Bibliography and Research Activity

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In order to understand the analysis described in this research one has to understand velocity aberration. The article below gives a simple explanation of the effect.

Velocity Aberration

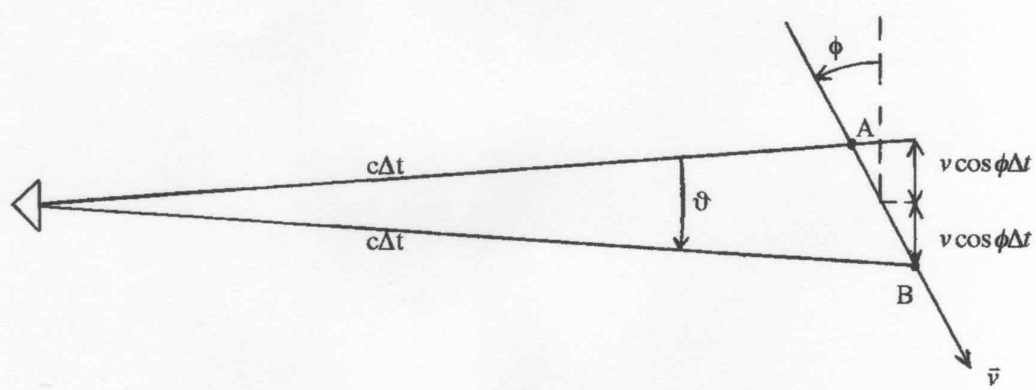
By David A. Arnold

In the inertial coordinate system of a retroreflector a beam of light entering the retroreflector will be returned along the same line that it entered. If there is a difference in velocity between the retroreflector and the transmitter, the beam will not be returned to the source. The analysis is easiest in the inertial coordinate system of the retroreflector. The usual situation is that the retroreflector is in orbit and the transmitter is on the ground. We will consider the retroreflector to be stationary and the transmitter to be moving.

In the diagram below, 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.



The strength of the return signal depends on the cross section of the reflected beam at the point in the diffraction pattern determined by the magnitude and direction of the component of the velocity aberration perpendicular to the line of sight.

The cross section can be visualized as the area of a diffuse reflector needed to give the same signal. A retroreflector achieves a high cross section by concentrating the energy into a very narrow beam directed at the receiver. A typical cross section of a retroreflector is on the order of one million square meters.

The range correction is the difference between the measured range to the retroreflector array and the distance to the center of the satellite.

1964 Electrical conduction in ice (P.R. Camp, W. Kiszenick, and D.A. Arnold). U.S. Army Cold Regions Research and Engineering Laboratory Res. Rep. 198; also in Proceedings of the International Symposium on the Physics of Ice, ed. by Reihl, Bullmer, and Englehardt, Plenum Press, New York, 1969.

Measurements of the surface and bulk conductivity of ice.

1968 Geos 1 observations at Malvern, England (J. Hewitt, J. Rolff, and D.A. Arnold). Smithsonian Astrophys. Obs. Spec. Rep. No. 272, 48 pp.

Measurements were done from plates using a modified version of the program used to process Baker Nunn satellite tracking films.

1971 Apollo contamination analysis (prepared). Charles Buffalano, Principal Investigator (MSFC), Charles A. Lundquist (SAO), James Cappelari, (Bellcomm), Ravi D. Sharma, (Bellcomm), W.I. Mclaughlin, (Bellcomm), David A. Arnold (SAO), Marjorie A Zamanian (SAO), Final Rep., NASA Grant NGR 09-015-105, Part I, July.

Microdensitometer measurements were made on photographs taken by the Baker Nunn satellite tracking camera of liquids vented into space from the Apollo missions.

1972 Calculation of retroreflector array transfer functions. Final Tech. Rep., NASA Grant NGR 09-015-196; NASA Cr-130696, December. This report includes: BEACON B & C, DIADEME D1C & D1D, PEOLE, GEOS 1 & 2, GEOS-C.

The cross section and range correction were computed for these satellites using software developed for the design of Lageos. The cross section is estimated from the active reflecting area of the cube corners since the specifications of the retroreflectors, such as dihedral angle offset, are not known.

1972 Timing (epoch) (D.A. Arnold and J.M. Thorp). In SAO ISAGEX Experience. I. Data Acquisition, ed. by E.M. Gaposchkin, Smithsonian Astrophys. Obs., pp. 29-30, May.

