Abstract. U.S. high school and middle school students are building and polishing a spherical, mirrored Starshine spacecraft for launch by NASA into a 51.6 degree, 390 km (220 NM), circular orbit from a Space Shuttle Hitchhiker canister in December of 1998. Following the spacecraft's ejection into an independent orbit, sunlight reflected from its 220 mirrors will be visually observed during pre-dawn and post-sunset twilight intervals by international students during its planned six-month orbital lifetime in a project designed to teach these students how to measure the density of Earth's atmosphere at Space Station altitudes. The project is being cosponsored by the Rocky Mountain NASA Space Grant Consortium and the NASA Headquarters Department of Education.

Introduction

In the early days of the Space Age, orbits of satellites such as Sputnik, Explorer and Vanguard were calculated from precisely timed optical measurements of right ascension and declination provided by coordinated teams of amateur astronomers located around the globe. Project Moonwatch, which was conducted under the leadership of Dr. Fred Whipple of the Smithsonian Astrophysical Observatory, was the first example of this technique, and it involved a maximum of 2700 amateurs at its peak in 1958. Another very active satellite tracking program with a significant amateur component was led for over thirty years by Dr. Desmond King-Hele of the Royal Aircraft Establishment in England. Not only were large numbers of satellite orbits determined with the aid of

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these sightings, but excellent science was accomplished with respect to Earth’s shape and the density of its atmosphere.

Project Starshine, a modern, student-based version of those early programs, is being made possible by improvements in computers, communication systems, global positioning systems, and space launch opportunities that have taken place in the past forty years. School children are rapidly obtaining access to computer-numerically-controlled (CNC) shop tools, Pentium-class desk-top computers, advanced orbital dynamics software, GPS receivers, and the InterNet. It is now, therefore, possible to update those early efforts, with the students themselves building the spacecraft, making the visual observations of the satellite on orbit, exchanging their data with other international student groups, performing the required astrodynamical calculations and deriving atmospheric density, instead of merely reporting their observations to adult scientists, as was the case in earlier times. The educational implications of such a modern program are sufficiently interesting that the NASA Headquarters Education Division agreed on April 22, 1997 to co-sponsor this project, to the extent of arranging a waiver of the cost of ejecting the spacecraft into independent orbit during a high-latitude Space Shuttle mission in December of 1998. The NASA Administrator also stated at a press conference in Salt Lake City, UT on August 13, 1997, that he agrees in principle with the concept of space grant consortia participating in the launching of one of these spacecraft per year throughout a solar cycle to permit student scientists to keep track of the response of the Earth’s atmosphere to cyclical changes in solar activity.

**Spacecraft Description**

The STARSHINE spacecraft is a hollow sphere, 0.5 m (19 in) in diameter, machined from 7075 T-6 aluminum. Recesses for 220 mirrors are machined into its surface. A 9-in Marman fixture, designed to mate with a standard NASA Hitchhiker retention and ejection system, is attached to one pole of the sphere. The gross weight of the spacecraft, including mirrors, can be varied between 27 kg (60 lb) and 68 kg (150 lb) by machining its inner wall to various thicknesses. When the altitude at which the spacecraft will be ejected into orbit has been specified by NASA later this year, the spacecraft weight will be adjusted so as to provide the proper ballistic coefficient to keep the spacecraft in orbit for approximately six months before it reenters and is vaporized. The December launch date and duration of orbital lifetime were selected so that students in the northern hemisphere can make their observations at the conclusion of the school day, rather than late at night, and so that the project can be completed by the end of the school year.

The 220 mirrors referred to above are cylinders 5 cm (2 in) in diameter by 1 cm (.038 in) thick and are also machined from 7075 T-6 aluminum. Their outer faces will be polished flat to within 10 wavelengths of visible light, or 0.0006cm (0.0002 in). They will then receive a monomolecular coat of Silicon Dioxide and will be bonded into machined recesses distributed across the surface of the sphere in a pattern that will be described later.

