Lares-2, the “Next Generation” Lageos
By

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Contents:

1. Brief history of my participation in the development of Lares-2

Lageos-1, Lageos-2, and Lares-1, use the same basic design. The ILRS workshop in 2002 was titled “Toward millimeter accuracy”. Twenty years later we finally have a one millimeter satellite.

Lares-2 started with an offer from ESA to provide a free launch on the maiden flight of the Vega-C rocket. Lares-1 needed to be redesigned to fit the size and weight requirements of the Vega-C rocket. The project needed the help of the ILRS to do the redesign.

The charter of the ILRS is published in the paper, “The International Laser Ranging Service”, Advances in Space Research, M.R.Pearlman, J.J.Degnan, J.M.Bosworth,
Volume 30, Issue 2, July 2002, Pages 135-143
https://www.sciencedirect.com/science/article/abs/pii/S0273117702002776
The abstract states, “The ILRS works with new satellite missions in the design and building of retroreflector targets to maximize data quality and quantity.”
ILRS has no funding to support this service to new missions. NASA funds cannot legally be used to support the work of a foreign agency. This problem needs to be addressed by ILRS in order to be able to fulfill its mission.

In March of 2016 Erricos Pavlis asked me to provide some preliminary analyses on possible designs. This request fits within the charter of the ILRS. I was happy to help.

I pointed out that Lares-1 could be redesigned to provide the one millimeter accuracy needed by space geodesy. This suggestion fits within the defined duties of the ILRS. This possibility was met with enthusiasm by all the parties.

Lageos and Lares-1 use the 1.5 inch uncoated retroreflector and floating mount designed for the Apollo Lunar retroreflector arrays. The 1.5 inch size was chosen to match the low Lunar velocity aberration. The Lunar design was used on Lageos-1. Instead of changing the size, a dihedral angle offset was added to account for the larger velocity aberration in earth orbit. The dihedral angle offset was increased a little more for Lares-1 which is in a lower earth orbit.

My basic proposal was to reduce the size of the retroreflector from 1.5 inches to 1.0 inches, remove the dihedral angle offset, and increase the number of retroreflectors to fill the sphere. This would increase the cost and procurement time. This would create a very tight schedule to meet the launch date.

I proposed using COTS (commercial-off-the-shelf) retroreflectors. These would have to be tested to see if they have the necessary optical quality. Reinhart Neubert and Ludwig Grunwaldt agreed to test samples of the COTS cubes. The testing showed COTS retroreflectors to have nearly the same optical quality as custom made retroreflectors. This made it possible to have faster procurement at lower cost. Ludwig also published a paper, ”Optical Tests of a Large Number of Small COTS Cubes”. https://cddis.nasa.gov/lw20/docs/2016/papers/69-Grunwaldt_paper.pdf

In July of 2016 there was a major change of scope to study the feasibility of a complete redesign of the satellite to achieve one millimeter accuracy.

The placement of the retroreflectors needed to accommodate the rods supporting the satellite in the rocket. This meant modifying the ring structure to either omit retroreflectors or increase the spacing between the rings. I pointed out that the only requirement was to have the spacing be as uniform as possible.

Antonio Paolozzi developed a method for packing the retroreflectors as closely as possible around the support rods without using a ring structure. I tested each configuration he developed to make sure the range correction met the desired accuracy.

By the fall of 2017 the new design was essentially complete. It was approved by ASI.

2. Velocity aberration.

The most important factors in the performance of a retroreflector array are the diffraction pattern of the array and the velocity aberration that determines the position of the receiver in the diffraction pattern. An understanding of velocity aberration is necessary for understanding this paper.