1973 SAO network: Instrumentation and data reduction (M.R. Pearlman, J.M. Thorp, C.R.H. Tsiang, D.A. Arnold, C.G. Lehr, and J. Wohn). In Smithsonian Astrophys. Obs. Spec. Rep.No. 353, pp. 13-84.

1973 Use of a Passive Stable Satellite for Earth-Physics Applications, Final Report, Grant NGR 09-015-164, Principal Investigator Dr. George C. Weiffenbach, April, 1973, Smithsonian Institution, Astrophysical Observatory.

Because of the strong effect of diffraction on the cross section of a retroreflector, I developed software for computing the diffraction pattern of various types of retroreflectors. This software was incorporated into a program for computing the cross section and range correction matrices in the far field. This program was used to study various types of retroreflectors and distributions of retroreflectors on a sphere. For thermal reasons, uncoated cubes were chosen with the same type of mounting as the Apollo Lunar retroreflectors. The diffraction pattern of the 1.5 inch cubes used on the Lunar reflectors is too narrow for the velocity aberration in earth orbit. The best solution from an optical point of view would have been to use a larger number of smaller cubes to widen the diffraction pattern. However, since this would have significantly increased the cost, the decision was made to add dihedral angle offsets to the 1.5 inch cubes. This gives larger range errors. Since the computed range correction with the larger cubes met the 5 mm accuracy specification, the decision was made to use the 1.5 inch cubes with dihedral angle offsets. Uncoated cubes start to lose total internal reflection beyond about 17 deg incidence angle depending on the clocking angle of the cube corner in its mounting. In order to avoid systematic effects from loss of total internal reflection, random clocking of the cubes was used. My work included analysis of the visibility of the satellite to the Baker-Nunn cameras needed to acquire the satellite.

The figures and graphs in section 5.3 Retroreflector Array, of the report give the results of the computer simulations. SAO Special Report 382 gives a complete description of the software developed to do the design of the retroreflector array.

1974 Optical transfer function of NTS-1 reflector array. Tech. Rep. RTOP 161-05-02, NASA Grant NGR 09-015-002, Suppl. No. 57,October.

The array uses coated hexagonal cube corners 15 mm across flats. Testing shows the cube corners are nearly diffraction limited.

1975 Optical transfer function of Starlette retroreflector array. Tech. Rep., RTOP 161-05-02, NASA Grant NGR 09-015-002, Suppl. No. 57, February.

Starlette is a 24 cm spherical satellite covered with 60 circular coated cube corners with a 32.8 mm diameter face. The cube corners have a dihedral angle offset to produce an average offset of the reflected beam of about 7 arcseconds (34 microradians).

1975 Optical and infrared transfer function of the Geos 3 retro-reflector array. Tech. Rep., RTOP 161-05-02, NASA Grant NGR 09-015-002, Suppl. No. 57, October.

The Geos-3 retroreflector array is a ring of cube corners on a conic frustrum tilted at 45 degrees. There is also an infrared cube corner for tracking at 1.06 microns wavelength. The optical cubes have hexagonal faces 35 mm across flats. The specification on the dihedral angle offset is 90 + 2"+/- .5". The cross section and range correction are computed vs incidence angle on the array. The systematic error of the range measurements is estimated to be on the order of 2 cm. This is primarily due to the large size of the array.

1976 Dumbbell gravity-gradient sensor: A new application of orbiting long tethers (G. Colombo, D.A. Arnold, J.H. Binsack, R.H. Gay, M.D. Grossi, D.A. Lautman, and O. Orringer). Smithsonian Astrophys. Obs. Rep. in Geoastronomy No. 2, June.

1977 Tethered satellite system for gravity gradiometry at low orbital height (G. Colombo, D.A. Arnold, E.M. Gaposchkin, M.D. Grossi, P.M. Kalaghan, and L.R. Kirschner). Presented at the Earth Dynamics Summer Workshop, Boulder, Colorado, July.

1977 Lageos orbital acquisition and initial assessment (M.R. Pearlman, J.M. Thorp, D.A. Arnold, and F.O. Vonbun). In Space Research XVII, ed. by M.J. Rycroft, Pergamon Press, Oxford, pp. 59-62.

The satellite was acquired using the Baker Nunn cameras, especially the one in Hawaii. Since the tracking data was sparse, some of the orbital elements of the rocket body were enforced in the orbital solution for the satellite to stabilize the iteration. Orbital simulations were done using the ejection velocity of the satellite to estimate the position of the satellite relative to the rocket body.

1978 Study of the dynamics of a tethered satellite system (Skyhook) (P.M. Kalaghan, D.A. Arnold, G. Colombo, M.D. Grossi, L.R. Kirschner, and O. Orringer). Final Rep., NASA Contract NAS8-32199, March.

