Calibration

Techniques/Targets

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Experience and Results of the 1991 MTLRS#1 USSR Campaign

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Abstract. In the fall 1991 the Modular, Transportable Laser Ranging System MTLRS#1 was operating in the USSR for collocation of the SLR systems in Riga, Simeiz and Kazivelli. In this paper we will summarize the results of the collocation experiments and we will show our (positive and negative) experiences, we got during this campaign in the USSR).

1. Introduction

The year 1991 was a special year for the mobile laser ranging systems. Due to the scheduled upgrades of the Modular Transportable Laser Ranging Systems MTLRS#1 (operated by the IfAG, Germany) and MTLRS#2 (operated by the OSG Kootwijk, Netherlands) neither a WEGENER-MEDLAS nor a Crustal Dynamics Project campaign was carried out in 1991.

After the successful upgrade of MTLRS#1 in the first half of 1991 (P. Sperber et al.) the system departed from Wettzell in August to make maesurements at two sites in the USSR.

In Riga/Latvia we operated close to the fixed SLR system, in Simeiz/Ucrainea the place for MTLRS#1 pad was choosen to collocate the two fixed SLR station in Simeiz (300 m distance to MTLRS#1) and Kazivelli (about 3 km distance).

2. Results

An overview about the number and quality of the MTLRS#1 passes is shown in Fig. 1 and Fig. 2.

The system arrived in Riga during week 32. Because the crew was not yet familiar with some new parts of the system, which were installed during the upgrade, it took some days, before the first data were collected successfully.

In week 34 we were faced with a problem, we never had before: In moscow parts of the soviet army putsched against gorbatchov. Due to the unclear and dangereous political and military situation we had to stop our observations again for nearly one week.

During the rest of measurements in Riga we were faced with extremely bad weather conditions. All this problems are showing in an unusual poor performance of MTLRS#1 in Riga. Neither the quantity (number of passes per week) nor the quality (number of normalpoints per pass) was completely satisfying.

After 43 Lageos passes we stopped the observations in Riga on October 3 rd and moved the sytem to Simeiz.

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Here the system was able to show its habitual performance. After 53 Lageos passes with more than eleven normalpoints per pass in average the campaign was finished on November 23 rd.

The computation of the collocation was performed by the computing center of the IfAG in Frankfurt/Main. The results are summarized in Fig. 3 - Fig. 5.

Fig. 3 shows the results of the Riga collocation. We got 16 simultaneos Lageos passes with a R.M.S. of 20 cm at the Riga system and 1 cm or 2 cm at MTLRS#1 depending whether a PMT or a single photon avalanche diode (I. Prochazka et al., P. Sperber et al.) was used as receiver.

Out of this 16 passes six passes with good residual overlap (for example: Fig. 4) were selected to calculate the range and epoch bias of the Riga SLR system. There is a small negative tendency in both biases, but compared to the error values and the R.M.S. of the Riga system we can't find a significant bias.

Fig. 5 summarizes the results of the collocation in Simeiz. Because of problems, the fixed stations only were able to observe few passes during the collocation, but all of the passes were simultaneous with MTLRS#1.

The data of the fixed stations are not yet delivered to the network, so until now a computation was not possible.

3. Experience

In this chapter we will summarize our experience during the on-site operartion and the transport of a dedicated geodetic system in the USSR.

2.2. Operation on stations

From the operational point of view there were no problems as long as the system was working near stations. All our requirements concerning electrical power, safety, infrastructure, etc. were fullfilled. In Riga also the supply of fuel and the hotel accomodation were satisfying.

On all stations an independent communication facility like Inmarsat is necessary. The only local data channnel is a very unreliable telex line.

In Simeiz, the hotel, food and fuelsituation is very inconvenient:

- A hotel near the station is far under western standard, an acceptable one is more than 40 km away.
- For fuel a big spare tank is necessary, because fuel is not always available.
- As there are no restaurants near the station, facalities are needed to prepare own food

Additionally most of the people only speak russian language.

In spite of this problems, the operation of a slr system near fixed stations is always possible, if some preparations are made to facilitate the life of the crew members.

2.2. Transport between stations

During the transport of a system from one station to the other the situation becomes very bad compared to the operation on stations.

- Communication channels to foreign countries are not available in short time
- Hotels only exist in big cities. Sleeping facilities for all persons in cars (caravans) are strongly recommended because most of the hotels are full without reservation four weeks in advance.

- Food is only available in hotels, so there are facilities necessary to cook in the cars.
- Security is a big problem, day and night guards are absolutely necessary.
- Fuel is not always availble, therefor big fuel tanks are needed in the cars.
- Car repair is possible, but takes a lot of time and you should have all spare parts with you.

The poeple only speak russian (or sometimes german), but are very friendly and will always try to help if there are problems.

3. Summary

In the second half of 1991 the MTLRS#1 was operating successfully in Riga and Simeiz to collocate the fixed laser ranging stations on this places.

The results of the collocation shows no significant problem at the Riga fixed slr station. The collocation in Simeiz is not yet computed.

To operate and transport a dedicated geodetic system like MTLRS#1 in in the underdeveloped regions of the USSR big efforts and preparations are necessary to become as independent as possible from the local infrastructure.

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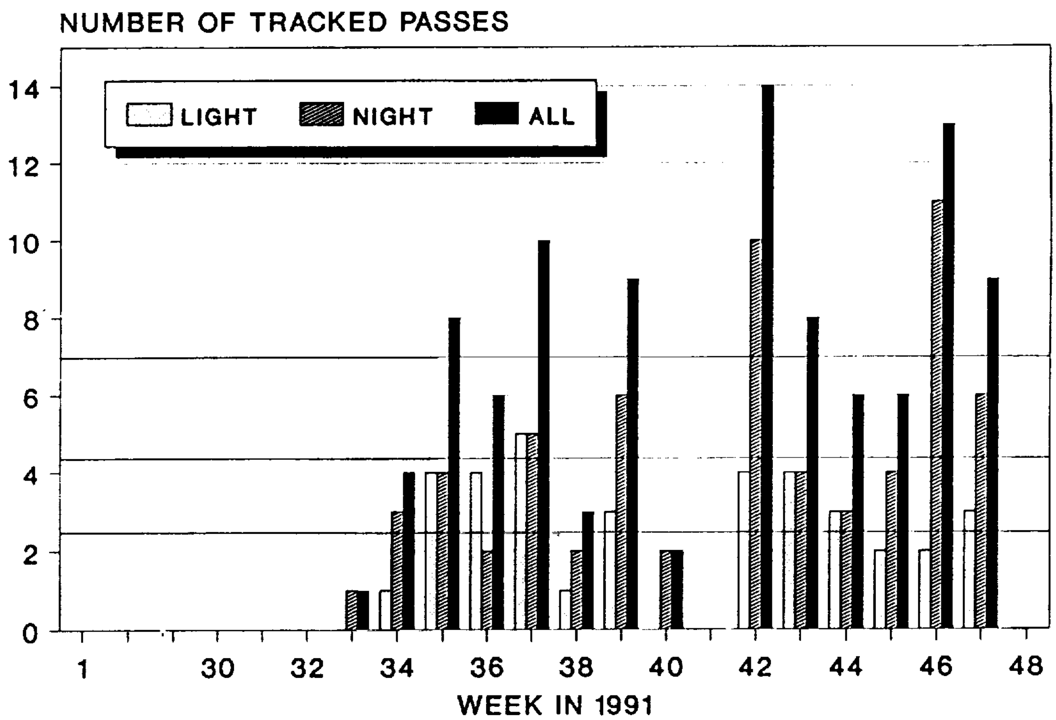

Fig. 1 Number of Lageos Passes in Riga and Simeiz

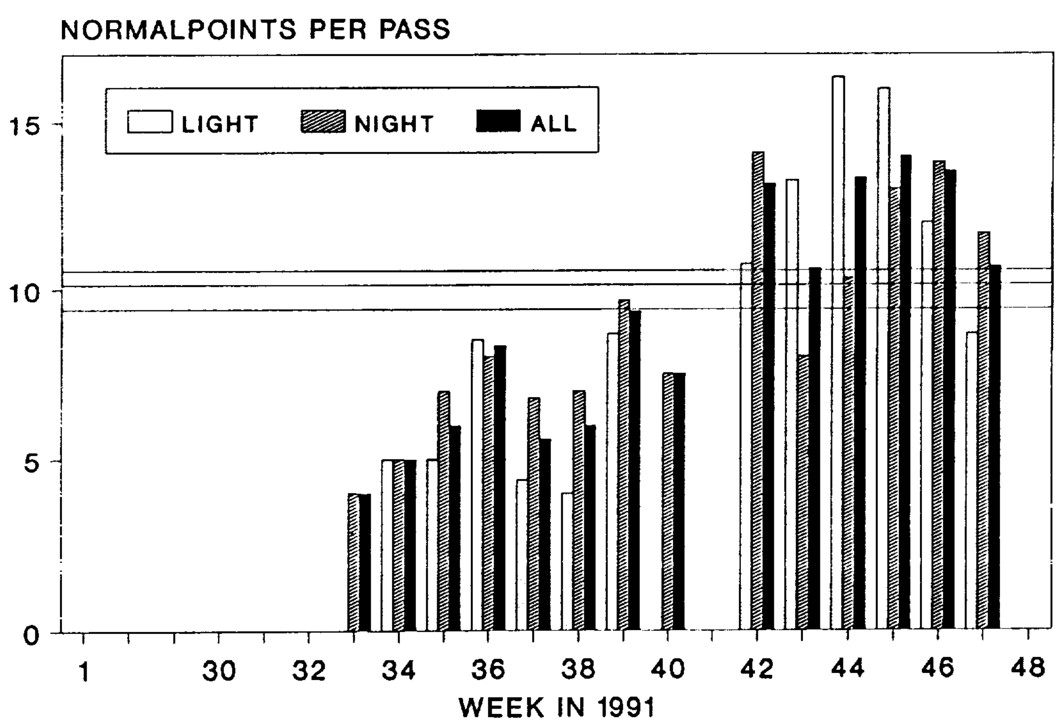

Fig. 2 Number of Normalpoints per Lageos pass in Riga and Simeiz

Results

Riga (1884)	MTLRS#1 (7560)
15868 Returns	27166 Returns (43 Passes)
R.M.S. 20 cm	1 cm (SPAD) - 2 cm (PMT)

Aug. 15 - Oct. 10

16 Simultaneous Passes

Range Bias 7560-1884 in cm	Epoch Bias 7560-1884 in microsec
-6.1	-24
-2.5	-30
-5.1	-58
-16.3	-23
-0.4	-4
-8.4	+66
-6.5 cm +- 5 cm	*-12 microsec +- 30*

