cells were not required to renew power consumption over the lifetime of the satellite. It was determined that a battery could sustain DISCO for the entire mission if the power budget could be kept low. All power comes from a Lithium-ion battery. As mentioned previously, it will carry 50 Amp-hours of power distributed at 12 VDC. The battery voltage will decrease over the lifetime of the mission, so several cells will be used in series to ensure that voltage levels will remain high enough for the power distribution electronics. Voltages ranging from 9 VDC to 12.5 VDC will be sufficient. This will ensure that the batteries can support the system until the near exhaustion of the cells. Figure 15 shows the expected battery discharge curve if CR123As are utilized.

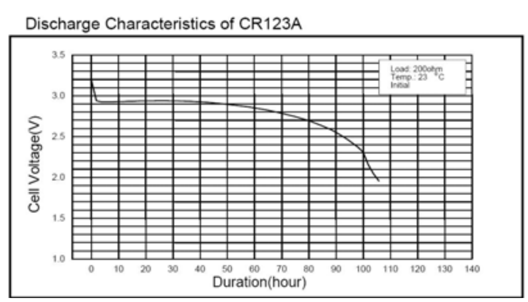

Figure 15. Battery discharge characteristics (four cells will be used in series to ensure that voltage levels stay above 9 VDC for the duration of the mission).

The sleep cycle of the microcontroller involves de-asserting the power control line, effectively causing the power regulation circuitry to deactivate the 15 VDC and 5 VDC lines and, as a result, disabling the peripheral sensors. Additionally, the microcontroller turns off the 12-bit ADC core and a 2.5 VDC internal reference.

Early in the testing phase, it was determined that the microcontroller was using more power than anticipated. By reducing the frequency of an external oscillating crystal from 4 MHz to 1 MHz frequency, the microcontroller clock frequency was also reduced. This resulted in being able to minimize current draw during sleep mode to 1.08 mA for the entire system.

Bill of Materials

Design of the DISCO system was conducted in collaboration with Prof. Gil Moore, Broad Reach Engineering, and the University of North Dakota. DISCO components were procured by Broad Reach Engineering and provided to the University of North Dakota for implementation and test. The cost breakdown is shown in Table 2.

Table 2. Bill of Materials for the DISCO System.

Component	Vendor	Cost/unit	Quantity	Total
Embedded Workbench development software	IAR Systems	$1,000	1	$1,000
Torque rod	ZARM Technik	$5,000	3	$15,000
Magnetometer	Billingsley magnetics	$2,727	1	$2,727
Spin-rate sensor	BEI Systron	$326	3	$978
Microcontroller	Texas Instruments	$6	1	$6
PCB	North Texas Circuit Board	$500	5 (1 EM & 4 FLT)	$2,500
Opto-FET	Micropac	$75	13	$975
Power FET	International Rectifier	$567	12	$6,804
Gold-plated connector	Amp	$37	10	$370
TOTAL				**$30,360**

SUMMARY & FUTURE DIRECTIONS

The beauty of DISCO's design lies in its simplicity. Although there have already been three highly successful STARSHINE missions, a great deal more scientific knowledge can be gained from the STARSHINE satellite if it can be viewed by the naked eye over the entire lifespan of its orbit. Additionally, this will help inspire even more K-12 students who are interested in the project. DISCO was designed, tested, and built at a very low cost. This magnetic spin-rate controller system will extend the spin characteristics up to three years, rather than the two-to-three months that former STARSHINE missions have experienced. Undoubtedly, this will help to provide more useful data for tracking the orbit degradation until complete decay from LEO. Since solar activity is currently approaching a minimum cycle, the orbit of STARSHINE 4/5 is expected to be notably longer than earlier iterations. A launch for the STARSHINE 4/5 is currently under negotiation for sometime in 2007 or 2008 onboard a Defense Advanced Research Projects Agency (DARPA) Falcon ELV.[3]

Acknowledgments

The University of North Dakota faculty member (author Schultz) and former electrical engineering graduate students (authors Lovseth, Giesinger, Wambsganss, and Hulst) wish to thank Broad Reach Engineering for their financial support and design expertise, which made this project a reality and a superb systems engineering training case study. In addition, the entire DISCO design team wishes to thank Prof. Gil Moore for his vision, dedication, and expertise in the conceptualization and integration of the DISCO magnetic spin-rate controller.

References

1. Moore, Gil, Lean, J., et. al. "Upper Atmosphere Densities Derived from STARSHINE Spacecraft Orbits." AIAA/USU Conference on Small Satellites. Logan, UT. August 11-14, 2003.
2. STARSHINE Web site. http://www.azinet.com/starshine. Updated February 5, 2003. Hosted by Azinet, LLC.
3. Moore, Gil, STARSHINE Project Director. Personal conversation. March 26, 2005.
4. Wolfe, William L. & George J. Zissis. *The Infrared Handbook.* The Infrared Information and Analysis (IRIA) Center, Environmental Research Institute of Michigan. 1978.
5. J.R. Wertz, *Space Mission Analysis and Design, 3rd Edition*, Space Technology Library, Microcosm, 1999.
6. J.J Sellers, *Understanding Space, An Introduction to Astronautics 2nd Edition*, Space Technology Series, McGraw-Hill, 2000.
7. Hyperphysics Web site. http://hyperphysics.phy-astr.gsu.edu/hbase/solids/hyst.html. Updated August 2000. Hosted by the Department of Physics and Astronomy, Georgia State University.
8. Heavens-above Web site. http://www.heavens-above.com. Updated daily. Hosted by the German Aerospace Center (DLR).
9. BEI Systron technologies, Inc. GYROCHIP Model HORIZON angular rate sensor data sheet. http://www.systron.com/pro_Horizon.asp. Updated 2003. Hosted by BEI Systron Donner Inertial Division.
10. Zarm Technik. MT2-1 Torque rod data sheet. http://www.zarm-technik.de/space. Updated 2000. Hosted by ZARM Technik.
11. Billingsley Magnetics. TFM100G2-S Specification data sheet. http://www.magnetometer.com/tfm100g2.htm. Updated 2000. Hosted by Billingsley Magnetics.
12. Texas Instruments. MSP430F149 data sheet. http://focus.ti.com/docs/prod/folders/print/msp430f149.html. Updated 2002. Hosted by Texas Instruments.
13. Weintritt, John, EP5, Electrical Power Systems, Lockheed Martin Space Operations. Personal conversation. February 23, 2005.
14. National Geomagnetism Program Web site. http://geomag.usgs.gov. Updated February 17, 2005. Hosted by U.S. Department of the Interior.