Development and on-orbit performance of moderate-cost spherical retroreflector arrays for the Starshine program

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Abstract: The Starshine program provided a successful test of a laser ranging array designed for a spherical satellite and built from standard commercially-available retroreflectors. The basic result from the on-going satellite laser ranging observations is that such a moderate-cost array has satisfactory on-orbit performance for altitudes below 470 km and has also demonstrated, to date, a year-long lifetime. The array contains thirty-one 1 cm retroreflectors arranged to suppress variability in laser radar cross section as a function of illumination orientation. The number and diameter of the retroreflectors resulted from parametric design studies to minimize both number retroreflectors in the array and the effects of velocity aberration. The experimental verification of the design is based on the observed raw data point density as determined from the field-generated normal points.

Key Words: spherical array, SLR, retroreflector, BK7 glass, on-orbit performance

1 Starshine program and SLR opportunity

The Starshine (Student Tracked Atmospheric Research Satellite Heuristic International Networking Experiment, `http://azinet.com/starshine/`) satellite program was originally created to promote math and science by combining classroom study with a real application. Students learn about orbits, astronomy, the Earth's atmosphere, and the construction and testing of satellite hardware. The Naval Research Laboratory's Naval Center for Space Technology (NCST) became involved in the Starshine program for three reasons:

1. The promotion of education;
2. The unique opportunity to study the effects of solar activity on the Earth's upper atmosphere with respect to atmospheric drag on satellites;

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3. The opportunity to use future Starshine satellites as low cost test beds for developing and testing space hardware and systems.

This third aspect is the focus of this report as Starshine provided a Satellite Laser Ranging (SLR) flight opportunity with considerable risk tolerance.

The NCST developed two different size satellites for the Starshine program. Starshine 1 is shown in Figure 1 (deployed: June 5, 1999; re-entry: February 18, 2000) and Starshine 2 (deployed: December 16, 2001; re-entry: April 26, 2002) were 18.7 inches in diameter and weighed approximately 87 pounds. Both satellites were deployed from the NASA Space Shuttles as Hitchhiker payloads. Starshine 3, also shown in Figure 1, (launched: September 29, 2001; re-entry currently estimated: March 9, 2003) is a 36 inches in diameter and weighs approximately 200 pounds. Starshine 3 was deployed into orbit by an Athena Launch Vehicle from Kodiak, Alaska. All three satellites were covered with aluminum mirrors. These mirrors, polished by school students from across the world, reflect sunlight to observers on the Earth. In addition, thirty-one retroreflectors were installed as shown in Figure 1 onto the surface of the Starshine 2 and Starshine 3 satellites.

The Starshine program used its risk tolerance to test the on-orbit performance of a spherical array built with less expensive lab-grade BK7 retroreflectors. The use of this type of retroreflector represented a significant cost savings over NRL's past usage of custom fused silica retroreflectors. The primary risk from using BK7 glass was whether its radiation sensitivity would result in a fast degradation in SLR link budget due to the orbital radiation environment. Further, BK7 retroreflectors in use[1] have a somewhat loser specification: $\frac{1}{8}$ wave surface finish, 3 arcsecond angular tolerance, and no surface coating. Success with the Starshine arrays had fairly immediate application within the Atmospheric Neutral Density Experiment (ANDE) program[2].

2 Random phase approximation design of SLR arrays

The random phase approximation is the basis for one of NRL's evaluation methods for SLR retroreflector arrays. As the method has already been described at some length[3, 4], only an abbreviated presentation of approximation's analytic definition will be given. The approach is used as a check of observational reliability and begins with Degnan's[5] expression for the number of photoelectrons available from a laser radar link,

$$N_{\mathrm{pe}} = \eta_D E_0 \left(\frac{\lambda}{hc}\right) \eta_T G_T \underbrace{\sigma_{\mathrm{LRCS}} \left(\frac{1}{4\pi R^2}\right)^2} A_R \eta_R T_a^2 T_c^2 \quad , \tag{1}$$