Fig. 3 Results of the collocation in Riga

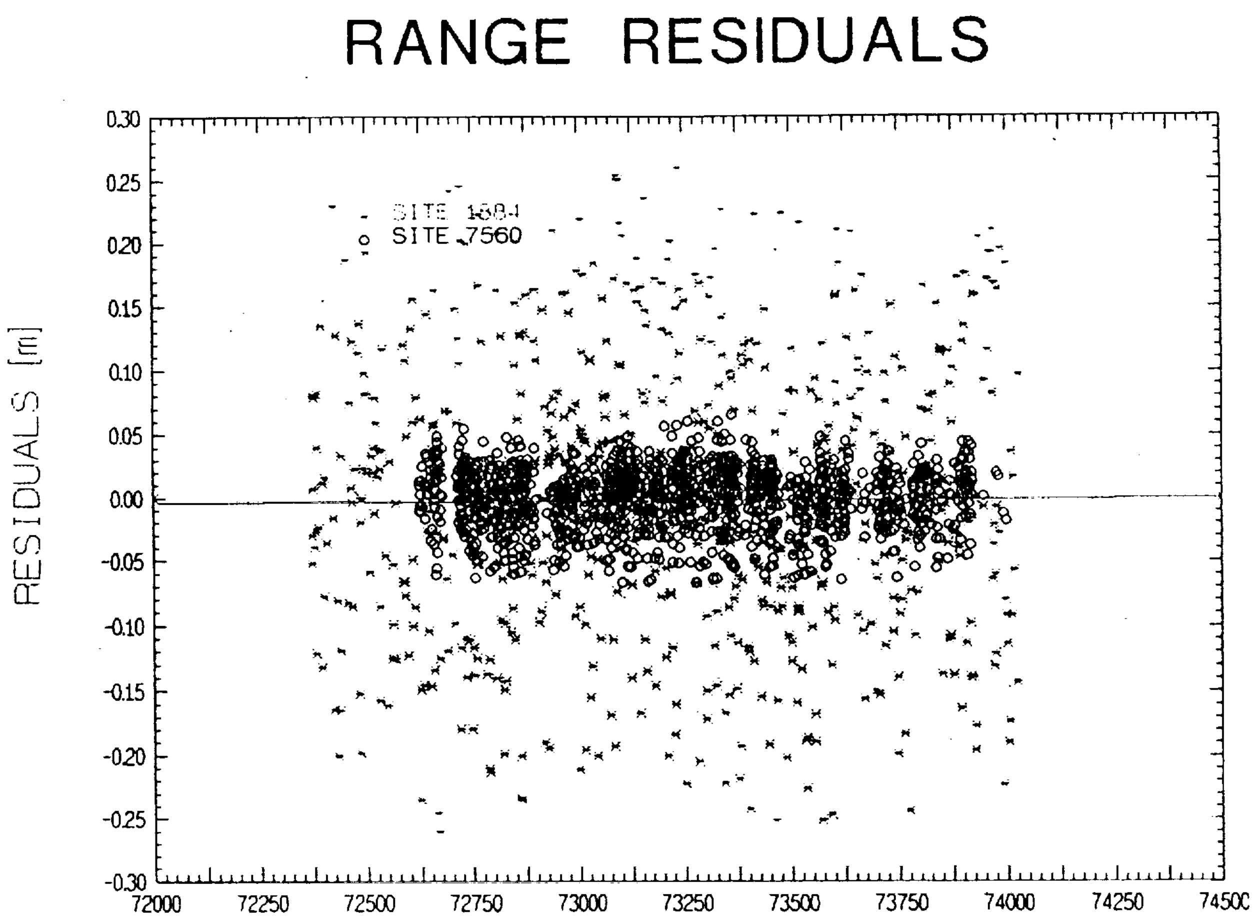

Fig. 4 Example of a Residual plot of a collocation pass between MTLRS-1 and the Riga fixed SLR station

Results

Simeiz (1873)	Kazivelli (1893)	MTLRS#1 (7561)
R.M.S. 10 cm	10 cm	1 cm - 2 cm
10 Passes	20 Passes	53 Passes

Oct. 14 - Nov. 23

Data not yet processed

Fig. 5 Results of the collocation in Simeiz

ETALON-1,-2 CENTER OF MASS CORRECTION AND ARRAY REFLECTIVITY

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ABSTRACT. Center of mass correction to be applied to measured ranges to the ETALON-1,-2 satellites are considered. Numerical values of the correction and reflectivity from retroreflector array are computed. The variations of these values with satellite orientation are investigated.

1. INTRODUCTION

In 1989 two identical passive satellites, ETALON-1,-2, developed for precise laser ranging measurements were launched in the Soviet Union into nearly circular high orbits (about 20,000 km). It was reported that the distance between the center of mass and the plane of probable reflection is 558 mm ,Tatevian,1989.

To evaluate the ETALON-1,-2 satellites for Earth rotation applications, the International Earth Rotation Service (IERS) Directing Board has announced an SLR campaign for the tracking of these satellites. The campaign took place for three months period from September 1, 1990 to December 1, 1990.

To discuss the various aspects of analysis of the ETALON-1,-2 laser ranging data carried out at the number of scientific center, the Institute of Astronomy of the USSR Academy of Sciences and the Soviet Mission Control Center organized the International symposium "ETALON-91" which took place in Moscow during June 3-9, 1991. Recognizing the requirement for precise information characterizing the ETALON-1,-2 satellites, the participants of the International Symposium meeting in Moscow recommended

1) that complete design and orbit insertion information on the ETALON-1,-2 satellites be released to the analyst participat-

ing in the international programs,

2) that the international community undertake experiments to measure ETALON satellite characteristics, such as spin rate and direction, photometry, calorimetry and other.

We undertook the study of the center of mass correction and array reflectivity of the ETALON satellites in order to ensure their accuracy.

2. OPTICAL CUBE-CORNER SPECIFICATIONS

The optical cube corners on ETALON-1,-2 satellites have hexagonal entrance faces, each with a width of 27.0 mm across flats. The length from vertex to face is H=19.1 mm. The optical cube-corners are made of fused silica and the reflecting faces are aluminium coated. The index of refraction of the fused silica is n_1= 1.455442 at λ_1=0.6943 μm and n_2=1.460915 at λ_1=0.5320 μm.

The dihedral angles between the back faces have offsets in order to compensate for velocity aberration. The divergence of the cube corner is about 32 μrad for half-maximum level.

3. GEOMETRY OF THE ARRAY

The ETALON satellite is a sphere 1294 mm in diameter with 2146 retroreflectors distributed over the surface (Figure 1). Six of the cube corners are made of germanium for infrared wavelength and the others 2140 are made of fused silica for use at visible wavelength.

The optical cube corners are arranged in 306 lattice frame with 7 cube corners in each one. The lattice frame are mounted over 14 separated zones. Their orientation is shown in Figure 2. The distribution of the lattice frames and cube corners over the zone is illustrated in Figure 3. Table 1 lists such distribution for each zone.

The cube corners are recessed below the surface of the sphere by 5.5 mm. This recession, together with the fact that the front face of a cube corner is flat, places the center of the front face of the cube corner closer to the center of the satellite than 647.0 mm radius of the satellite.

Table 1. Distribution of the cube corners through zones
(+:Yes; O:No)

System of cube corners	A_1	A_2	A_3	A_4	A_5	A_6	$Б_1$	$Б_2$	$Б_3$	$Б_4$	B_1	B_2	B_3	B_4
0	+	0	+	0	+	+	+	+	+	+	+	+	+	+
0.1–0.6	+	+	+	+	+	+	+	+	+	+	+	+	+	+
1.–3.	+	+	+	+	+	+	+	+	+	+	+	+	+	+
4.1–4.3	0	0	0	0	0	0	+	+	+	+	+	+	+	+
4.4; 4.5	0	0	0	0	0	0	+	+	+	+	+	+	+	+
4.6	0	0	0	0	0	0	+	+	+	+	+	+	+	+
Number of cube corners	133	132	133	132	133	133	175	175	175	175	161	161	161	161

4. OPTICAL CUBE CORNER REFLECTIVITY

The reflectivity E of the ETALON-1,-2 optical cube corners is given below as a function of incidence angle. The angle Φ is measured from the normal N to the front face, and the angle A^1 is the angle to the projection of the incident beam onto the front face; both these angles are shown in Figure 4,5. The variations of the cutoff angles for reflection Φ_c (and refracted angle Φ_c^1) with the azimuth A^1 are illustrated in Table 2 and Figure 6. These variations repeat every 60^o in A^1 and the values Φ_c for 30^o-A^1 are equal to those for 30^o+A^1.

Table 2. Cutoff angles for reflection Φ_c as a function of azimuth A^1

A^1, deg	Φ_{c1},deg	Φ_{c2},deg	Φ_c^1, deg
0	66.965	67.479	39.220
10	61.031	61.421	36.949
20	58.064	58.410	35.667
30	57.147	57.482	35.253

In computing the reflectivity E it was assumed that the cube corners had perfect-metal reflecting faces and no dihedral-angle offset. In Figure 7 each curve is the calculated total reflectivity and is proportional to the active reflecting area.The curves include reflection losses at the front face in entering and leaving the cube corner by laser beam. All curves are normalized to unity at normal incidence. The active reflecting area at normal incidence is 631.33 mm^2 for a hexagonal cube corner whose width W=27.0 mm across flats. The active reflecting area and the reflectivity repeat every 60^o in A^1 In additional, the values E for 30^o-A^1 are equal to those for 30^o+A^1. The curves for the two different wavelengths are fairly similar. The results were used to calculate the center of mass correction and array reflectivity.

5. ARRAY COORDINATE SYSTEM

The coordinate system used to describe the geometry of the array is as follows (Figure 8).As a rule the position and orientation of each cube corner in the array are given by the six numbers: x, y, z B,L,A. The origin of the x-y-z coordinate system is in the center of satellite. X,Y and Z are in the directions of the centers A_1, A_3 and A_2 zones respectively. The angles B and L are given in an $x^1-y^1-z^1$ coordinate system, which is parallel to the x-y-z system and the origin is in the center of front face of each cube corner. The azimuth angles A are given in $\xi-\eta-\zeta$ coordinate system. Its origin is at the center of the front face, its ξ axis normal to the front face, ζ in the direction of increasing B, and η in the direction of increasing L. The orientation angle A is measured counterclockwise from ζ axis to the projection of one of the back edges of the cube corner onto front face, as shown in Figure 8.

The direction of the incident beam V in the array coordinate system is given by the angles φ and λ: both these angles are shown in Figure 8. To compute the incidence angles Φ and A^1 on the cube corner, the vector V must be expressed in the $\xi-\eta-\zeta$ coordinate system (Figure 8). The conversion between the coordinate systems of the array and incident beam is accomplished by rotating the coordinate system of V first about the z-axis by the angle L unticlockwise and then about new y-axis by the angle B clockwise.

For the ETALON-1,-2 cube corners the angles A are unknown but the cube corners have been installed so as to give a uniform diffraction divergence independent of satellite orientation. The divergence of the retroreflector array is about 42 μrad for half - maximum level. Taking into account these aspects and the total reflectivity of the ETALON-1,-2 optical cube corners and their recessions,the active reflecting area of each retroreflectors has been averaged for $A^1=0^o, 1^o,...,30^o$.

6.METHOD OF COMPUTING THE CENTER OF MASS CORRECTION

The center of mass correction to be applied to measured ranges is the distance of the centroid of the computed total energy of the return from the center of gravity of the satellite. Computation of the range correction includes a correction for the optical path length of the ray within the cube corner. The correction listed is the one-way correction

$$\rho = \sum_{k=1}^{N} \rho_k E_k \Big/ \sum_{k=1}^{N} E_k$$

where ρ_k is the distance of the apparent reflection point for the k-th retroreflector from the plane through the center of mass of the satellite perpendicular to the incident beam. Constant E_k giving the intensity of the reflection from the k-th cube corner is proportional to the active reflecting area. N is the number of the cube corners contributing to the reflected signal.

The apparent reflection point as a function of the angle Φ between the incident beam and the normal to the front face of the cube corner is given by the expression

$$\rho_k = r\cos\Phi_k - H\sqrt{n^2-\sin^2\Phi_k} ,$$

where r=distance from the center of the satellite to the front face of the cube corner (641.7 mm), Φ_k=the incidence angle on the k-th cube corner, H=the length of the cube corner (19.1 mm), n=the index of refraction.

In computing the center of mass correction ρ and array reflectivity $E(=\sum E_k)$, the cube corners have been modeled as isothermal, geometrically perfect reflectors with perfect reflecting coatings on the back faces. The reflection losses at the front face as the laser beam enters and leaves the cube corners are taken into account.