Four rare earth Boron permanent magnets 2.5 cm (1 in) in diameter by 25 cm (10 in) long will be mounted in drilled channels in the wall of the sphere, parallel to the spacecraft’s spin, or Z, axis. The purpose of the magnets is to align the spin axis of the spacecraft with the local earth field vector at every point in its orbit. This is a technique long employed by both professional and amateur satellite organizations to provide a rudimentary form of attitude stabilization.3 Utilization of this simple technique will cause the spacecraft’s spin axis to align itself parallel to the Earth’s surface when it is at the magnetic equator, then pitch downward from a plane parallel to the Earth’s surface by as much as seventy degrees when the spacecraft is at its maximum travel north of the magnetic equator, and to pitch up by the same amount when it is at its most southerly orbital location. The spin axis will also slowly rotate in the yaw plane, so as to always point to magnetic North, as the spacecraft travels around the Earth in its inclined orbit.

A spacecraft spin rate of four revolutions per minute will be achieved by either the classical amateur radio technique of using alternating black and white “measuring tape” solar photon vanes,5 or by means of a pre-loaded torsion spring and gyroscopic mass assembly on a shaft connected to the spacecraft by a high-friction bearing on the spacecraft’s Z axis. If the latter technique is chosen, the torsion spring will be released at separation of the spacecraft from the Hitchhiker canister, in order to spin the gyroscopic mass, which will then transfer its angular momentum, over time, to the spacecraft through bearing friction, until the spacecraft rotates in the opposite direction at a rate of four revolutions per minute. A tradeoff is presently under way to select the simplest technique. In the case of the photon vane approach, the spin rate

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will be limited to not more than four revolutions per minute by the use of hysteretic dampers and by eddy currents in the spacecraft shell.\footnote{Pro. R. Gilbert Moore}

**Mirror Sizing and Placement**

The mirrors on this spacecraft are designed to enhance its optical visibility, so that observers on the ground will not require gain optics to make their measurements of its position against the star background as it passes across their local sky. For comparison, the Vanguard II satellite which was launched into orbit on Feb. 17, 1959, and which will still be orbiting for another 150 years or so, was a polished aluminum sphere almost identical in size and weight to Starshine.\footnote{Starshine’s mirrors and its orbit are designed to produce a flash of optical magnitude \(+2\) when a single mirror is fully sun-illuminated as it rises above the horizon at a range from the observer of 1997 km (1128 NM), and to produce a flash of optical magnitude \(-1.6\) when it is directly overhead at a range of 300 km. The derivation of these brightness values is given in the Appendix. These values compare with a magnitude of \(+2\) for Polaris and \(-1.6\) for Sirius, the brightest star in the night sky. For reference purposes, a change in optical magnitude of \(1\) is equal to a factor of approximately \(2.5\) in brightness, and negative values are brighter than positive values. The human eye is capable of seeing objects as faint as \(+5\) magnitude, which is four orders of optical magnitude, or \(2.5 \times 2.5 \times 2.5 \times 2.5 = 40\) times fainter than a Starshine mirror at its maximum range.}

Starshine’s mirrors and its orbit are designed to produce a flash of optical magnitude \(+1\) when a single mirror is fully sun-illuminated as it rises above the horizon at a range from the observer of 1997 km (1128 NM), and to produce a flash of optical magnitude \(-1.6\) when it is directly overhead at a range of 300 km. The derivation of these brightness values is given in the Appendix. These values compare with a magnitude of \(+2\) for Polaris and \(-1.6\) for Sirius, the brightest star in the night sky. For reference purposes, a change in optical magnitude of \(1\) is equal to a factor of approximately \(2.5\) in brightness, and negative values are brighter than positive values. The human eye is capable of seeing objects as faint as \(+5\) magnitude, which is four orders of optical magnitude, or \(2.5 \times 2.5 \times 2.5 \times 2.5 = 40\) times fainter than a Starshine mirror at its maximum range.