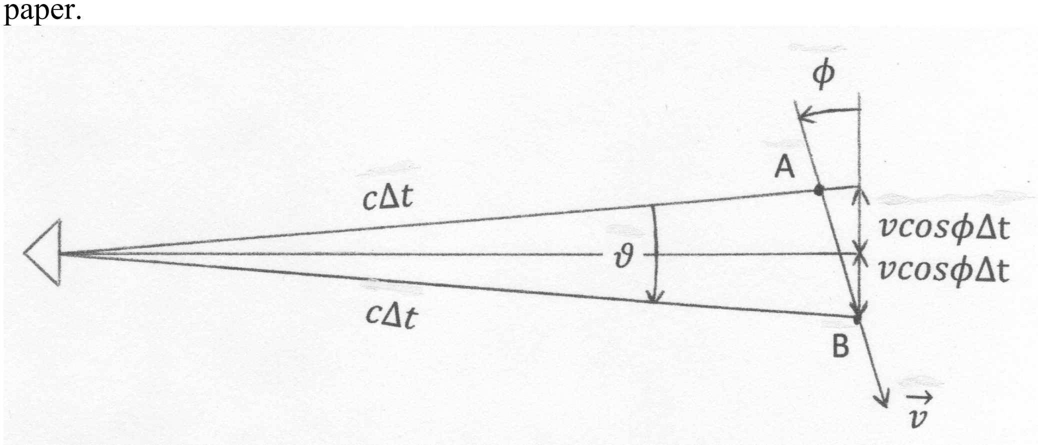


Figure 2.1 Velocity aberration.

A transmitter emits a pulse of light at point A which travels in time Δt at velocity c to a retroreflector. The center of the reflected beam returns to point A after another time interval Δt. In time $2\Delta t$, the transmitter moving at velocity v at an angle ϕ from a line perpendicular to the line of sight moves to point B. In order for the transmitter to receive any of the reflected light at point B, the angular radius ϑ of the reflected beam must be at least

$$\vartheta = \frac{2v cos\phi \Delta t}{c\Delta t} = 2\frac{v}{c}cos\phi$$

where ϑ is the velocity aberration. In laser ranging the retroreflector is moving and the transmitter is stationary. The displacement of the reflected beam is in the direction of motion of the satellite. The receiver is somewhere within a ring in the diffraction pattern of radius ϑ. The width of the ring is determined by the variation of $\cos(\phi)$ and the orbital velocity v.

3. Using smaller retroreflectors.

The size of the diffraction pattern is inversely proportional to the diameter of the retroreflector. The 1.5 inch retroreflectors used on Lageos and Lares-1 are too large to match the velocity aberration. A dihedral angle offset was used to provide the necessary beam spread. This creates a messy diffraction pattern and an asymmetry when linear polarization is used in an uncoated retroreflector. The large size creates more thermal problems because the optical path length in the glass is longer.

If there is no dihedral angle offset, an uncoated cube still has a ring of spots around the central peak due to phase changes from total internal reflection. The size of the retroreflector can be chosen to put the ring of spots at the required velocity aberration. For the Lageos altitude, the optimum size is about 1.0 inches. The pattern is shown in Figure 3.1.

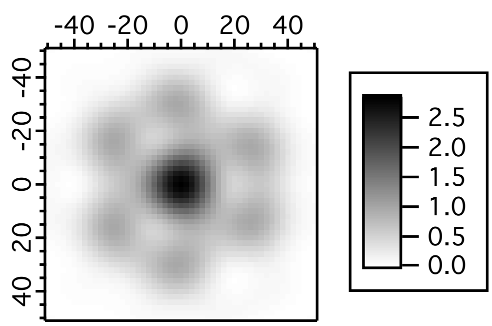
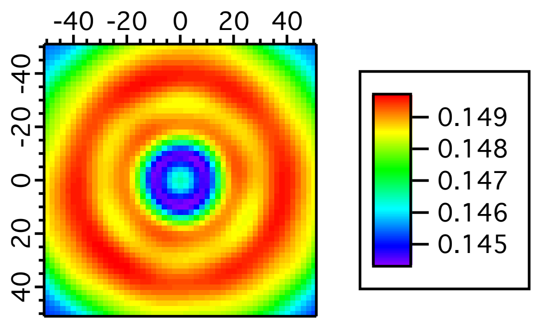


Figure 3.1. Diffraction pattern of a one inch uncoated retroreflector with no dihedral angle offset (axes in microradians, cross section in million sq m). The retroreflectors can be clocked to form a uniform ring.

4. Polarization asymmetry

The following simulations have been done for a spherical satellite approximately 40 cm in diameter covered with uncoated retroreflectors. The diffraction pattern is averaged over a large number of orientations.