1978 Optical and infrared transfer function of the Lageos retroreflector array. Tech. Rep., RTOP 161-05-02, NASA Grant NGR 09-015-002, Suppl. No. 57, May.

The cross section and range correction matrices are computed using the software developed for the design of the array. The systematic error in the range correction is estimated to be about 3 mm. This is slightly better than the specification of 5 mm.

1978 Method of calculating retroreflector-array transfer functions. Smithsonian Astrophys. Obs. Spec. Rep. No. 382, 165 pp.

This report is a complete description of the software written to design the retroreflector array for Lageos. The software has been used to calculate the cross section and range correction for dozens of satellites since that time. It has also been used to design retroreflector arrays for various satellites.

In the words of Dr. Reinhart Neubert in an email to Dr. Giuseppe Bianco, Jan. 4, 2019, "His famous SAO special report 382 'method of calculating retroreflector-array transfer functions' is the knowledge base for all working in the field."

1979 Orbiting tether's electrodynamic interactions (M.P. Anderson, D.A. Arnold, G. Colombo, M. Dobrowolny, M.D. Grossi and, L.R. Kirschner). Final Rep., NASA Contract NAS5-25077, April.

1979 System noise analysis of the Dumbbell tethered satellite for gravity-gradient measurements (D.A. Arnold, G. Colombo, N. Lanham and, G. Nystrom). Final Rep., NASA Grant NSG 8063, October.

1980 Transmission-line model of the interaction of a long metal wire with the ionosphere (D.A. Arnold and M. Dobrowolny). Radio Sci., vol. 15, No. 6, November-December.

1981 Study of Certain Launching Techniques Using Long Orbiting Tethers. Final Rep., NASA Grant NAG-8008, February.

1981 Investigation of electrodynamic stabilization and control of long orbiting tethers (G. Colombo, M.D. Grossi, M. Dobrowolny and D.A. Arnold). NASA Contract NAS8-33691, Interim Report, March.

1982 Study of certain tether safety issues, and the use of tethers for payload orbital transfer (G. Colombo, M.D. Grossi, D.A. Arnold, and M. Martinez-Sanchez). Semiannual Progress Report, NASA Contract NAS8-33691, March.

1982 Study of tethered satellite active attitude control (G. Colombo and D.A. Arnold). Interim Report, NASA Contract NAS8-33691, October.

1983 Orbital transfer and release of tethered payloads (G. Colombo, M.D. Grossi, and D.A. Arnold). Final Report, NASA Contract NAS8-33691, March.

1984 Tether dynamics software review, high resolution tether dynamics studies, advanced tether applications (G. Colombo, D.A. Arnold, G. Gullahorn, and R.S. Taylor). Final Report, NASA Contract NAS8-35036, January.

1984 Engineering Study of the Electrodynamic Tether as a Spaceborne Generator of Electric Power (D.A. Arnold, H.G. Booker, M. Dobrowolny, and M.D. Grossi), Technical Report, NASA Contract NAS8-35497, June.

1984 Orbital Pumping. Technical Note TP84-001, NASA Contract NAS8-35036, August.

1984 Analytical Investigation of the Dynamics of Tethered Constellations in Earth Orbit (E. Lorenzini, D.A. Arnold, and M.D. Grossi). Final Report, NASA Contract NAS8-35497, December.

1985 Study of Orbiting Constellations (TESCONS) in Space, Phase II, Studies of Selected Applications in Space (E. Lorenzini, D.A. Arnold, J.W. Slowey, and M.D. Grossi). Final Report, Martin Marietta Aerospace, Contract RH4-394019, January.

1985 Study of an Orbiting Tethered Dumbbell System Having Positive Orbital Energy (E. Lorenzini, D.A. Arnold, and G.E. Gullahorn). Addendum to the Final Report NASA Contract NAS8-35497, February.

1985 Efficiency of a Self-Powered Spaceborne ELF/ULF Radiator. Technical Note TP85-007, November.

1986 Retrieval of a Tethered Satellite System Using a Deployable Ballast. Technical Note TP86-004, NASA Contract NAS8-36160, October.

1986 The Behavior of Long Tethers In Space, presented at the NASA/AIAA/PSN International Conference on Tethers in Space, Arlington, VA, September.

1987 The Behavior of Long Tethers in Space. The Journal of the Astronautical Sciences, Vol. 35, No. 1, January-March.

1987 Tether Tutorial. Presented at the PSN/NASA/ESA Second International Conference on Tethers in Space, Venice, Italy, October.