A single Starshine mirror will thus be readily visible in the twilight sky (spacecraft in sunlight, observer in penumbra) at elevation angles greater than 20°, under reasonable conditions of atmospheric transparency and light pollution, when that mirror is in full phase; that is, when the sun is below the horizon and directly behind the observer, and the mirror is pointing directly at the observer. However, as the satellite passes across the sky, its solar phase angle changes from \(0\) deg to \(90\) deg, which reduces the mirror’s brightness by \(\cos \phi\). A second complicating factor is that the reflected image of the sun from a plane mirror has an angular width of only \(\frac{1}{3} \)°. Thus, the reflected light from each mirror will only illuminate a half-degree swath in space or on the ground as the satellite passes through the observer’s field of view. Large gaps in visibility would occur if the spacecraft were to assume a fixed orientation in space, unless thousands of mirrors could be mounted on its surface. Since the size of the mirrors has been set at 5 mm (2 in) in diameter by brightness considerations, and the diameter of the spacecraft is limited by the Hitchhiker canister to \(\frac{1}{2}\) m (19 in), only some 220 mirrors can be accommodated on its surface. (The Marman mounting foot eliminates space for approximately ten mirrors.) It is therefore necessary to place these mirrors in 16 rows, each containing 14 mirrors, along great circles of longitude on the exterior of the spacecraft, to stagger these rows in latitude by \(1°\) relative to the preceding row, and to rotate the spacecraft about an axis through which these great circles pass, in order for flashes of sunlight to be visible to each ground observer during every pass.

It would be desirable to rotate the spacecraft several times per second, in order to provide ease of tracking to the ground observer. However, the retina of the average eye has a visual persistence of only one tenth of a second; any flash of light shorter than one tenth of a second will be perceived to be dimmer than a flash of equal intensity that persists for a longer time period. The spin rate for the Starshine spacecraft must therefore be limited to one-half degree per tenth of a second, or five degrees per second, or 360 degrees per 72 seconds, unless one is willing to reduce the apparent brightness of the flashes.

However, if a sleepy, shivering student observer only sees the spacecraft once every minute or so, he or she will likely have difficulty keeping track of its passage across the sky and locating its path through the star field. After one or a few negative experiences, a large number of students might become disinterested in the project, and the observational data base could conceivably shrink substantially. Therefore, a compromise spin rate of four revolutions per minute has been selected. This will result in a diminution of flash brightness of two orders of optical magnitude, or a factor of 6.25, so that the flashes will vary from about \(+3\) on the horizon to \(+0.6\) directly overhead. The flashes will in this case appear at intervals of every fifteen seconds, which it is hoped will be sufficiently frequent to provide a given observer with...
The continuity of track and will be bright enough to hold his or her interest.

Spinning the spacecraft more rapidly would reduce the brightness to such a level that observers would need to employ binoculars or telescopes to observe the passage of the spacecraft, as was the case in the programs of the 1950s and 1960s mentioned in the introduction to this paper. However, since the principal objective of Starshine is to provide as wide as possible an opportunity for young people around the world to participate in a stimulating educational experience, the use of gain optics is definitely not desirable. Economic considerations would eliminate many observers, and significant complications in sighting coordination would result.

**Orbit Determination Methodology**

Surprising as it may seem, it is possible to compute the classical orbital elements of a satellite to rather good accuracy, using the “angles-only” method, based solely on visual measurements of the topocentric right ascension and declination of the satellite at precise times, with no knowledge of the range of the satellite from the observer. The concept of angles-only determination of orbits of astronomical objects has existed for over two hundred years - ever since it was published by Pierre Simon de Laplace in 1780. Unfortunately for Laplace, however, his method was far too complex to permit solution by hand computational techniques; in fact, only with the advent of the modern computer has it been possible to test his concept in a practical sense.

There are three main techniques that are used today: Laplace’s original method, a Gaussian technique, and a double-iteration. The Gaussian method fits data to all three points and is valid for all the data. This approach is better suited for near-Earth satellites, but the formulation limits the spread of data (usually less than 60° apart). Remember that each of these techniques is fundamentally deficient because it lacks range information. Iteration or more processing overcomes this problem, but not without additional complexity and computation.