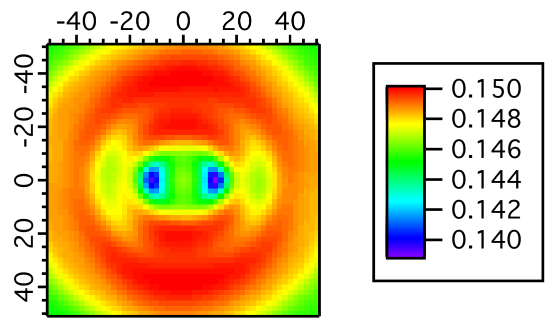
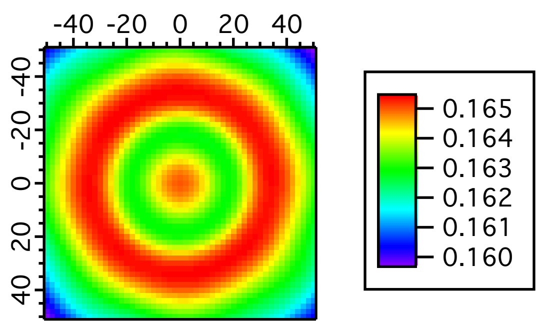


Fig. 4.1. (left) Centroid (m), circular polarization, 1.5 inch retroreflectors, 1.25 arcsecond dihedral angle offset.
Fig. 4.2. (right) Centroid (m), linear vertical polarization, 1.5 inch retroreflectors, 1.25 arcsecond dihedral angle offset.



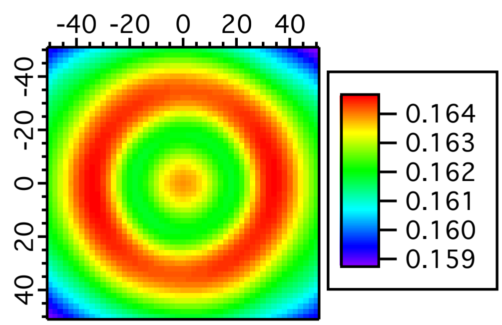
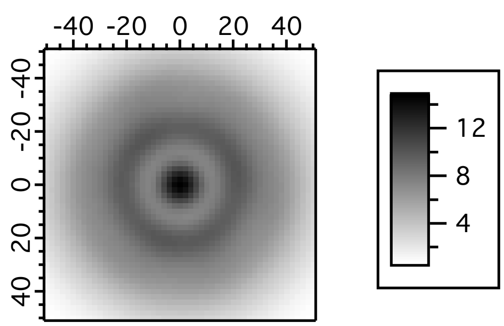


Fig. 4.3. (left) Centroid (m), circular polarization, 1.0 inch retroreflectors, no dihedral angle offset.
Fig. 4.4. (Right) Centroid (m), linear vertical polarization, 1.0 inch retroreflectors, no dihedral angle offset.

The polarization asymmetry can be eliminated by using circular polarization or by removing the dihedral angle offset. The next four far field patterns are the cross section patterns corresponding to the four centroid patterns shown above.



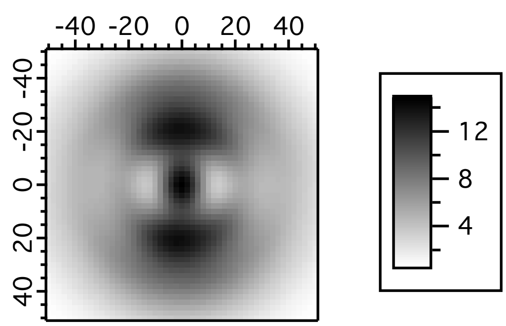
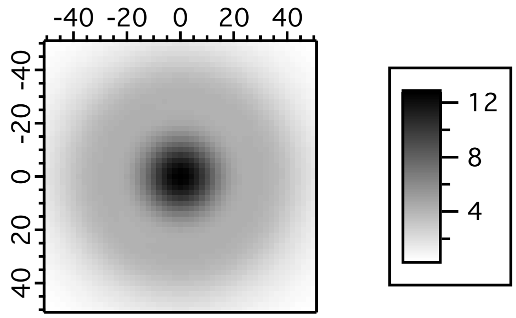


Fig. 4.5. (Left) Cross section (million sq m), circular polarization, 1.5 inch retroreflectors, 1.25 arcsecond dihedral angle offset.
Fig. 4.6. (Right) Cross section (million sq m), linear vertical polarization, 1.5 inch retroreflectors, 1.25 arcsecond dihedral angle offset.