1987 Study of an Orbiting Tethered Dumbbell System Having Positive Orbital Energy. Presented at the Second International Conference on Tethers in Space, Venice, Italy, October.

1989 Retrieval Dynamics, Vol 1, Dynamics Workshop Proceedings,Third International Conference on Tethers in Space, San Francisco, CA, May.

1992 Topex LRA Analysis, Status Report, 11/6/92
Topex LRA Analysis, Status Report, 12/3/92

The TOPEX/POSEIDON satellite was launched August 10, 1992. the satellite has been making measurements of the global oceans since September, 1992. It became apparent from the orbital analysis of the laser tracking data that there were unexplained ranging errors up to 5 cm. The specification for the laser tracking was 1 or 2 cm.

The array is a double ring of cube corners about 80 cm in diameter with 128 cubes in the first ring and 64 cubes in the second ring. The rings is tilted 40 degrees. Because the array is so large there is large spreading of the reflected laser pulse. The centroid of the return signal varies by about 5 cm within the far field diffraction pattern. the range correction needs to be computed as a matrix in the far field diffraction pattern. This requires modeling the diffraction pattern of each active cube corner. The signals from each cube corner have to be combined to determine the range correction at each point in the far field diffraction matrix. The location of the receiver in the far field pattern is determined by the magnitude and direction of the velocity aberration.

An attempt was made to model the diffraction patterns using program RETRO. See "Cube Corner Retroreflector (RETRO) Program, Functional Design Description and User's Guide Revision 2, Prepared for Goddard Space Flight Center by Computer Sciences Corporation Under Contract NAS 5-24300, Task assignment 033, May 1979."

To the best of my knowledge this method of making range corrections to laser data has never been done before, or since. The range corrections determined using program RETRO were apparently not working.

I was asked to consult on the problem using software I developed during the design of LAGEOS. The software had not been used for 14 years. It existed only on punched cards stored in a warehouse. I was able to get the cards read by the only card reader still available in the Boston area. This made it possible to recreate the program.

The diffraction patterns of the individual cube corners had been measured before launch. I compared the measured patterns with the patterns from Program RETRO and my own software. The patterns computed by my program seemed similar but out of order. Examination of the equipment used to make the measurements showed that the cube corners were being rotated about a different axis than assumed in in the theoretical calculations. When the revised theoretical calculations were compared with the measured patterns, the patterns computed by my own SAO software showed good agreement. However, no consistent method of matching the RETRO computed patterns was discovered.

Because the tracking stations do not measure the centroid, the range correction matrices had to be calculated for each type of station. This was done by Dr. Thomas Varghese using diffraction matrices for each cube corner computed by the SAO program. This reduced the range errors in the orbital analysis to about 1 or 2 cm to meet the specification for the precision orbit determination.

1993 Hydrogen Maser Clock (HMC) Project, Instrument Critical Design Review, NAS8-39194, 15 December, 1993.

The intent of this project was to measure the time of a hydrogen maser clock on the spacecraft using a laser signal sent from a tracking station. The laser pulse triggers a reading of the clock and simultaneously measures the range by measuring the two way travel time of the laser pulse. I designed a retroreflector array that uses small 10 mm coated cubes. This gives a more compact array with better range accuracy. I don't think an array with such small cubes was ever built before. The principal investigator on the project was Robert Vessot at SAO. It was originally to be tested aboard the European Space Agency's EURECA spacecraft, and then, following cancellation of the planned EURECA re-flight, on the Russian Mir space station. At present (Dec 1996), the flight portion of the HMC program has been terminated, and the flight model maser and its electronics are undergoing laboratory testing at SAO.

1993 The Investigation of Tethered Satellite System Dynamics, Final Report, NASA Contract NAS8-36160, August.

2002 Retroreflector Array Transfer Functions, 13th International Workshop on Laser Ranging, Washington, DC, Oct

This paper is a study of various types of retroreflector arrays used for laser tracking including the following:

1. Introduction
2. LARES Preliminary transfer function
3. LAGEOS wavelength correction 850nm-524nm
4. Cross section of APOLLO Lunar retroreflector arrays
5. Parametric thermal analysis of a hollow retroreflector
6. Retroreflector arrays for high altitude satellites
7. Measured diffraction patterns of Russian cube corners
8. Thermal simulations of Russian cube corners
9. Laboratory tests of cube corners
10. Modeling of the response of a SPAD detector