Gauss’s method of orbit determination from angles-only data receives mixed reviews from the astrodynamics community. The opinions range from little concern because the method works best for interplanetary studies, to feeling that it’s not very accurate for satellite-orbit determination, to reverence for the achievement realized at a time when data was limited. Long et al. suggest it works best when the angular separation between observations is less than about 60°. The method performs remarkably well when the observations are separated by 10° or less. This separation translates to observations that are (at most) about five to ten minutes apart for low-Earth satellites. The use of volunteer student observers in large numbers is thus very compatible with the Gaussian method. Of course, one should always analyze the orbits he or she intends to process before establishing how often to collect data. The success of Gauss’s method also depends on the method used to determine the f and g series. Whatever the case, when properly formulated, the Gaussian routine is a modestly robust way to determined a satellite’s position with angles-only data.

The first few steps of all angles-only orbit determination techniques are the same. The fundamental problem consists of determining the satellite’s state vector, which requires six independent quantities. For optical observations, we need geocentric or topocentric right ascension and declination. Because sensor sites don’t exist at the center of the Earth, we will utilize topocentric observations, and a minimum of three observations will let us form three line-of-sight vectors. We may tend to view these unit vectors as position vectors, but they’re not. The method chosen for the present project to find these angles is to observe the satellite visually under appropriate lighting conditions and determine them by comparison with the star background. This technique assumes the star positions are accurately known. Be aware that the stellar right ascensions and declinations, as cataloged, are geocentric, whereas the optical observations for the stars and satellites yield topocentric right ascensions and declinations. However, stars are so distant that the difference in the two quantities is negligible. In contrast, topocentric values for satellites in low-Earth orbits can differ greatly from geocentric right ascension and declination. As an aside, we can also use β and el, but we must first convert them. Finally, it’s crucial to use a common reference frame for all processing, which requires us to do precession and nutation calculations for mean and true equinoxes and equators. Typically, the observations are obtained in a true-equator true-equinox frame. The calculations should proceed in a common inertial frame - usually the J2000.

Once the line-of-site vectors are formed, the different techniques diverge in their solution approaches. The Gaussian technique takes several pages of
development, but central to the process is the solution of an eighth-order polynomial for the middle observation slant range. Once this value is selected, the remaining parts of the algorithm find the remaining answers for the problem. Unfortunately, because the technique is simple guessing at a value for the range, the answers can vary widely. This leads to the inevitable conclusion that a differential correction technique is required to further "smooth," or process the results as large quantities of data are generated.

The basics of estimation theory span an entire chapter in Vallado, but are presented here at only a high level: In essence, we're trying to take each of the individual answers from the Gaussian technique and statistically determine which is the best with respect to a criterion. The criterion we use is that of least squares, and we try to minimize the sum of the square of the residuals of each trial run. We still require propagation of the estimated state vector through time, and we must have a way of determining the sensitivity of the observations to changes in the state. This latter quantity is called the partial derivative matrix, A, and it may be found through a variety of techniques. We have found computer code that will accomplish this numerically, and we propose to use a batch processing scheme to process the optical observations for the Starshine satellite into its classical orbital elements.

It is, of course, important to know to good precision the latitude, longitude and altitude of all the student observing sites, as well as the times of their observations, in order to be able to perform accurate computations of the satellite’s orbit. In view of the difficulty of obtaining precise positions of sites all over the world by conventional, map-based techniques, it has been decided that Global Positioning System receivers will be utilized for this purpose. Although typical civilian receivers will perform with adequate precision for our purposes, they are unlikely to be available to every school group that may wish to participate in the Starshine project. Therefore, initial contact has been made with the U.S. Department of Defense relative to having GPS-equipped personnel establish the positions of all the schools attended by military dependents at bases distributed worldwide. Once these positions are known, it is hoped that the measurements can be extended to include schools near those bases, as well.

Precise timing of spacecraft positions relative to the star field will be possible through use of those same GPS receivers, or, alternatively, through use of WWV timing signals received by cooperating amateur radio operators during satellite passes. WWV signals are broadcast globally on carrier frequencies of 2.5, 5, 10, 15, 20, 25, 30 and 35 MHz 24 hours per day.