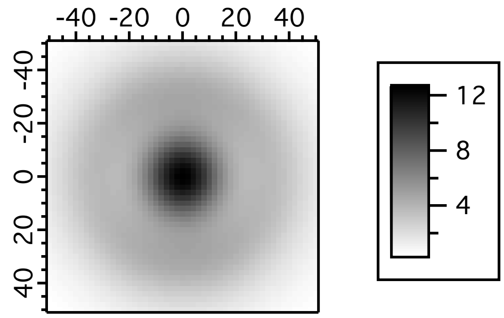


Fig. 4.7. Cross section (million sq m), circular polarization, 1.0 inch retroreflectors, no dihedral angle offset.
Fig. 4.8. Cross section (million sq m), linear vertical polarization, 1.0 inch retroreflectors, no dihedral angle offset.

The pattern in the last figure has good circular symmetry since there is no dihedral angle offset. This makes tracking easier since the signal is consistent and independent of polarization angle.

The maximum and minimum values of the centroid have been computed around circles of increasing radius in the far field. The asymmetry has been computed as the maximum minus the minimum around the circle. This difference has been plotted vs the magnitude of the velocity aberration. A comparison of the asymmetry for Figs. 4.2, 4.3, and 4.4 is plotted in Fig. 4.9.

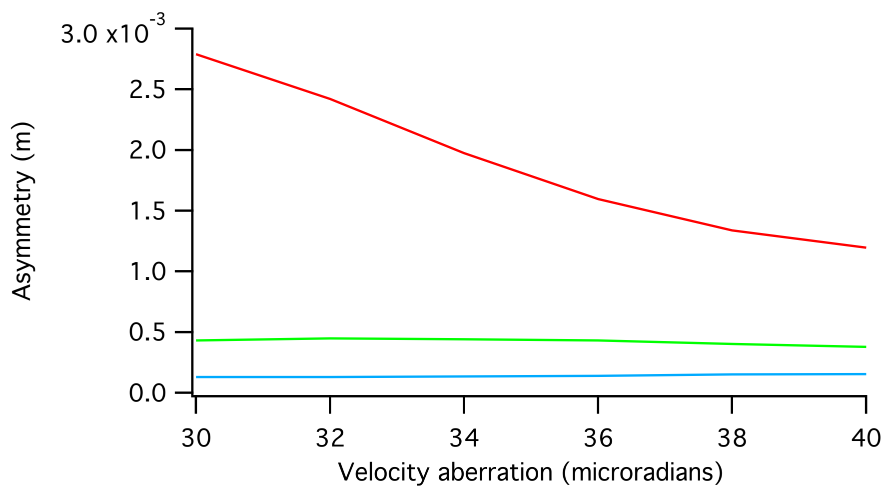


Fig. 4.9. Asymmetry in the centroid vs velocity aberration

The red line (top) is for the 1.5 inch retroreflector with a 1.25 arcsecond dihedral angle offset and linear polarization. The green line (middle) is for a 1.0 inch retroreflector with linear polarization and no dihedral angle offset. The blue line (bottom) is for a 1.0 inch retroreflector with circular polarization and no dihedral angle offset. With the 1.0 inch retroreflectors and no dihedral angle offset the asymmetry is less than .5 mm.

5. Centroid vs velocity aberration.

This section computes the dependence of the centroid on velocity aberration for a 1.5 inch retroreflector and a 1.0 inch retroreflector. Linear vertical polarization is used since this is the worst case. The variation of the centroid around circles of increasing radius in the far field has been computed. The average, maximum, and minimum around the circles has been computed at each point. The results for a 1.5 inch retroreflector (Fig. 4.2) are plotted in Fig. 5.1.