2002 Velocity aberration, 13th International Workshop on Laser Ranging, Washington, DC, Oct.

The retroreflectors used on Meteor-2/Fizeau and Westpac were designed to eliminate velocity aberration by proper choice of the index of refraction of the glass used in the retroreflectors. This is based on the paper "Effect of motion of the optical medium in optical location" by V.P. Vasil’ev, V.A. Grishmanovskii, L.F. Pliev, and T.P. Startsev *Scientifie-Research Institute of Precision Instrument-Making, 111250, Moscow* (submitted 3 February 1992) Pis’ma Zh. Eksp. Teor. Fiz. 55, No. 6, 317-320 (25 March 1992). This paper derives the following expression for the velocity aberration:

$$\Delta\alpha_{\max} = \frac{2V}{c}\left(n+1-n^2\right)$$

Where V is the orbital velocity of the satellite, c is the velocity of light, and n is the refractive index of the cube corner medium. For n= 1.618 the compensation is perfect.

The retroreflectors were designed assuming there would be no velocity aberration. The receiver would be on the central peak of the diffraction pattern. Measurements of the signal strength from these satellites does not show the expected improvement from eliminating velocity aberration. When I examined the derivation of the equations I discovered an error in the equations as shown in the paper presented at the 13th ILRS workshop. When this error is corrected the usual expression for the velocity aberration 2v/c is obtained.

2002 Wavelength Dependence of the Range Correction, 13th International Workshop on Laser Ranging, Washington, DC, Oct

One way of computing the atmospheric correction for satellite laser ranging is to use two wavelengths. The range correction between wavelengths .4 and .8 microns for Lageos is about 1.5 mm on the average. However, it is not consistent. The dispersion is a factor of 12 to 15. The error in using two wavelength ranging is greater than the uncertainty in the existing models for the atmospheric correction.

2003 Cross Section of ILRS Satellites, ILRS Fall Workshop, Koetzting, Germany, Oct

This paper gives an estimate of the theoretical cross section of various satellites using the best available method when complete information is not available.

THEORETICAL CROSS SECTION
(Million sq m)

SATELLITE	ALTITUDE	CURRENT	REVISED		
			Minimum	Average	Maximum
Starlette	950	0.65	1.00	1.80	2.5
Lageos	6000	7.00	9.00	15.00	23.0
Etalon	19000	60.00	-	55.00	-
Topex	1300	2.00	6.00	33.00	83.0
BeaconC	940	3.60	0.00	13.00	35.0
Ajisai	1400	12.00	-	23.00	-
Gfo-1	800	2.00	.07	.50	1.1
Stella	950	0.65	1.00	1.80	2.5
Jason	1300	0.30	.20	.80	1.7
GPS	20000	40.00	-	19.00	-
Champ	500	1.80	.05	1.00	3.4
Westpac	835	0.03	0.00	.04	.4
ERS	800	0.30	.20	.85	1.6
Glonass396	20000	360.00	-	240.00	-
Glonass132	20000		-	80.00	-
Envisat	800	0.30	.20	.85	1.6
LRE	25000	1.25	-	2.00	-
SUNSAT	600	0.20	.04	.40	1.4

2003 Spectral Analysis of LAGEOS Range Data, Arnold, D, Bianco, G, ILRS Fall Workshop, Koetzting, Germany, Oct

Spectral analysis of range data has been used to determine the spin rate of Lageos. This paper performs a spectral analysis of theoretically computed ranges with the satellite spinning. The satellite is viewed at various angles from the spin axis. This gives similar results to the analysis of actual range data.

2003 Germanium Flashes in LAGEOS-2 Photometry Data, Arnold, D, Appleby, G, Sherwood, R, ILRS Fall Workshop, Koetzting, Germany, Oct

The spin rate of Lageos has been determined by photometric observation of solar reflections from the surface of the cube corners as the satellite rotates. There are 4 germanium cubes on Lageos. The reflectivity of the cubes is about 4 percent for the optical cubes and about 50 percent for the infrared germanium cubes. Since the placement of the germanium cubes is not symmetrical the stronger germanium flashes should make it possible to determine the phase of the rotation. Analysis of the photometric data shows no evidence of germanium flashes.

I obtained some of the data to try to try to find the germanium flashes. The transmitted pulse shows up in the data at a rate of 10 pps and amplitude of about 1600 counts. The optical flashes show up at a rate of one per second with an amplitude of about 100 counts. The bin size was one millisecond. The data had been plotted with a maximum range of 200 counts. The germanium reflections would be offscale. The solar flashes last a few tens of bins. I changed the bin size from one to 5 milliseconds to get better averaging. I eliminated the laser pulses which occupy only one or two millisecond bins. I plotted the data with a larger maximum plotting scale. The germanium flashes that had been offscale in the original plots showed up with the proper spacing between optical and germanium cubes.