Sighting Prediction Methodology

Once Starshine has been deployed, initial predictions will be made of its position, based on the orbit of the Space Shuttle that carried it aloft, as provided by tracking data from the Air Force Satellite Control Network (AFSCN) headquarters at Falcon Air Force Base, CO, and the planned separation velocity of the spacecraft from the orbiter. The student tracking network will be alerted via the InterNet, and sightings will be reported via the same medium by the first successful observers. Calculations of the satellite’s classical orbital elements will be made on PCs by high school students and refined as additional observations come in. These orbital elements will be entered into Satellite Tool Kit software provided to the project by Analytical Graphics, Inc., and predictions of future sightings for the worldwide student observational network will be generated. An iterative process will be employed to refine the satellite’s orbit.

Comparisons will be made from time to time with AFSCN data to determine how well the student’s values measure up to the professional values. Computations of atmospheric density will be then be performed by techniques utilized for decades by King-Hele. Unfortunately, density measurements obtained in this initial mission will be averaged over the whole Earth, due to the circular nature of the spacecraft’s orbit. At some future date, it is hoped than a highly eccentric orbit will become available, which will result in the students’ ability to distinguish between daytime and nighttime density values, as well as latitude-dependent values.

Mirror Polishing Techniques

The individual Starshine mirrors are being polished by middle school students located mainly in the Intermountain West but distributed around the United States, using techniques employed for decades by members of the amateur astronomy community. Mirror polishing lesson plans for middle school teachers are being developed by one of the authors of the present paper, with assistance from the Optical and Photonics Division of Hill Air Force Base and
from the Albuquerque Astronomical Society, for publication in the Starshine Web Page on the InterNet in the fall of 1997. It has been determined that polishing of 7075 T6 aluminum surfaces to a flatness of ten wavelengths of visible light can be performed by relays of middle school students in a total time of approximately 50-80 hours, using materials and optical fringe-measuring devices within the means of typical middle schools in the U.S.

Approximately 250 mirrors will be machined from rod stock at the start of the 1997-8 fall school term by Bridgerland Area Technology Center high school shop students in Logan, Utah, and will be distributed to interested schools on a first-come, first-served basis. Names of the participating students, faculty and staff will be collected at the conclusion of the polishing process at each school, for microfilming and attachment to the back of “their” mirror. The mirrors will be shipped to the Optical and Photonics Division of Hill Air Force Base in Ogden, Utah, for final flatness inspection and the subsequent application of a Silicon Dioxide protective coating. The 220 best mirrors will then be shipped to the Space Dynamics Laboratory of Utah State University for bonding to the spacecraft, using a low-outgassing, NASA-approved, two-component epoxy bonding system.

**Spacecraft Machining Procedures**

Students at the Bridgerland Area Technology Center have to date manufactured a series of half-scale models and three full-scale models of the Starshine spacecraft, and will complete the full-scale flight article in the 1998 spring semester. The first step in the manufacture of the flight spacecraft is to cut plates of 7075 T6 aluminum raw material into sizes that can be handled and fit into various CNC machines. This consists of cutting 6-in-thick blocks into 20-in squares and then trimming the corners off to make a crude octagon.

The students will place these three raw sections, one at a time, into a Vertical Machining Center. They will write a brief CAD CAM program to begin rough machining several circular step pockets, so as to hollow out the inside of the structure. After roughing is completed, they will write a second program to mill the mating and anchoring flanges that will be used to join the separate pieces into a hollow sphere.

They will rotate the blocks to the side not machined and secure each one independently. They will then write a new CAD CAM machining program to rough out a section of the sphere, using a ball end mill, to give a smoother surface finish. The final surface finish will be produced by installing the roughed section on a CNC lathe and programming a contour on each section.

Producing the surface of the recessed holder for each individual mirror will be accomplished by mounting a compound rotary table on a manual mill and attaching one of the three sections described above to the rotary table. Its exact origin will be dialed in and located. For each row of mirrors, the section will be rotated, indexed to the desired mirror location, and a flat will be milled for the mirror to sit on.

**Summary and Conclusions**

Project Starshine, a novel space-related educational opportunity for students of all ages, is well underway. The basic optical and structural design work for the spacecraft has been completed, and mirrors are being built, polished and coated. They will be installed on the spacecraft shell, and environmental testing of the assembled flight article will be performed in the spring semester of 1998.