and concentrates on two bracketed factors which involve retroreflector array design and satellite's orbit. The overall form of the laser radar cross section, given by

$$\sigma_{\mathrm{LRCS}}(k_x, k_y) = \rho \frac{4\pi}{\lambda^2} |\tilde{a}(k_x, k_y)|^2 \quad , \tag{2}$$

where $\tilde{a}(k_x, k_y)$ is the far field diffraction pattern, is set by the array design. The specific angular frequency pair k_x, k_y of relevance at each point in time during an observational pass and the $1/R^4$ range loss are determined by the orbit as seen from the SLR station.

Figure 1: Starshine 1 (upper left panel). Individual retroreflector mounting on Starshine 2 and a few student-polished mirrors (upper right panel). Starshine 3 during vibe test setup (bottom panel).

For an array, Equation 2 takes the form

$$\sigma_{\mathrm{LRCS}} = \rho \frac{4\pi}{\lambda^2} \left| \left(\sum_{m=1}^{L} \tilde{a}_m e^{i\alpha_m} \right) \left(\sum_{n=1}^{L} \tilde{a}_n^* e^{-i\alpha_n} \right) \right| \quad , \tag{3}$$

$$= \rho \frac{4\pi}{\lambda^2} \left| \sum_{m=1}^{L} \sum_{n=1}^{L} \tilde{a}_m \tilde{a}_n^* e^{i(\alpha_m - \alpha_n)} \right| \quad . \tag{4}$$

$$\tag{5}$$

For brief interval τ, α_m and α_n phase relations appear in the averaged LRCS as

$$\overline{\sigma_{\mathrm{LRCS}}} = \rho \frac{4\pi}{\lambda^2} \left| \sum_{m=1}^{L} \sum_{n=1}^{L} \frac{\tilde{a}_m \tilde{a}_n^*}{\tau} \int_0^{\tau} e^{i[\alpha(t)_m - \alpha(t)_n]} dt \right| \quad , \tag{6}$$

$$= \rho \frac{4\pi}{\lambda^2} \sum_{m=1}^{L} |\tilde{a}_m|^2 \quad . \qquad (7)$$

Equation 7 will be a serviceable approximation provided a low correlation exists between α_m and α_n. The NRL code computes the far field diffraction patterns of the individual retroreflectors that appear in Equation 7 with a direct space numerical integral rather than by FFT methods. Consequently, it is possible to simulate arbitrary illumination geometries and angular frequencies.

3 Spherical SLR array design and Monte Carlo Simulations

Since Starshine's motions on orbit were expected to include both slow (about 1 revolution per minute) through non-spinning satellite configurations, ideally the retroreflector array would have a uniform response from any direction. Uniform direction distributions in 3-dimensions exist for only the small number of cases where the face normal directions of a regular solid can be used ($n = 4$ - tetrahedron, 6 - cube, 8 - octahedron, 12 - dodecahedron, and 20 - icosahedron). Fortunately, Hardin, Sloane and Smith[6], solved the closely related problem of determining the directions to the points on a unit sphere where n charges have the minimum electrostatic energy for $n = 4 \rightarrow 132$, 192, 212, 272, and 282. In addition, Sloane maintains a web-site library of their solutions for these direction distributions. These direction distributions can be used as the retroreflector positions for spherical arrays. Clouse *et al.*[7] have used a similar approach in their design of a fifty-element spherical retroreflector array.