2004 Asymmetric Radiation Pressure on LAGEOS, Arnold, D, Appleby, G. 14th International Workshop on Laser Ranging, San Fernando, Spain, Oct

Orbital analysis shows an asymmetric radiation pressure on Lageos. This is discussed in the paper "LAGEOS Satellites Germanium Cube-Corner-Reflectors and the Asymmetric Reflectivity Effect", David M. Lucchesi, Celestial Mechanics and Dynamical Astronomy 88:269-291, 2004. The paper attributes the asymmetric radiation pressure to the difference in reflectivity of the optical and germanium cube corners. The paper models an optical cube corner as a black body. This is not correct. A black body absorbs all the incident radiation. At normal incidence, an optical cube reflects all the radiation. The momentum transfer is twice as great as for a black body. The germanium cube is modeled as reflecting all the radiation. This is not correct. The germanium cube reflects 50 percent and absorbs 50 percent.

2004 Identifying Single Retro Tracks with A 2kHz SLR System - Simulations and Actual Results, Arnold, D, Kirchner, G, 14th International Workshop on Laser Ranging, San Fernando, Spain, Oct

Single photoelectron returns with a short laser pulse are capable of identifying individual cube corners if the spacing between the cubes is larger than the length of the pulse. If the pulse length is larger than the spacing, the plots give the appearance of showing individual retroreflectors. However, the simulations show that the peaks are actually a combination of a several close retroreflectors. Simulation have been done for Lageos viewing the rotating satellite at different angles from the spin axis. The plots look similar to the plots of measured laser ranging data.

2005 Cross Section of the APOLLO Lunar Retroreflector arrays, David Arnold, July, http://ilrs.gsfc.nasa.gov/docs/apollo_arrays.pdf

Lunar retroreflectors are recessed to reduce solar heating. The cross section calculations were done by ray tracing instead of using the program described in SAO Special Report 382..

2005 Hollow Retroreflectors, ILRS Technical Workshop, Eastbourne, Great Britain, Oct.

This report gives a summary of the different types of hollow cubes, the advantages and disadvantages of each, satellites that use hollow cubes, and analysis of the thermal problems. The primary thermal problem is the different expansion coefficient of the glue in the joints.

2006 Retroreflector Arrays for High Altitude Satellites, EGU General Assembly, Vienna, Austria, April

This report lists various possibilities for the design of retroreflector arrays for high altitude satellites. The tables below give summaries of some options.

The table below gives a summary of options for achieving a cross section of 100 million sq meters at the altitude of Galileo. The values can be scaled for another cross section.

Design	# of cubes	Diam. in	Area sq cm	Mass g
uncoated	50	1.3	428	1000
coated	400	0.5	508	460
hollow	400	0.5	508	201
hollow	36	1.4	356	400
GPS	160	1.06	1008	1760

The table below gives a summary of options for achieving a cross section of 1 billion sq meters at geosynchronous altitude.

Design	# of cubes	Diam. In.	Area sq cm	Mass g
Uncoated	165	1.7	2415	7457
Coated	1153	.7	2863	3638
Hollow	1153	.7	2863	1590
Hollow	122	1.8	2003	2863
Single dihedral	22	2.0	446	708

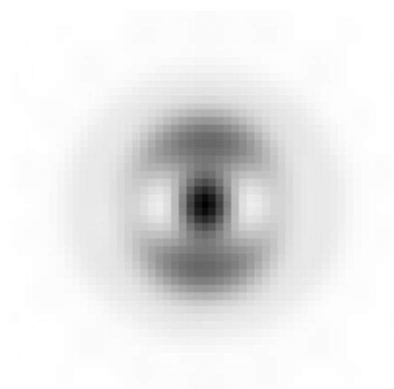
2006 Retroreflector Studies, 15th International Workshop on Laser Ranging, Canberra, Australia, Oct.