7. APPARENT REFLECTION POINT AND SPREAD IN RANGE

The cube corners contributing to the reflected signal are contained in a spherical cap whose angular radius (half angle) is the cutoff angle of the cube corner. The earliest possible reflection would come from a reflector directly facing the incident beam, and the latest, from a cube corner near the cutoff angle. Apparent spread in range is the difference between the apparent reflection points for these two cases along the direction of illumination.

Since the cube corners are nonuniformly distributed over the sphere of the ETALON-1,-2 and recessed below the satellite surface there are variations of the earliest and latest reflection points. Table 3 lists the apparent reflection points along the line of sight measured from the center of satellite for various cases: 1) the earliest possible reflection point (a cube corner whose face is normal to the incident beam); 2) the earliest point where an incident beam in the center of A_2 zone could be up to about 4^o from nearest cube corner (replacing an optical cube with an germanium cube); 3) the earliest point where an incident beam could be up to about 8^o from the nearest cube corner (replacing two lattice frame of 14 cube corners with the supporting holder); 4) the last possible reflection point where the active reflecting area goes to zero; 5) the last possible reflection point where there is a sharp decrease in reflectivity because of the recession of the cube corners.

Replacing an optical cube corner in zones A_2 and A_4 with a germanium cubes, which is opaque to visible light, reduces the distance of apparent reflection point by about 1.5 mm. The maximum variation of the earliest reflection point is about 5.9 mm in replacing 14 cube corners with supporting holders in B_1, B_2, B_3 and B_4 zones. The total range spread without taking into account the recession of the reflectors is about 400 mm. The recession reduces the range spread approximately by 2 times. Figure 9 illustrates these results.

Table 3. Apparent reflection points for various incident angles

Φ,deg	λ,μm	n	ρ_k,mm	Reflection point
0	0.6943	1.4554	613.9	Earliest reflection point
0	0.5320	1.4609	613.8	Earliest reflection point
3.9287	0.6943	1.4554	612.4	Nearest to the center A_2 zone
3.9287	0.5320	1.4609	612.3	Nearest to the center A_2 zone
7.8574	0.6943	1.4554	608.0	Nearest to the supporting holder
7.8574	0.5320	1.4609	607.9	Nearest to the supporting holder
43.6000	0.6943	1.4554	440.2	Latest recession reflection point
43.6000	0.5320	1.4609	440.1	Latest recession reflection point
66.9650	0.6943	1.4554	229.6	Latest of cutoff angle reflection
67.4790	0.5320	1.4609	224.2	Latest of cutoff angle reflection

8. VARIATION OF THE CENTER OF MASS CORRECTION WITH SATELLITE ORIENTATION

The surface of the ETALON-1,-2 satellites is nonuniformly covered by the cube corners. As a result the center of mass correction and the reflecting properties depend on the satellite orientation. A set of 2522 sampling points were distributed over the surface of the sphere to study the variation of the center of mass correction with ETALON-1,-2 orientation. Table 4 lists these results for two laser wavelengths.

The mean range correction ρ for ETALON-1,-2 is about 576.0mm for all orientations. The standard deviation of range correction $\Delta\rho$ is 3.2mm. The results obtained show the extreme variations in the range correction over all orientations from a high of about 583.4mm to a low of about 567.3mm. The difference between the maximum and minimum range correction is 16.1mm.

The variations of the range correction with the period of 90° in λ coordinate for orientation of the ETALON-1,-2 satellites are due to the symmetry in the configuration of the cube corners from different viewing angles.

Table 4. Variation of the center of mass correction with ETALON-1,-2 orientation

λ_1=0.6943 μm				λ_2=0.5320 μm			
Correction		Orientation		Correction		Orientation	
ρ,mm	$\Delta\rho$,mm	φ,deg	λ,deg	ρ,mm	$\Delta\rho$,mm	φ,deg	λ,deg
583.5	7.5	0	$0+90^0k$	583.3	7.5	0	$0+90^0k$
567.5	-8.6	-45	$5+90^0k$	567.1	-8.6	-45	$5+90^0k$
576.1	0.0	45	$75+90^0k$	575.8	0.0	45	$75+90^0k$

where k is digit.

The average range corrections at each longitude and latitude have also been computed to look for systematic effects. Figures 10, 11 illustrate the variations of the range corrections at all longitudes and latitudes. They are contained within 16.1mm interval and have periodical components along φ and λ coordinates.

9. VARIATION OF THE ARRAY REFLECTIVITY WITH SATELLITE ORIENTATION

Array reflectivity over 2522 orientations of the ETALON-1,-2 satellites have been studied. Table 5 lists these results for two wavelengths.

The mean array reflectivity for ETALON-1,-2 is about 65.8 cube corners for all orientations. The standard deviation of the array reflectivity is 3.9 cube corners. The results obtained show extreme variations in the array reflectivity over all orientations from a high of about 74.2 cube corners to a low of about 53.8 cube corners for all orientations. The difference between the maximum and minimum array reflectivity is about 20.4 cube corners that is the variation of the reflected energy is about 30 percents over all orientations.

Table 5. Variation of the array reflectivity with ETALON-1,-2 orientation

λ_1=0.6943 μm				λ_2=0.5320 μm			
Reflectivity		Orientation		Reflectivity		Orientation	
E,c.c.	E,c.c.	φ,deg	λ,deg	E,c.c.	E,c.c.	φ,deg	λ,deg
74.1	8.6	35	$45+90^{o}k$	74.4	8.6	35	$45+90^{o}k$
53.6	-12.0	-45	$5+90^{o}k$	53.9	-12.0	-45	$5+90^{o}k$
65.6	0.0	0	$25+90^{o}k$	65.9	0.0	0	$25+90^{o}k$

where k is digit.

The variations of the array reflectivity with the period of 90 degrees in λ coordinate for orientation of the ETALON-1,-2 satellites are due to the symmetry in the configuration of the cube corners from different viewing angles.

For the purpose of illustrating more detailed studies of the reflectivity properties, the sampling points have been looked at individually to find one whose properties are close to the average for all orientations. The point at $\varphi=45^{o}$, $\lambda=75^{o}$ has nearly the average range correction and reflectivity, so it has been used for above purpose. Figures 12 are histograms of the contribution to the reflected signal from each 1-cm interval along the line of sight starting from the earliest reflection point. The origin of the distance scale is the center of satellite. These histograms are for a direction of illumination given by $\varphi=45^{o}$ and $\lambda=75^{o}$. For this direction the total effective reflecting area is 66.8 times the area of one cube corner, and the mean apparent reflection point is 576.0mm from the center of the satellite. The cube corner shown on the histogram is the closest possible position to the observer.(None of the cube corner points exactly at the observer for this particular direction of illumination. The earliest and latest apparent reflection points for this case are 613.5mm and 440.7mm, respectively). Table 6 lists the data used to plot the histogram: the equivalent number of cube corners at normal incidence, the percentage of the total return and the cumulative percentage in each 1-cm interval,starting from the earliest reflection point.

Table 6. Total return in each 1-cm interval starting from the earliest apparent reflection point

Interval	Equivalent number of cube corners		% of total return		Cumulative %	
	λ_1	λ_2	λ_1	λ_2	λ_1	λ_2
1	16.62	17.24	25.00	25.68	25.00	25.68
2	9.38	7.90	14.11	11.77	39.11	37.45
3	9.22	8.16	13 87	12.16	52.98	49.61
4	5.38	8.87	8.09	13.21	61.07	62 82
5	4.51	5.53	6.78	8.23	67.85	71.05
6	5.23	4.17	7.87	6.22	75.72	77.27
7	3.99	3.58	6.00	5.33	81.72	82.60
8	3.46	3.31	5.21	4.93	86.93	87.53
9	2.78	2.79	4.18	4.16	91.11	91.69
10	2.41	1.98	3.62	2.94	94.73	94.63
11	1.26	1.38	1.89	2.06	96.62	96.69
12	1.21	0.97	1.82	1.45	98.44	98.14
13	0.56	0.77	0.85	1.14	99.29	99.28
14	0.28	0.24	0.42	0.35	99.70	99.63
15	0.12	0.16	0.18	0.25	99.88	99.88
16	0.07	0.06	0.10	0.09	99.98	99.97
17	0.02	0.02	0.02	0.03	100.00	100.00

A quarter of the return energy comes from the first 1-cm interval, over half the return energy comes from the first 3-cm interval, and over 90% comes from the first 9-cm interval. The center of mass correction is at 576.0mm, which is 37.5mm in back of the first reflection point.

The average array reflectivity at each latitude and longitude have also been computed to look for systematic effects. The variations of the average array reflectivity at all latitudes and longitudes are contained within 21 cube corners and have periodical components. Figures 13 and 14 illustrate these regularities. These variations are similar to ones in the range correction of ETALON-1,-2 satellites.

The effects of the recession of cube corners in concentrating the energy and computing the range correction have been studied. The center of mass correction and array reflectivity, if the cube corners were not recessed, would be 540.7mm and 126.53 cube corners respectively.

10. CONCLUSION

The ETALON-1,-2 center of mass correction is about 576.0mm for both laser wavelengths. This value is 18mm more than value which was published by Tatevian,1989. The range correction has periodical peak-to peak variations of about 2 cm with satellite orientation. These peculiarities give the possibility to derive for ETALON-1,-2 spin rate and direction using the precise laser ranging measurements to the satellites with SLR systems of 3-rd generation.

The mean array reflectivity for ETALON-1,-2 satellites is about 66 cube corners. Difference between the maximum and minimum array reflectivity is about 21 cube corners or 30% over all satellite orientations.

Such regularities in ETALON-1,-2 center of mass correction and array reflectivity are due to the symmetry with respect to the X-axis in the dissemination of the cube corners over the satellite surface.

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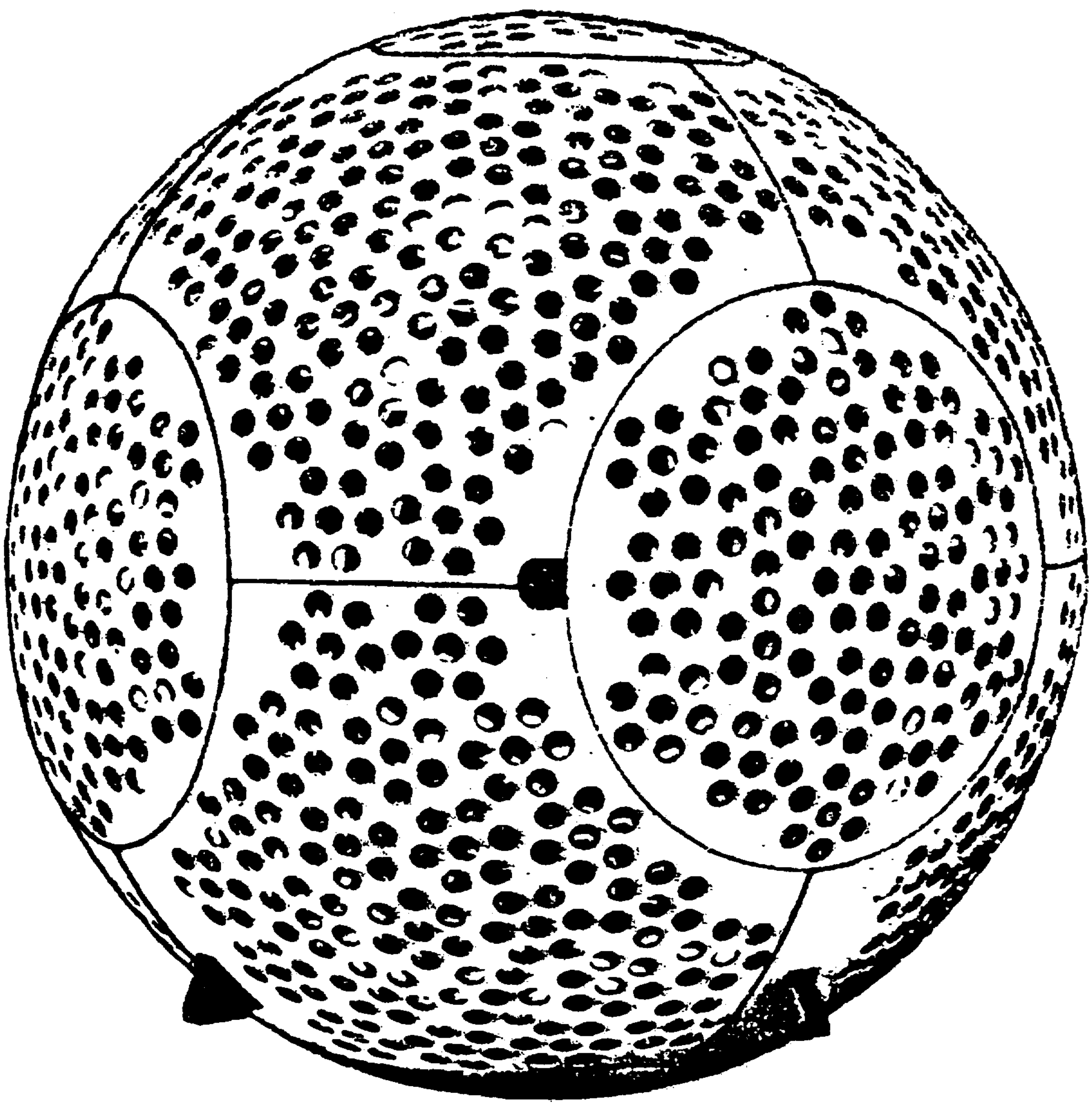