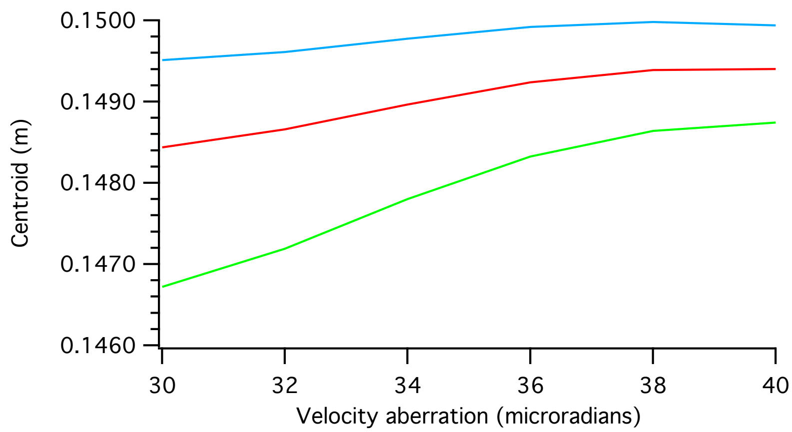


Fig. 5.1. Centroid vs velocity aberration for a 1. 5 inch cube with linear polarization.

The red line (middle) is the average centroid around a circle in the far field. The green line (bottom) is the minimum. The blue line (top) is the maximum.

The average (red curve) for the 1.5 inch cube changes by .74 mm from 32 to 40 microradians. In principle, a correction could be applied as a function of velocity aberration. However, the asymmetry of the pattern can cause changes in centroid up to almost 3 mm depending on the angle between the velocity aberration and the polarization.

The same analysis has been done for a 1.0 inch uncoated cube with no dihedral angle offset and linear polarization (Fig. 4.4). The results are plotted in Fig. 5.2.

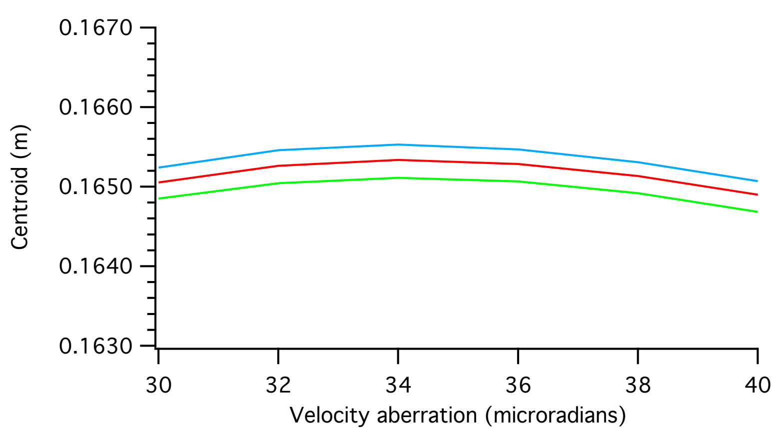


Fig. 5.2. Centroid vs velocity aberration for a 1.0 inch retroreflector with linear polarization. The red line (middle) is the average centroid around a circle in the far field. The green line (bottom) is the minimum. The blue line (top) is the maximum.

The change of the red curve is .47 mm for the 1.0 inch retroreflector.

6. Thermal simulations.

If there were no thermal gradients the range correction would be constant. It could be measured in the lab before launch. It could be computed theoretically using the parameters of the retroreflectors and the measured dihedral angle offsets.

The objective of the thermal design is to reduce the thermal gradients to a level where their effect can be neglected.

Antonio Paolozzi ran a number of thermal simulations under different conditions for a 1.0 inch circular uncoated retroreflector. Reinhart Neubert computed far field patterns from the phase fronts of the thermal simulations. I also plotted and analyzed the far field patterns. Four of those simulations have been selected as representing particularly significant conditions.

Due to manufacturing errors, there is always some dihedral angle offset that may be either positive or negative. The phase difference due to thermal gradients and dihedral angle offsets can be additive, or the effects can partially cancel each other. This analysis includes the combined effect of both thermal gradients and dihedral angle offsets.

The fractional change in cross section has been computed for the four selected cases. The results are shown in Table 6.1.

Case	Core temperature	Reflector Temperature	Fractional change in cross section
11 radiation only	303	250	.0444
17 radiation only	343	298	.4156
16 radiation only	413	360	.6637
12 conduction + radiation	303	293	.5653

Table 6.1. Data for the four thermal cases.

The fractional change is plotted vs temperature of the retroreflector in Figure 6.1.