This report discusses the following topics:

1. Introduction
2. LARES Preliminary transfer function
3. LAGEOS wavelength correction 850nm-524nm
4. Cross section of APOLLO Lunar retroreflector arrays
5. Parametric thermal analysis of a hollow retroreflector
6. Retroreflector arrays for high altitude satellites
7. Measured diffraction patterns of Russian cube corners
8. Thermal simulations of Russian cube corners
9. Laboratory tests of cube corners
10. Modeling of the response of a SPAD detector

2007 Cross Section of the ETS-VIII Retroreflector Array, ILRS Workshop on Laser Ranging, Grasse, France, Sept.

This report calculates the cross section matrix of the ETS-VIII retroreflector array as a function of incidence angle on the array. The 1.6 inch cubes were chosen to put the velocity aberration on the first diffraction ring of an uncoated cube corner. This eliminates the need for a dihedral angle offset. In fact, an offset of .5 arcseconds was used. This introduces an asymmetry in the diffraction pattern as shown below.



2008 Measuring Signal Strength, 16th International Workshop on Laser Ranging, Poznan, Poland, October

This paper describes the difficulty of measuring the signal strength of various satellites using laser range data. It is possible to measure the relative signal strength between two satellites with reasonable accuracy. However, it there is no reliable way to measure absolute signal strength because of the uncertainty in the parameters needed to calculate the signal strength. The T2L2 satellite has a sensor for measuring the strength of the incoming laser beam. That might help to understand some of the factors affecting signal strength at least on the uplink.

2009 Uncoated Cubes for GNSS satellites, International Workshop on Laser Ranging, Metsovo, Greece, September.

This paper shows that it is possible to obtain the necessary beam spread to account for velocity aberration by changing the size of an uncoated cube corner so that the velocity aberration falls on the first diffraction ring. The conclusions of the paper are:

1. Uncoated cubes have a natural beam spread due to phase changes from total internal reflection. No dihedral offset is needed.
2. Orienting sets of 4 cubes at 0, 30, 60, & 90 degrees produces a smooth circular pattern.
3. Adding a dihedral angle offset causes an asymmetry that cannot be removed. This gives inconsistent signal strength.

2010 Creation of the new industry-standard space test of laser retroreflectors for the GNSS and LAGEOS, **Advances in Space Research**, S. Dell'Agnello, G.O. Delle Monache, D.G. Currie, R. Vittori, C. Cantone, M. Garattini, A. Boni, M. Martini, C. Lops, N. Intaglietta, R. Tauraso,
D.A. Arnold, M.R. Pearlman, G. Bianco, S. Zerbini, M. Maiello, S. Berardi,
L. Porcelli, C.O. Alley, J.F. McGarry, C. Sciarretta, V. Luceri, T.W. Zagwodzki, November.

2011 LARES Laser Relativity Satellite, I. Ciufolini, A. Paolozzi, E. Pavlis, R. Koenig, J. Ries, R. Matzner, R. Neubert, D. Rubincam, D. Arnold, V. Slabinski, G. Sindoni, C. Paris, M. Ramiconi, D. Spano, C. Vendittozzi, H. Neumayer, 17th International Workshop on Laser Ranging, Koetzig, Germany, May

This paper describes the design of the first LARES satellite launched in 2012. It is basically a modified version of the Lageos satellites. LARES uses 1.5 inch uncoated cubes with a dihedral angle offset of 1.5 arcseconds. The offset is slightly larger than LAGEOS to account for the larger velocity aberration at the lower altitude.

2012 Final Transfer Function of the LARES Retroreflector Array, ILRS Technical Workshop, Frascati, Italy, November

This was a poster presentation giving the transfer function of the LARES satellite. It was expected to be the final calculation. However, two later calculations were presented in 2013 and 2014.

2013 Preliminary Transfer Function of the LARES Satellite, 18th International Workshop on Laser Ranging, Fujuyoshida, Japan, November

This is a second computation of the transfer function of the LARES satellite

2014 Final Transfer Function of the LARES Retroreflector Array, 19th International Workshop on Laser Ranging, Annapolis, Maryland, October.

This is the last calculation of the transfer function of the LARES satellite

2015 Nominal SARAL Transfer Function (Frank Lemoine, Editor), NASA/TM-2015-217533, July https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20160007904.pdf

The SARAL retroreflector array is identical to the ERS and ENVISAT arrays. This is an extension to 90 degrees incidence angle of the calculations done for ERS. The paper gives a calculation of the cross section and range correction using the programs described in SAO Special Report 382. An alternative method for estimating the range correction using the closest retroreflector is presented.