FIG. 1. ETALON-1,-2 SATELLITE

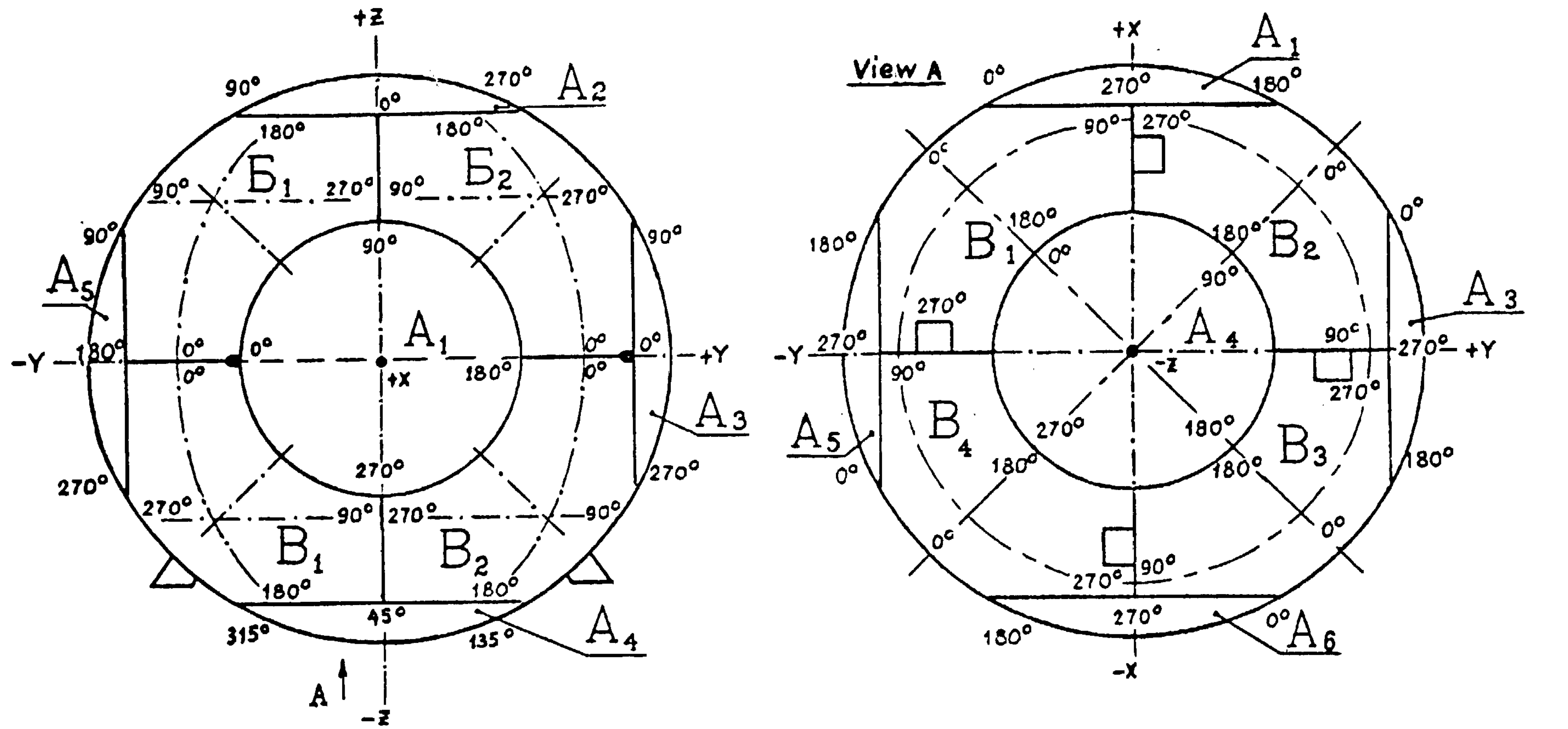

Fig.2. Zones of the retroreflectors and their orientation

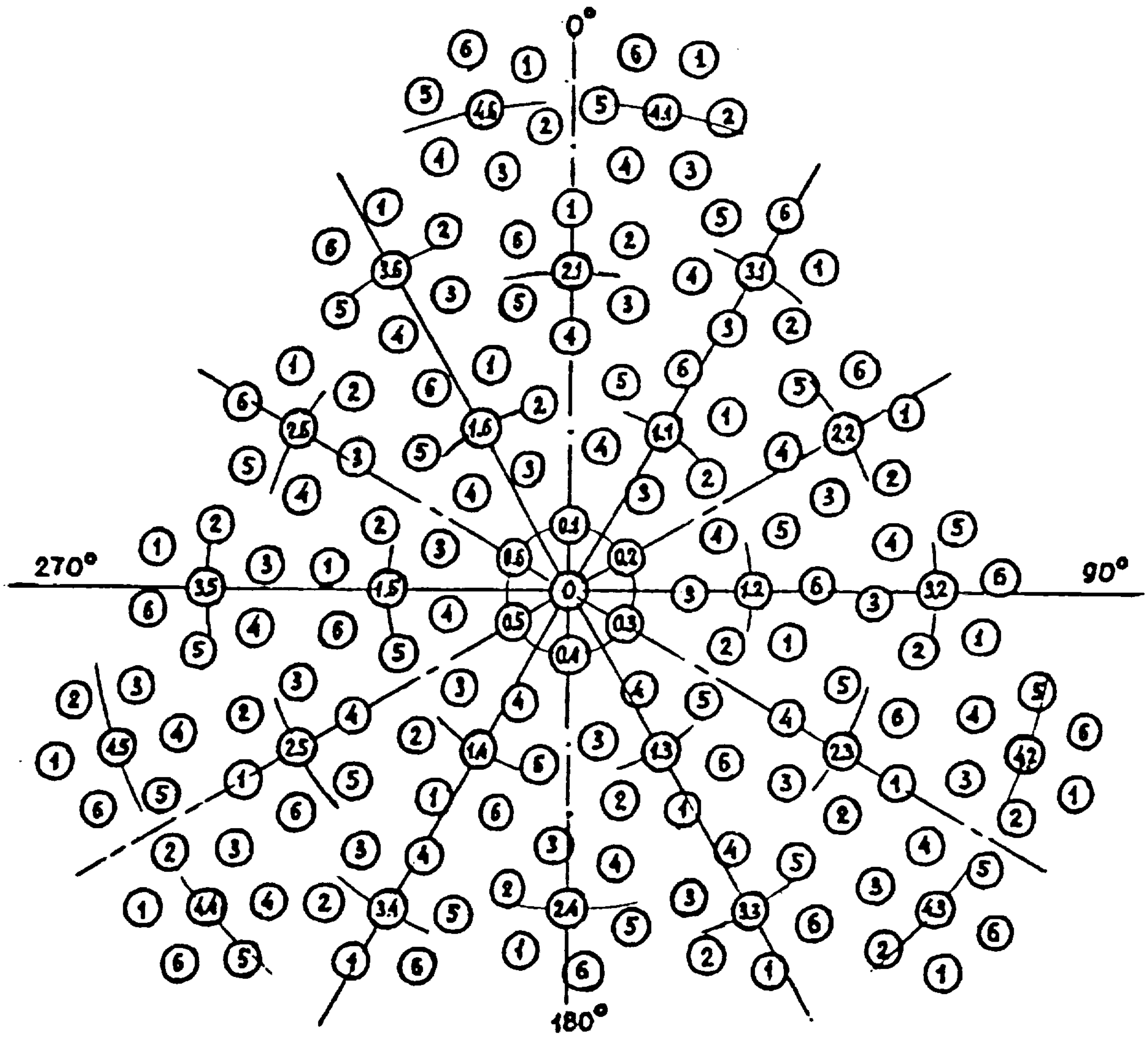

Fig. 3. DISTRIBUTION OF THE LATTICE FRAME AND RETROREFLECTORS OVER A ZONE

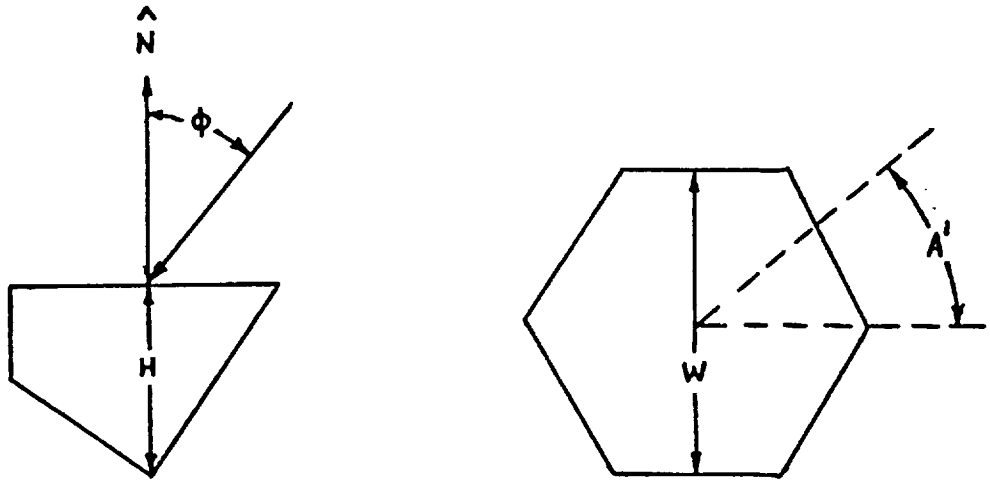

Fig. 4. Direction of incident beam

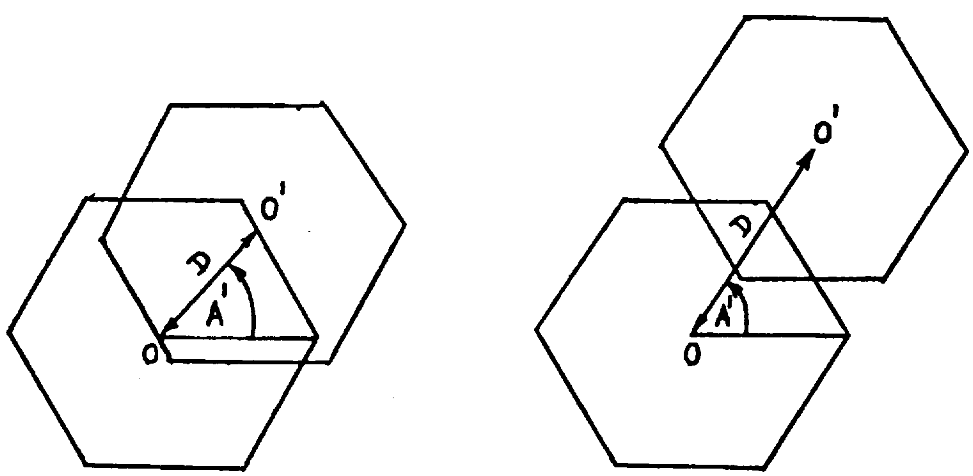

Fig. 5. Active reflecting area: separation of input and output apertures

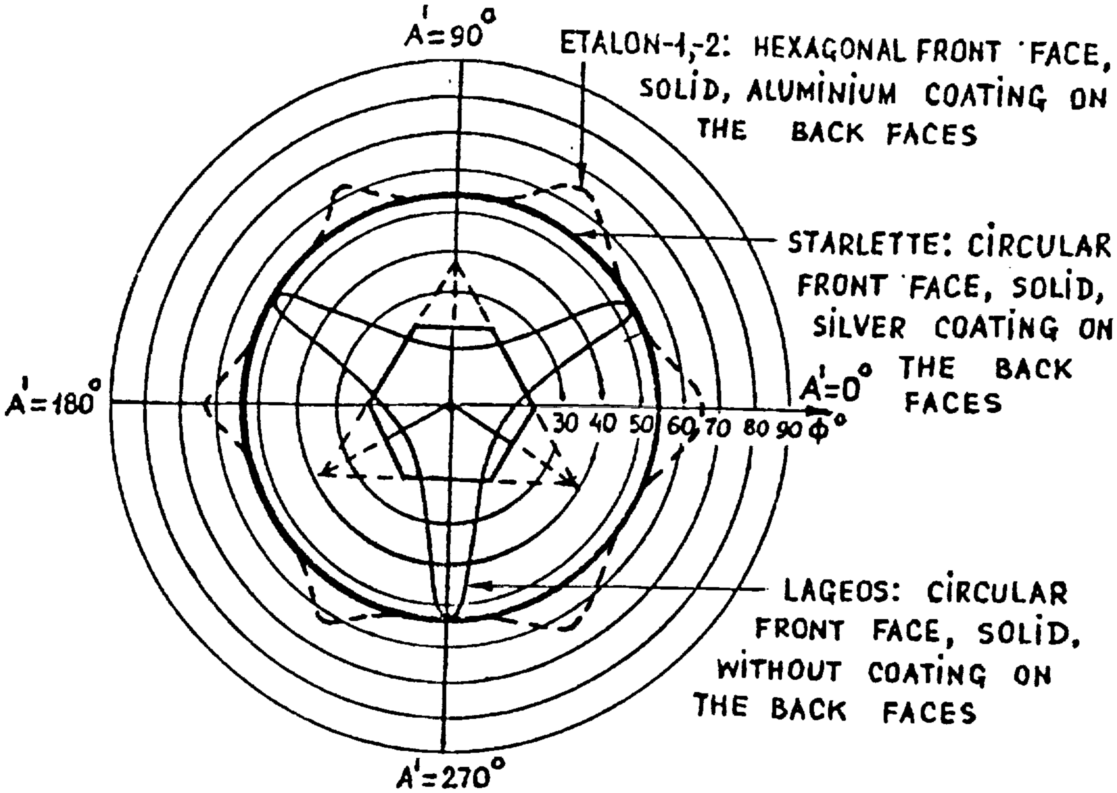

FIG. 6. VARIATIONS OF THE CUTOFF ANGLES FOR REFLECTION Φ WITH THE AZIMUTH A'

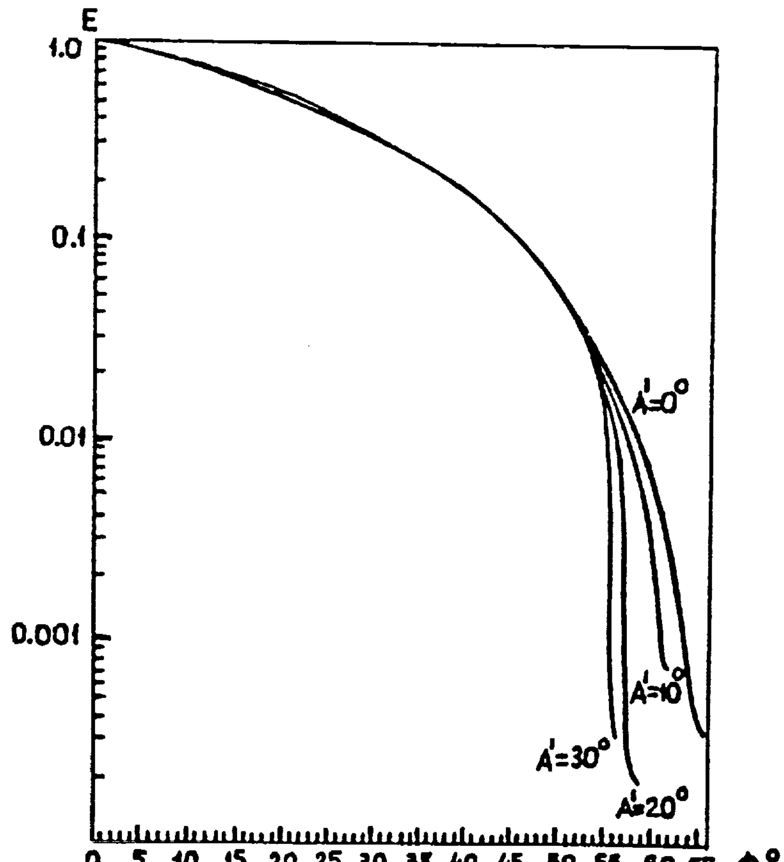

FIG.7. TOTAL REFLECTIVITY OF ETALON-1,-2 CUBE CORNER FOR DIFFERENT AZIMUTHS A', λ=0.6943μm.