Integration of the spacecraft with Hitchhiker hardware will take place at the NASA Goddard Space Flight Center in the summer of 1998, following which it will be transported to the NASA Kennedy Space Center and installed in the cargo bay of Endeavor in the fall of 1998 for flight to orbit on the STS-96 Space Station construction mission in December of 1998.

An InterNet web page is being created, and procedures are being developed to permit entry of sighting data by international students. Code is being developed to permit computation on personal computers of the spacecraft’s classical orbital elements from angles-only data. An orbital dynamics workshop is scheduled for late September 1997 at a NASA teacher workshop on the campus of Weber State University, and several more will be conducted at various locations during the 1997-8 school year. From these workshops, InterNet-based instruction packages will be developed and integrated into the Starshine home page for viewing on demand by students in all corners of the globe.

Following completion of the first mission, the program results will be carefully evaluated by the Rocky Mountain NASA Space Grant Consortium and
the NASA Headquarters Education Division. They will pass their recommendations along to the Space Grant Consortium selected to implement the next phase of the Starshine project.

Acknowledgements

The authors are most grateful to a veritable host of individuals and organizations for helping to get this project started. Among the individuals most heavily involved are, in no particular order: NASA's Dan Goldin, Frank Owens, Pam Mountjoy, Bob Parker, Marianne Albjerg, Joe Rothenberg, Bob Gabrys, Chris Dunker, Susan Olden, Dave Shrewesberry, George Abbey, Paul Maley, John Taylor and Garth Hull; U.S. Senator Bob Bennett (R-UT); Hansen Planetarium’s Win Horton, Mike Peterson, Sheri Barton Trbovich, and Richard Cox; Utah State University’s Allan Steed, Frank Redd, Doran Baker, Roy Esplin, Paul Huber, John Vanderford, Pete Mace and John Raitt; Jim Mayo and Don Killpatrick of RDA/Logicon; Bob Fugate, Rich Rast, Imelda De La Rue and Dave Spencer of the USAF Phillips Laboratory; Lorin Peck, Dick Healy, Rod Carter, Stan Geniusz and John McCleary of Hill Air Force Base; Rich Vineyard and John Sohl of Weber State University; Brad Smith of Hawaii; Jim Christensen and Brett Moulding of the Utah State Office of Education; Suzanne Winters of Utah Governor Mike Leavitt’s Office; and Jim Pagliasotti of the Aerospace States Association.

References


Appendix

Visual Magnitude of a Starshine Mirror

<table>
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<th>Constant</th>
<th>Unit</th>
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Definitions of Functions


$V_{mag} = -2.5 \times 10^v - 3$ Spectral Flux Density for zero visual magnitude

$E_{A}(\lambda) = \frac{E_{B}(\lambda) K_{E}}{K_{B}}$ Function to compute Spectral Flux Density given visual magnitude

$E_{B}(\lambda) = \frac{K_{B} E_{A}(\lambda) K_{B}}{K_{E}}$ Function to find magnitude given spectral flux density

Appendix

$S_{(L,T)} = \frac{2 \pi}{(L/T)^2}$ Function to Compute Blackbody Spectral Radiance

$E_{(L,T)} = E_{(L,T)} (L/T)^2$ Function to compute Spectral Flux Density for circular source where L is angular diameter

Calculations

$\text{Max} \cdot \sqrt{R_1 \cdot D_{opt} - R_2 \cdot a_{rad}}$ Maximum range to satellite

$E_{A}(\lambda) = 0.55$ deg Angular Diameter of Sun

$E_{B}(\lambda) = 0.01$ deg Angular Diameter of Mirror

$E_{1} = \frac{E_{2}}{E_{3}}$ Spectral Flux for perfect mirror

$E_{1} = \frac{E_{2}}{E_{3}} = 1.25 \times 10^{-2} \text{ W m}^{-2} \text{ cm}^{-2} \text{ sr}^{-1}$ Perfect Mirror

$E_{1} = \frac{E_{2}}{E_{3}} = 1.04 \times 10^{-2} \text{ W m}^{-2} \text{ cm}^{-2} \text{ sr}^{-1}$ Perfect Mirror

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