Combining the random phase approximation estimate for an array's σ_{LRCS} and Sloane's direction library allowed a monte-carlo-based study of expected performance as a function design parameters. First, we generated a set of circular orbital pass geometries for NRL's SLR station near Washington, D.C. Then, for an array employing a given number for retroreflectors, at each point on each pass we computed σ_{LRCS} with the appropriate velocity aberration for 25 random orientations. The monte carlo's 25 orientations were used to estimate the mean and standard deviation of the array's $\sigma_{\mathrm{LRCS}}/R^4$ dependence as a function of time through the simulated pass. Figure 2 shows an example of the monte carlo result. A perfect array would have a very low relative variability given by the ratio of the standard deviation to the mean through out the pass. As might be expected, increasing the number of retroreflectors reduces the relative variability of $\sigma_{\mathrm{LRCS}}/R^4$ as well as increasing the average value. There is a noticeable slowing in the improvements seen for arrays with more than 31 retroreflectors. It also appears that the relative variability is mainly a function of the average local angular neighborhood about the retroreflectors. For 31 retroreflectors, each retroreflector has, on average, 5 other retroreflectors within field of view limit – 3 closer, 2 slightly further away. Figure 3 shows the field of view (FOV) coverage of a 31 element array employing the $n = 31$ Sloane direction distribution.

The final flight configuration of the Starshine array accommodated other properties beyond the number of retroreflectors. Starshine has a restricted set of directions determined by the mechanical mounting system. We selected the best fit from the 878 possible directions to the $n = 31$ Sloane direction distribution and repeated the monte carlo performance

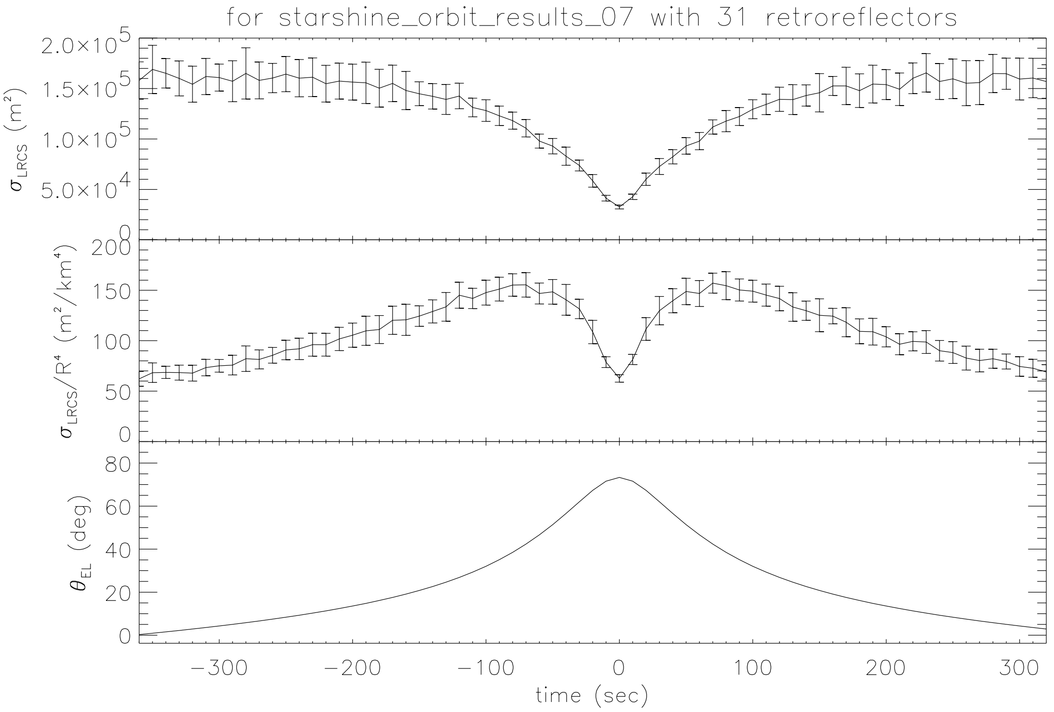

Figure 2: Typical monte carlo results. For a perfect array, the middle panel plot would be flat with very narrow uncertainty brackets.

evaluation. There were only small increases in the relative variability. The retroreflector diameter was based on the results of some early ANDE design studies in which we had varied the retroreflector diameters. Increasing the retroreflector diameter above 1 cm will increase σ_{LRCS} at some points in the pass. However, for a low orbit such as Starshine's, velocity aberration losses at high elevation angles become quite pronounced for a retroreflector diameter above 1 cm.