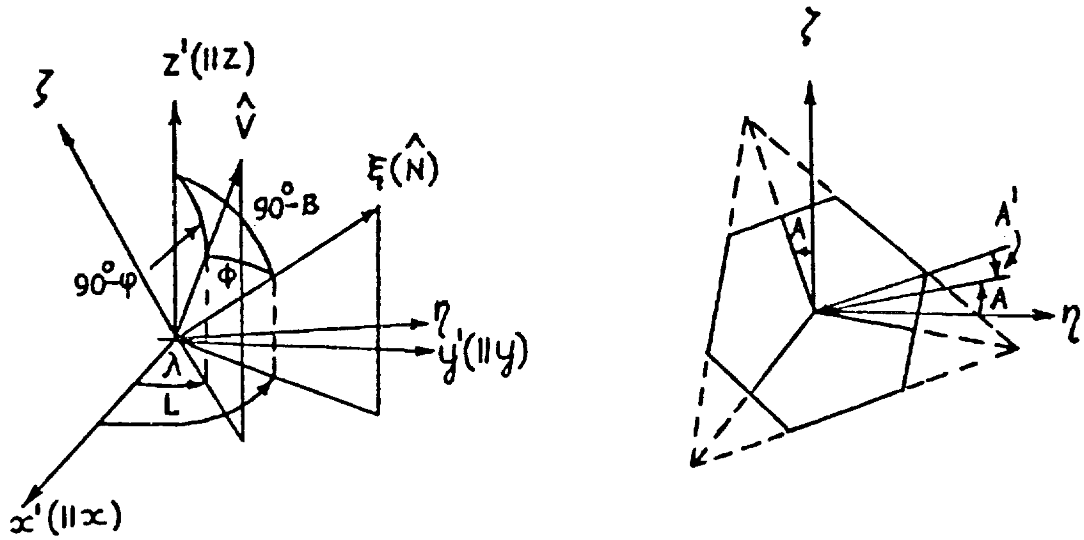

FIG. 8. COORDINATE SYSTEMS FOR RETROREFLECTOR POSITION AND ORIENTATION

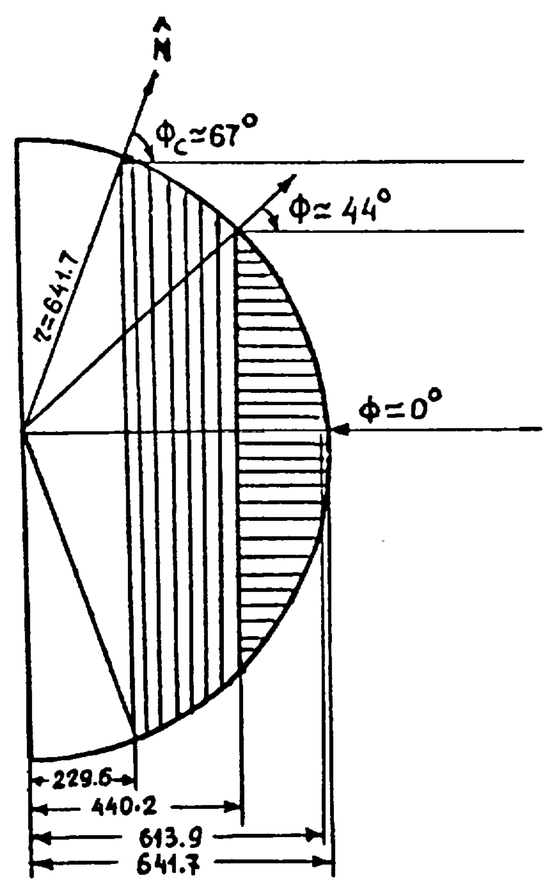

Fig. 9. APPARENT REFLECTION POINTS AND SPREAD IN RANGE

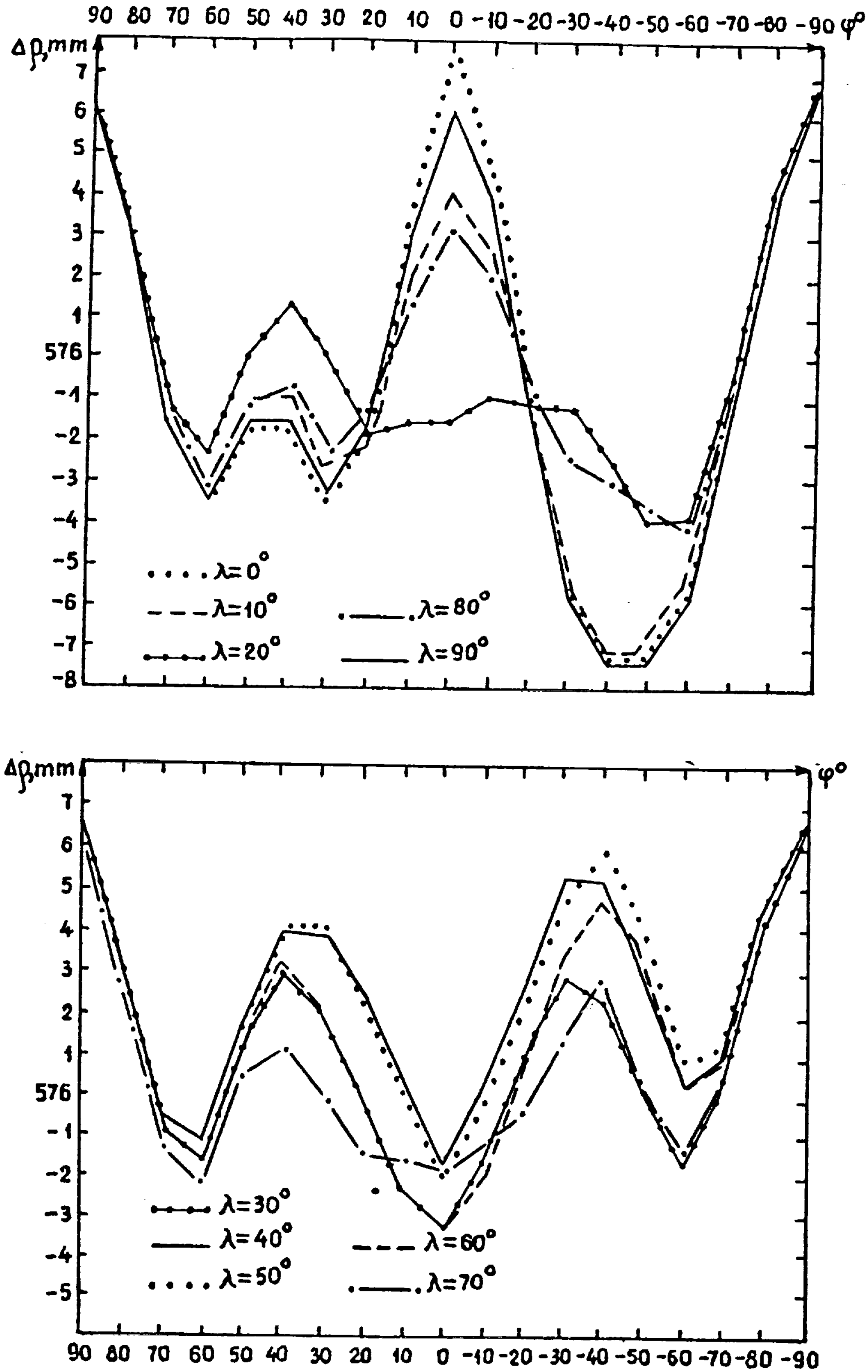

FIG. 10. VARIATION OF ETALON-1,-2 CENTER OF MASS CORRECTION AT EACH LONGITUDE

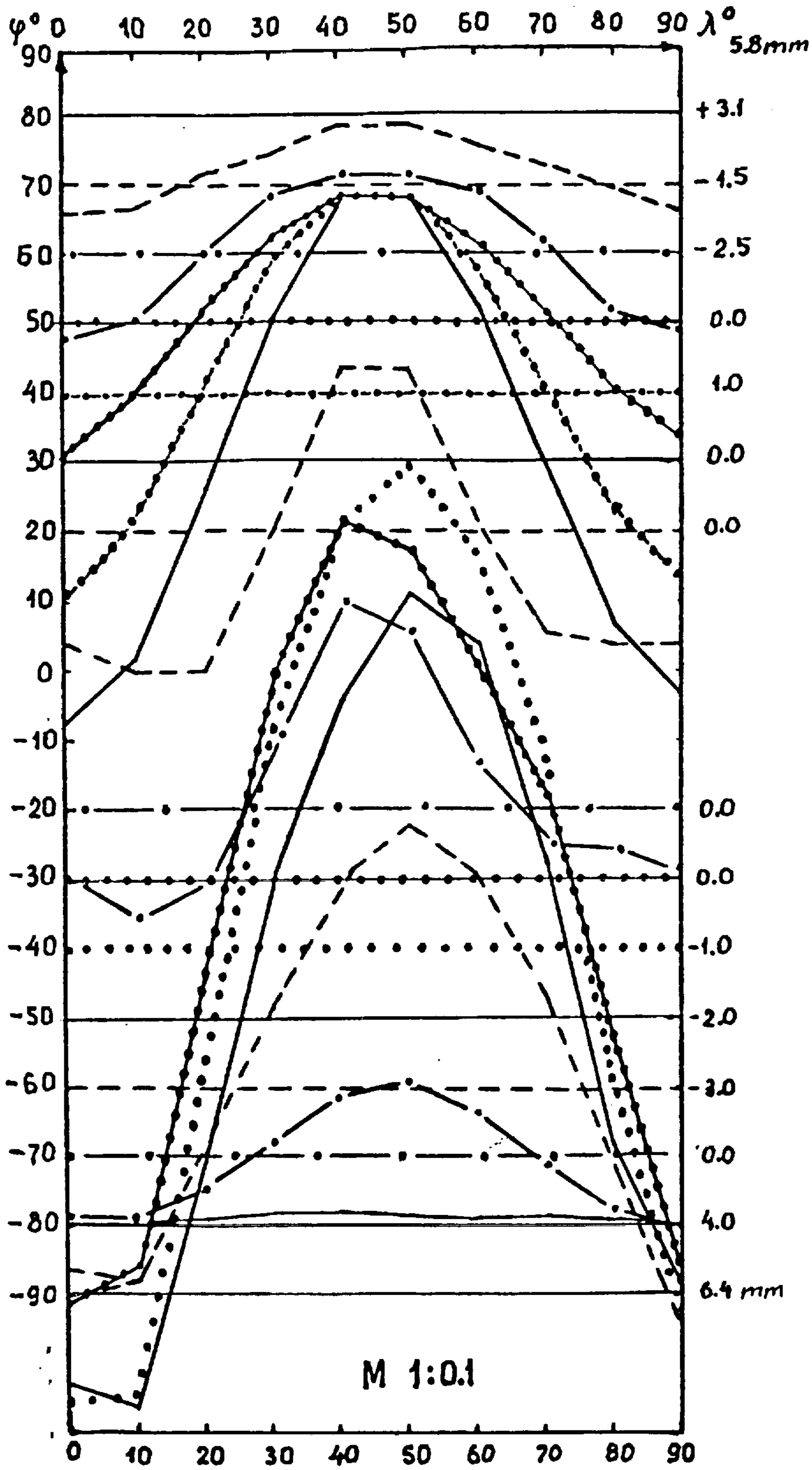

Fig. 11a. VARIATION OF ETALON-1,-2 CENTER OF MASS CORRECTION AT EACH LATITUDE

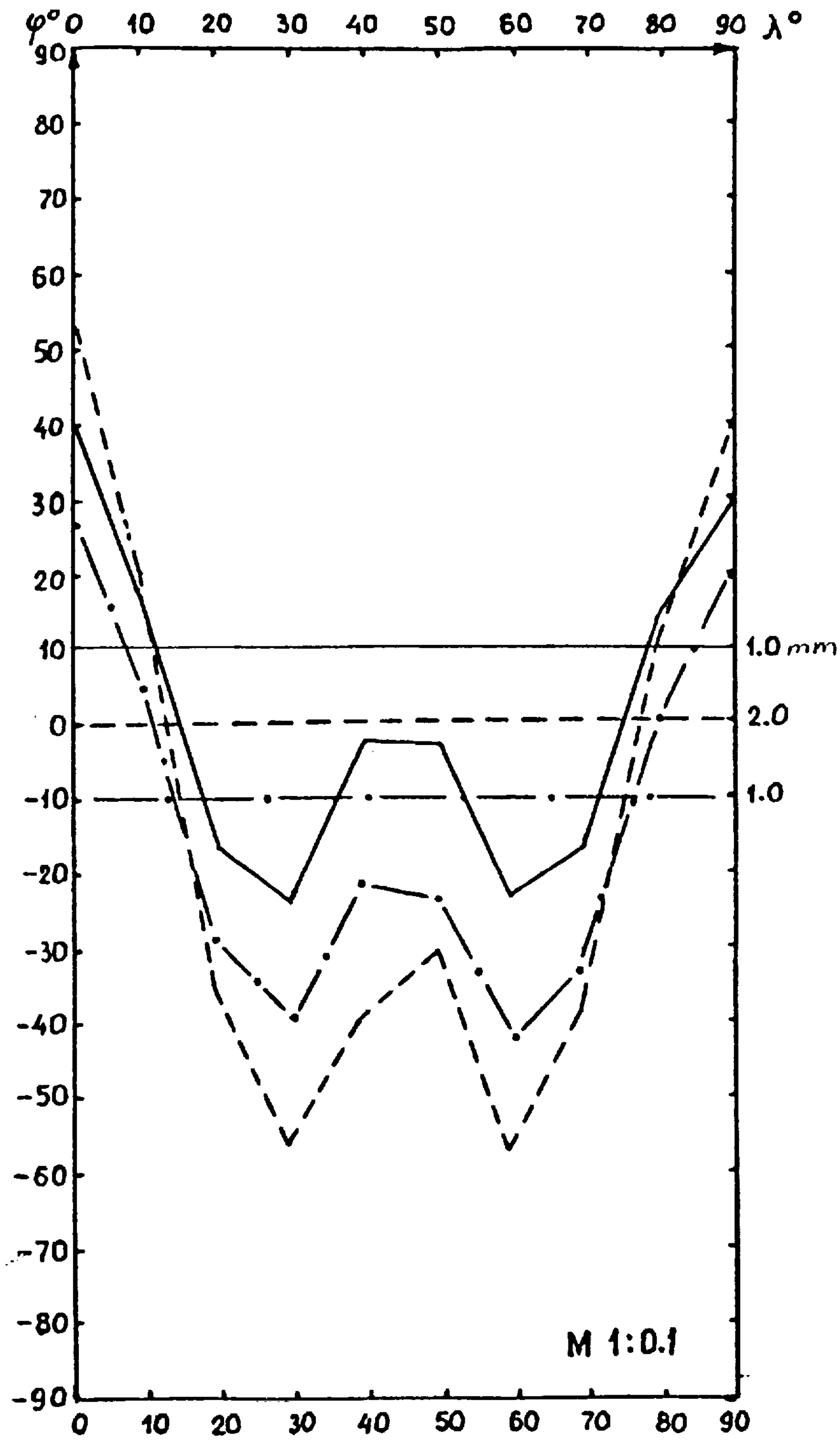

Fig. 11b. VARIATION OF ETALON-1,-2 CENTER OF MASS CORRECTION AT EACH LATITUDE

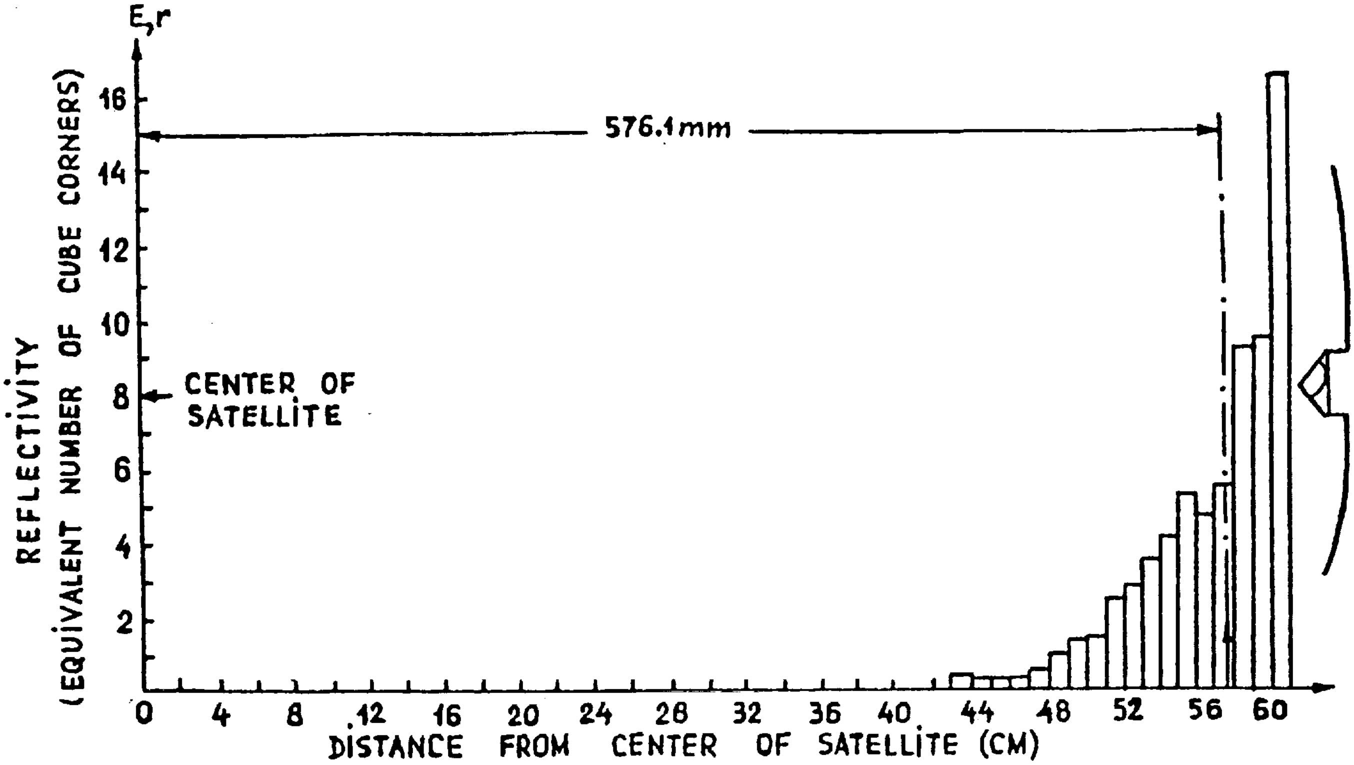

Fig. 12a. Reflectivity histogram of ETALON-1,-2; $\lambda = 0.6943\,\mu m$

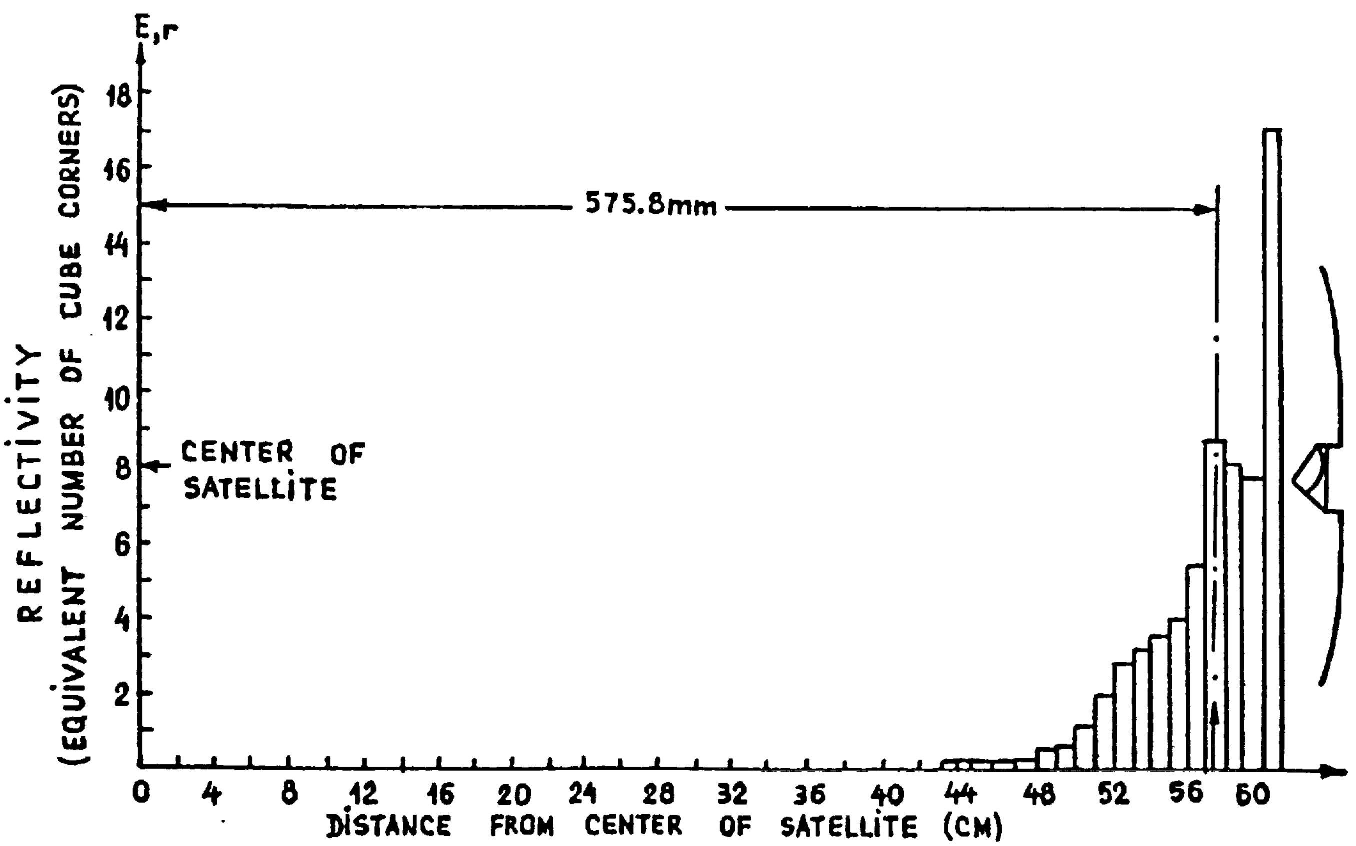

Fig. 12b. Reflectivity histogram of ETALON-1,-2; $\lambda = 0.5320\,\mu m$

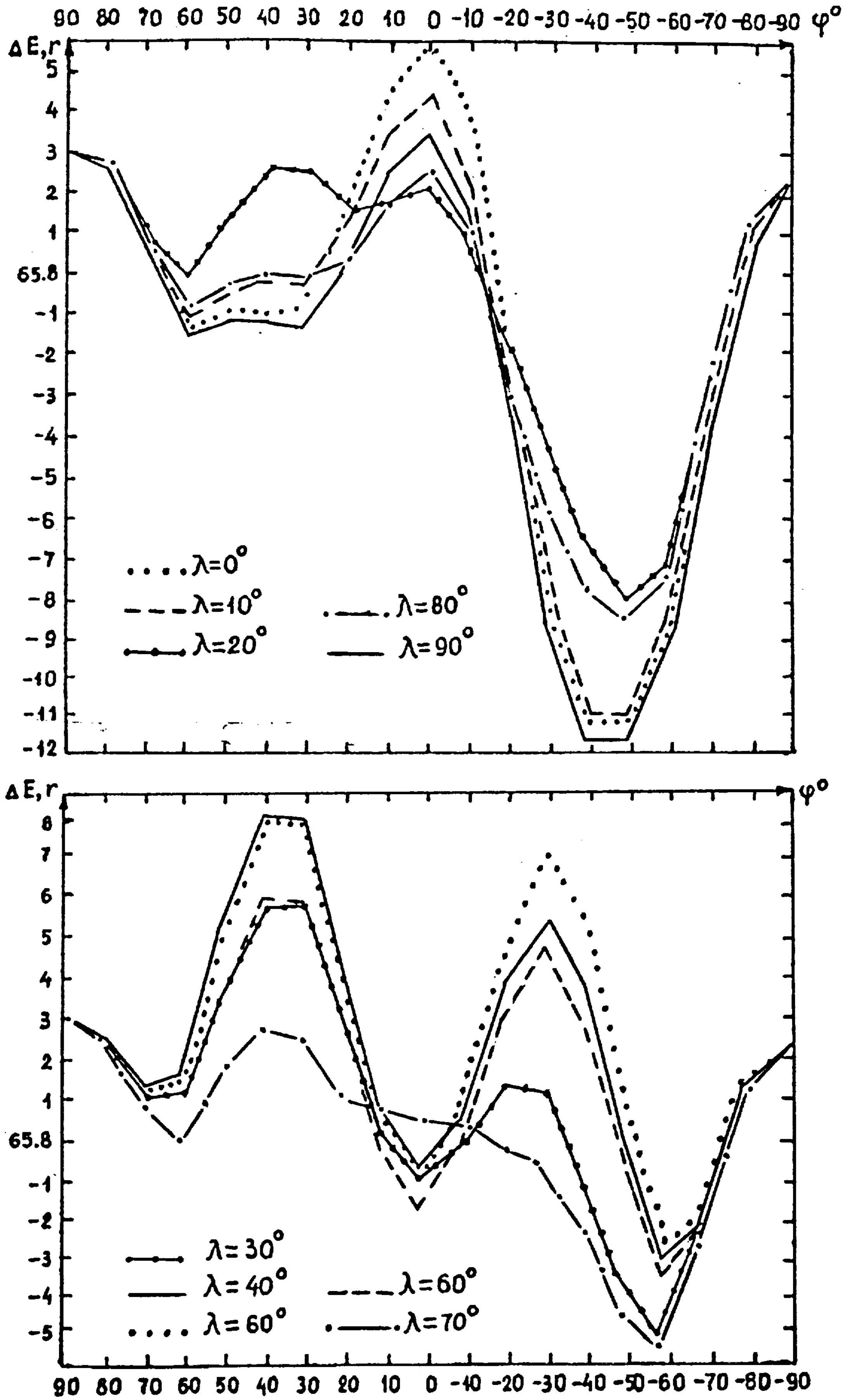

FIG. 13. VARIATION OF ETALON-1,-2 REFLECTIVITY AT EACH LONGITUDE

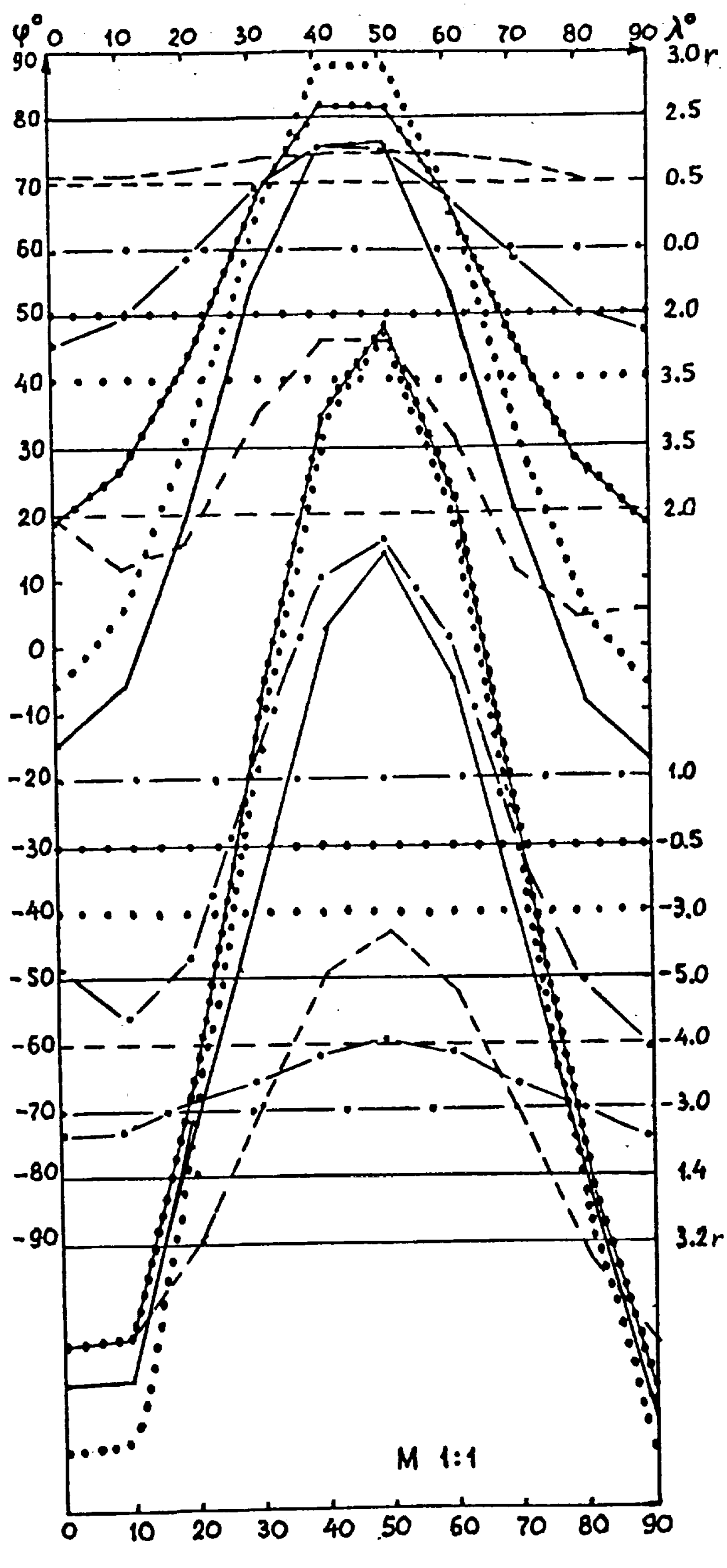

Fig. 14a. VARIATION OF ETALON-1,-2 REFLECTIVITY AT EACH LATITUDE

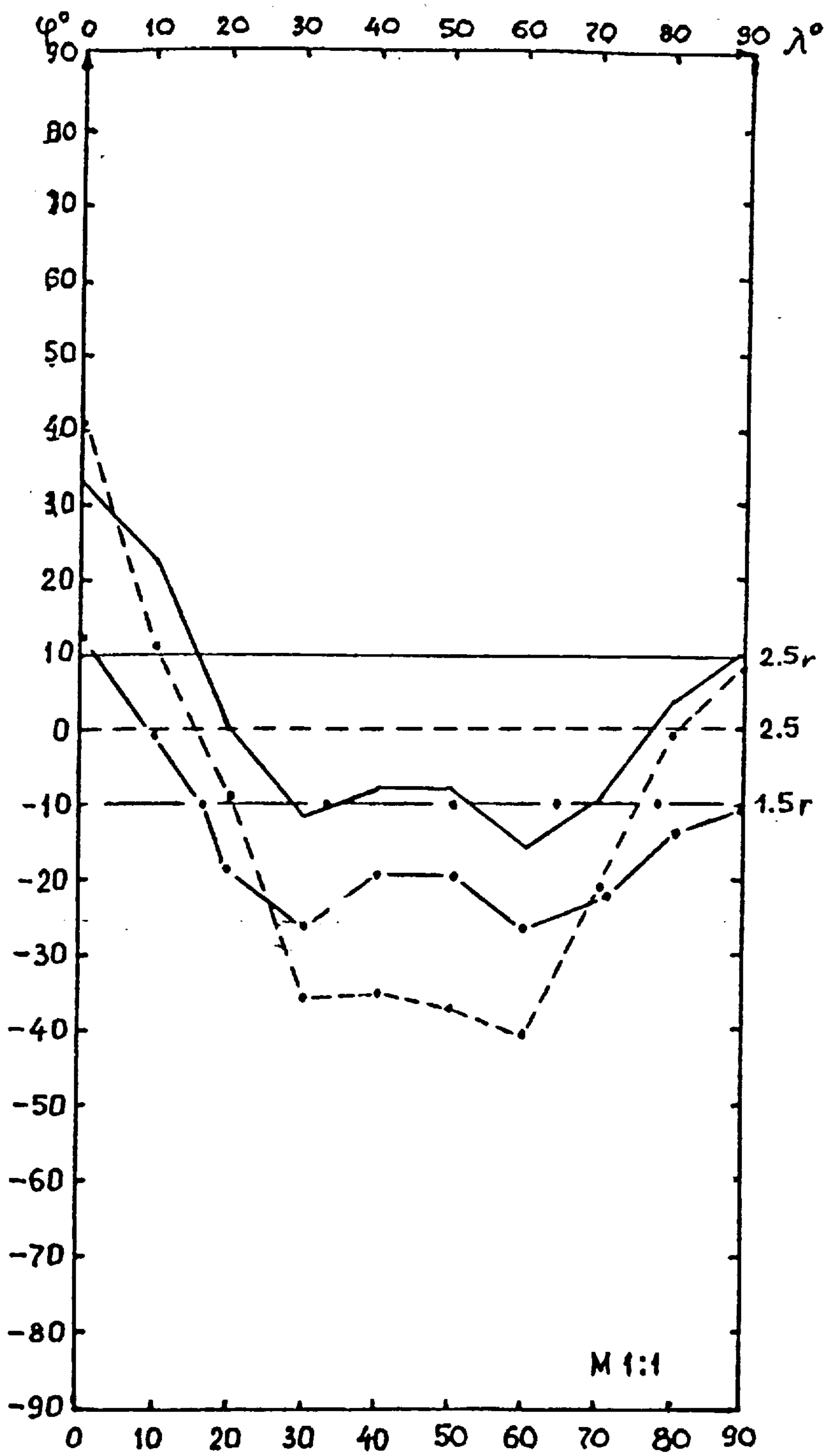

FIG. 14b. VARIATION OF ETALON-1,-2 REFLECTIVITY AT EACH LATITUDE

Test Results from LAGEOS-2 Optical Characterization Using Pulsed Lasers

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Abstract

Laser Geodynamic Satellite (LAGEOS-2) has undergone extensive optical testing at NASA Goddard Space Flight Center during 1989. The techniques included measuring the far field diffraction pattern using cw and pulsed lasers. In the pulsed measurement technique, response of the satellite was studied by measuring the FFDP as a function of pulsewidth, wavelength, polarization, position in the FFDP, detector/processing techniques, and satellite orientation. The purpose of the pulsed laser testing was two-fold: (1) Characterize the satellite optical response with the detector and signal processing electronics currently used in most SLR stations using the Portable laser ranging