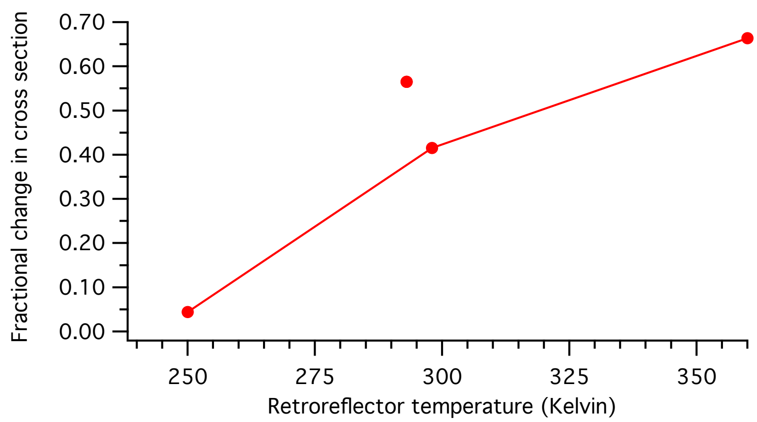


Fig. 6.1. Fractional change in cross section vs retroreflector temperature.

This figure shows that the thermal gradients depend primarily on the temperature of the retroreflector. At 250 deg Kelvin, the thermal effect is small enough to be neglected.

The point that lies above the curve is case 12 with conduction between the mount and the retroreflector. This conduction is avoided by having a floating mount. I worked with Antonio to develop a new floating mount that would constrain the cube without causing conduction, or significantly obscuring the front face, or causing loss of total internal reflection at the back faces. I proposed a way to test the floating mount in a gravity environment.

In order to be able to compute the temperature of the retroreflectors I have derived a set of equations for the equilibrium temperature of the satellite and retroreflectors from the physical parameters of the satellite and the retroreflectors. The equations are given in the ASR paper "Thermal-Optical design of a geodetic satellite for one millimeter accuracy."
https://www.sciencedirect.com/science/article/abs/pii/S0273117720300491?via%3Dihub
I wish to thank Richard Matzner for kindly checking the derivation of the equations.

7. Summary.

The use of small retroreflectors eliminates the need for dihedral angle offsets. This allows the use of inexpensive COTS retroreflectors. The small retroreflectors produce a much more accurate isothermal range correction. If the temperature of the retroreflector is less than about 250 deg K the percent change in cross section due to thermal gradients should be negligible. In this case the isothermal range correction will be very close to the actual range correction in orbit.

8. Appendix – remaining work

The work remaining to be done on Lares-2 includes the following:

A. Compute a transfer function for the Lares-2 retroreflector array. I have done this for Lageos, Lares-1, and many other satellites tracked by ILRS. The details of the design have not yet been released. The information on the ASI website shows that the actual design does not correspond to any of the cases I studied during the design process.

B. Compare the predicted performance of the array with any pre-launch tests that have been done. I was not involved in the pre-launch testing and have no knowledge of what was done. Measuring the range correction (CoM) is very complicated as described in “Prelaunch Optical Characterization of the Laser Geodynamic Satellite (LAGEOS 2)”. NASA Technical Paper 3400 September 1993, https://ilrs.gsfc.nasa.gov/docs/nasa_tp3400.pdf .

C. Compute precise histograms of the satellite using the diffraction pattern. The active reflecting area used by ILRS is an approximation that can introduce systematic errors. ILRS uses tracking data that has many sources of error. It assumes there is a uniform distribution of retroreflectors. The actual configuration is not used

D. Compare the use of the Correlation Method of determining the CoM with using the centroid. The Correlation Method eliminates the data clipping problem as shown in the paper https://cddis.nasa.gov/2017_Technical_Workshop/docs/presentations/session3/ilrsTW2017_s3_Arnold.pdf

E. Build and test a new retroreflector design that can be used on high altitude satellites and the moon. It has high accuracy, no coherent interference, and has low weight and space requirements.

F. Build and test a new retroreflector design that can be used on low altitude satellites to provide accurate range measurements at low cost.

G. Find a way to preserve program TRANSFR that is essential for designing high accuracy retroreflector arrays for geodetic satellites such Lageos, Lares, Grasp, and earth physics satellites.

H. Study the design of IRNSS to determine why it does not work when exposed to direct sunlight.

There is no funding to support the remaining work.