4 Observational results and verification

To date there have been 74 SLR passes for Starshine 3 from November 2001 through August 2002. Multiple SLR stations were responsible for the acquisition and ranging of Starshine 3's during the 74 passes. Further, there is sufficient return for closed-loop tracking once it has been acquired. The distribution of normal point return ratio as function of range shown in Figure 4 is qualitatively similar other LEO targets. No clear time-in-orbit dependence has seen to date in the return strength suggesting that the BK7 retroreflectors have not degraded over the first year.

The initial acquisition of Starshine 3 for an SLR pass has required an accurate orbit estimate due to its low altitude. During the past year we have developed and tested operational arrangements for the prompt transfer Naval Space Command orbit estimates for Starshine 3 to SLR stations. We expect to reuse these methods as part of the ANDE observation oper-

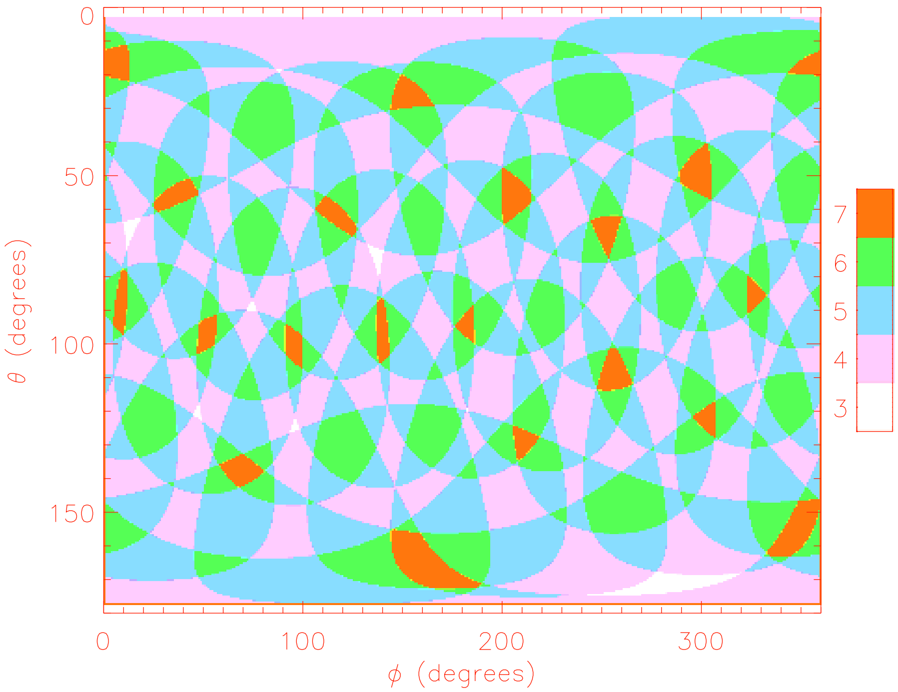

Figure 3: Surface plot showing the number of retroreflectors seen within field of view limits from a given direction for an array using the $n = 31$ Sloane direction distribution. The array assumes 1 cm diameter BK7 retroreflectors with a refraction index of 1.51947 at 532 nm and an inset of 0.1016 cm (or 0.040″). The resulting FOV cut off is at $\theta_{inci} = 49.2903°$.

ations.