standard, and (2) to characterize the satellite response for various conditions using the highest bandwidth optical detector (streak camera) available for the next generation of SLR technology. The portable ranging standard employed multiple measurement devices and an optical calibration scheme to eliminate range-dependent and amplitude-dependent systematics. These precautions were taken to eliminate/minimize instrumental errors and provide maximum accuracy. For LAGEOS orbit (6000 Km) ground stations are located 34 to 38 μ-radians off the axis of the return signal from the satellite; therefore an optical mask was used to restrict the field of view (FOV) of detection to this annular region of the far-field diffraction pattern (FFDP). The two measurement techniques were implemented using an aperture sharing scheme and complemented each other by providing mutual verification.

The results indicate a variation of range correction as a function of satellite orientation and location within the far-field diffraction pattern. Range correction as a function of wavelength shows a maximum at 532 nm. For other wavelengths, the FFDP of normal-incidence cube-corners is detuned, providing a greater contribution to the integrated response from cube-corners farther away from the observer. Constant-fraction processing of the detected pulse provided more consistent results than peak and leading-edge. Changes in the orientation of the E-vector of the linearly polarized light showed a systematic variation of $\lesssim$ 2mm in the polar regions of the satellite. A consistent difference in RC of $\simeq$ 2 mm between linearly polarized light and circularly polarized light was also observed. The test results showed that a range correction of $\simeq$ 251 mm is applicable to the third-generation SLR systems operating at the multi-photoelectron (MPE) level. The use of short ($\simeq$15 ps) laser pulses and streak cameras would provide time resolved signature of the satellite allowing improved (1mm accuracy) range correction.