2015 Retroreflector Array for a Satellite in an Eccentric Orbit, Presentation 2.8, gnssb_session, ILRS Technical Workshop, Matera, Italy, October

An eccentric orbit presents problems because of the large range of velocity aberration. The proposed array uses half inch coated cubes with no dihedral angle offset. The cross section is high for low velocity aberration and low for high velocity aberration. The velocity aberration is low at apogee (long range) and high at perigee (short range). This design help to keep the cross section more constant over the whole orbit. The range correction is nearly linear with velocity aberration. A range correction could be applied vs velocity aberration to achieve millimeter accuracy.

2016 "LAGEOS-2: Polarization, Pulse length, Signal strength, and detection system", 20th International Workshop on Laser Ranging, Potsdam, Germany, October.

This paper discussed how the range correction for Lageos-2 varies with polarization of the transmitted laser pulse, pulse length, signal strength, and type of detection system. There is an interaction between dihedral angle offsets and linear polarization that creates an asymmetry in the range correction of 2-3 millimeters. The range correction for constant fraction detection systems can decrease by several millimeters as the pulse length increases. For a constant fraction detection system, the polarization asymmetry disappears for short pulse lengths. The range corrections for different stations lie between about 243 mm for centroid detection, and about 255 mm for short pulse length lasers using a constant fraction discriminator.

2017 Use of Correlation Function to Determine the Range Correction with Data Clipping, ILRS Technical Workshop, Latvia, Riga, October

The range is measured by some type of leading edge detection system. This can introduce systematic errors as a result of variations in pulse shape in multi-photoelectron systems. The pulse shape for Lageos has a long tail. In single photoelectron systems data clipping during the process of eliminating noise points can produce systematic errors by elimination real data in the tail.

This paper proposes to use a correlation method for measuring the range. The received pulse shape is the convolution of the transmitted laser pulse shape, the transfer function of the retroreflector array, and the response function of the detection system. This received pulse shape can be computed theoretically to give a histogram h(x).

High repetition rate single photoelectron systems can plot the received pulse shape p(x) in a relatively short time. This received pulse shape can be correlated with the theoretical pulse shape by moving the two shapes relative to each other by an offset d and computing

$$\int h(x)p(x)$$

at each offset d. The offset d that gives the maximum value of the integral is the best fit range correction. This method uses all the data and relies on the shape of the pulse rather than the leading edge. Omitting some of the tail has no effect on the pulse shape of the remaining part of the pulse.

2017 Range Correction for LAGEOS-2 vs Pulse width, Detector rise time, Signal Strength, and Type of Detection System, ILRS Technical Workshop, Latvia, Riga, October

This paper was a presentation at the analysis working group meeting to review various sources of error in Lageos ranging data that can show up in the scientific analysis of the data by the analysis working group. This paper is mostly a repeat of the presentation on Lageos-2 given in 2016 at the ILRS workshop in Potsdam, Germany. The new material is the discussion of data clipping and how the correlation method could eliminate this source of error.

2017 Design of the LARES-2 Array, ILRS Technical Workshop, Latvia, Riga, October

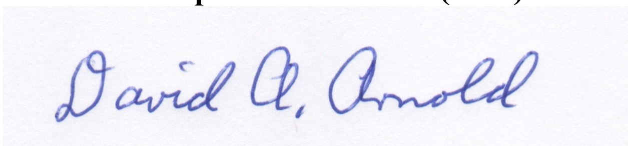
This was a poster presentation describing the current state of the design of the LARES-2 retroreflector array.

2018 Thermal-Optical Design of a Geodetic Satellite for one Millimeter Accuracy (presented by E. Pavlis), 21st International Workshop on Laser Ranging, Canberra, Australia, November

The accuracy of Lageos-1, Lageos-2, and Lares-1 is limited by the use of 1.5 inch uncoated cubes that are too large for the velocity aberration and require dihedral angle offsets. This paper describes how to eliminate this source of error by using 1.0 inch uncoated cubes. This eliminates the polarization bias and the irregular pulse shapes created by the use of dihedral angle offsets. The smaller size reduces the effect of thermal gradients significantly. In combination with keeping the temperature of the retroreflector as low as possible, thermal effects can be made negligible. The range correction in orbit is constant with time. It is the same as the isothermal range correction that can be computed theoretically or measured in the laboratory.

2018 Laser geodetic satellites: a high-accuracy scientific tool, Journal of Geodesy, M. Pearlman, D. Arnold, M. Davis, F. Barlier, R. Biancale, V. Vasiliev, I. Ciufolini, A. Paolozzi, E.C. Pavlis, K. Sosnica, M. Bloßfeld, December

2020 Thermal-optical design of a geodetic satellite for one millimeter accuracy, Advances in Space Research 65 (2020) 2276-2289, May



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