Beyond simply demonstrating that Starshine 3's retroreflector array would reliably close an SLR link, the full rate data also allowed study of the satellite dynamics. The rate at which the second ring contributors appear with respect to the closest in the normal point residuals gave an indication of the satellite's slowing rotation.[8]

5 Conclusions

Based on the observational results, we draw the following conclusions:

- The monte-carlo simulation based on random phase approximation has been verified by on-orbit performance.
- BK7 retroreflectors manufactured to lab-grade tolerances will provide lifetimes of at least one year for SLR arrays deployed at LEO altitudes

Further, we can now realistically expect the SLR tracking of ANDE to be straightforward based on the similarity of its retroreflector array and orbit to those of Starshine. Such SLR observations of ANDE will contribute to the program's effort to refine the measured neural atmosphere between 200 km and 450 km. The quality of the ANDE science return

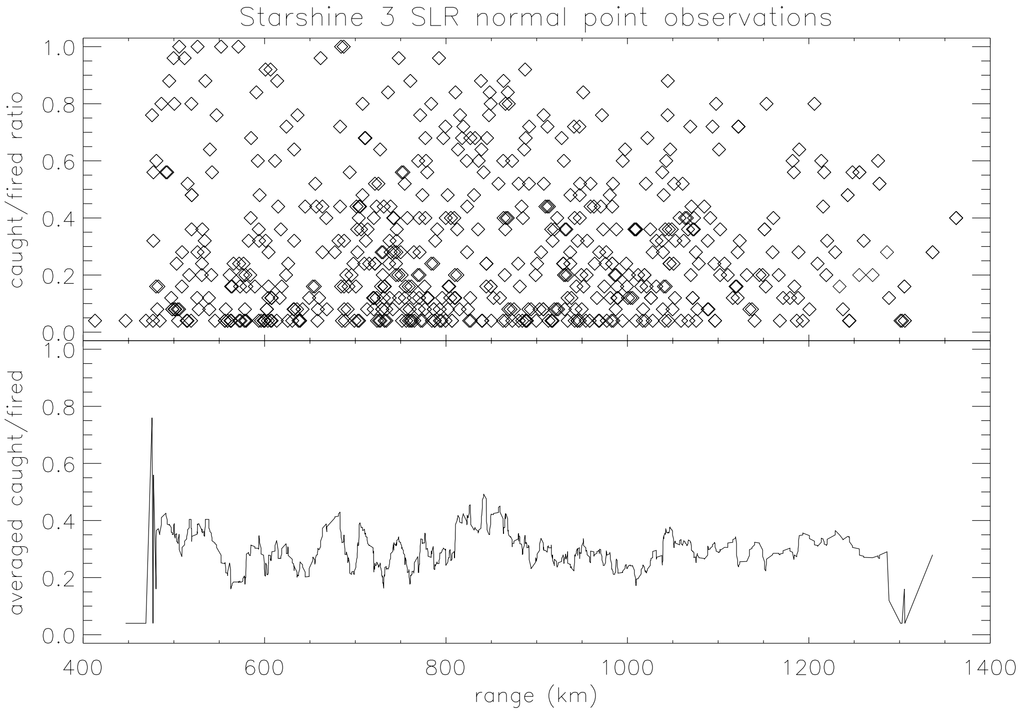

Figure 4: Caught/fired ratio of Starshine normal points as a function of range (upper panel). Block-average by 30 caught/fired ratio of Starshine normal points as a function of range (lower panel).

should improve as SLR ranging accuracy improves towards a ±5 cm limit. For a higher SLR ranging accuracy, variations in the ANDE target signature itself would become the dominant uncertainty in the analysis. From the standpoint of temporal coverage, SLR observation campaigns of ANDE that are relatively brief while having wider spatial coverage will be the most useful in improving the neural atmosphere results. The ANDE program office is currently planning to support such observation campaigns with orbital predicts as representative times of solar and geomagnetic levels occur.

The Starshine program would like to thank the ILRS for SLR observations of Starshine 3 to date as well as hosting school children at some of the sites. Both activities address NASA's mission of K-12 educational outreach. We would be grateful for any future SLR observations by the ILRS. In particularly, such observations would give some indication of the BK7 retroreflector performance and whether any drop has occurred.

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