BACKGROUND

- LAGEOS-1 launched on May 4, 1976; 5900km orbit; 110° inclination.
- Prior to launch, the satellite was optically tested (532nm, 60ps) at GSFC.
- Remarkable progress in SLR technology over 15 years and the projections for the future required understanding of LAGEOS-2 LRA better than LAGEOS-1.
- Major emphasis to accurately (submillimeter) determine the range offset to satellite CM from the effective reflection point.
- Elaborate experimental schemes with state of the art instrumentation and expanded parameteric study than LAGEOS-1.
- Satellite manufactured by Aeritalia for ASI.
- LAGEOS-2 scheduled for deployment Oct. 15, 1992; 5900km orbit 52° inclination.

SATELLITE FEATURES:

MECHANICAL

- Spherical satellite with a DIAMETER of 599.87mm.
- Two hemispherical shells with outer skin made of aluminum.
- Core of the satellite has brass to improve mass..
- Cylindrical core for preferred spin axis (N-S).
- Total mass 405.38 kgm.
- Hemispherical shells and the brass core held together by a steel shaft.
- 426 cube corner cavities.
- Center of gravity and center of geometry are nearly coin-ciden (0.078mm)..

SATELLITE FEATURES:

OPTICAL

- 426 cube corners; fused silica (422), germanium (4).
- UV-near IR supported by FS; Ge for infrared ranging..
- FS cubes distributed with symmetry about the polar axis; Ge cubes distributed as a tetrahedron.
- Special grade of FS (Suprasil 1, Special T19) for material homogenity and isotropy..
- Clear aperture 38.1 mm; face to apex depth 27.84mm..
- Dihedral offset of 1.5 arc sec for FS cubes; no dihedral offset for Ge cubes.
- No metallic coating; only TIR to enhance reflection from CCs close to the incoming laser beam.
- TIR cubes are sensitive to polarization affecting FFDP and therefore range correction.

OPTICAL CHARACTERIZATION

PURPOSE

- Range correction to center of mass from effective reflection point.
- Target spread function.
- Lidar cross section.

APPROACH

- Measure the temporal response of the satellite using mode-locked lasers and fast detectors (streak camera, photodiode, MCP-PMT) as a function of wavelength, pulsewidth, polarization, position in the FFDP, satellite orientation, detection bandwidth and, type of signal processing; Compute and deduce the satellite characteristics.

MEASUREMENT PARAMETERS

LASER
- Wavelength: Pulsed 1064, 532, 355nm
- Polarization: Linear (horizontal, vertical), circular
- Pulsewidth: 60ps (1064nm); 140ps, 45ps, 25ps (532nm), 30ps (355nm)

DETECTOR
- Temporal Resolution: 2.5ps (streak camera); 100ps (photo-diode) 500 ps (MCP-PMT)
- Photoelectron Level: 10-100 (MCP-PMT); 1000-10000 (SC); 100000 - (Photodiode)

SIGNAL PROCESSING
- Peak
- Half Max.
- Centroid
- Constant Fraction

SATELLITE ORIENTATION
- Polar
- Equatorial
- Others

Velocity Aberration: Various positions in the annular (34-38 microradian) region of the FFDP.

EXPERIMENTAL APPROACH

PULSE MEASUREMENT
- Mode-locked laser for illumination.
- Temporal detectors in the focal plane.
- Detection limited to useful region in the FFDP.

ADVANTAGES
- Net effect of coherent/incoherent superposition of FFDPs directly measured.
- More direct than cw case since instrumentatiion used is similar to those currently used for SLR; easy to verify spaceborne performance.
- Computationally simple.
- Less sensitive to air currents, vibration, etc.

DISADVANTAGES
- Experimental measurement is complex.
- Allows only discrete measurement of the FFDP.

LAGEOS-2 RESULTS

POLARIZATION EFFECT

- **Although LAGEOS-1 testing showed no significant effect on polarization, analysis of LAGEOS-2 RC using pulsed laser measurement showed ± 1.5mm in the polar region**
- **Pulsed laser measurement showed ≈ 2mm offset between circular and linear polarization consistently for all pulse widths**

PULSE LENGTH/DETECTION METHOD

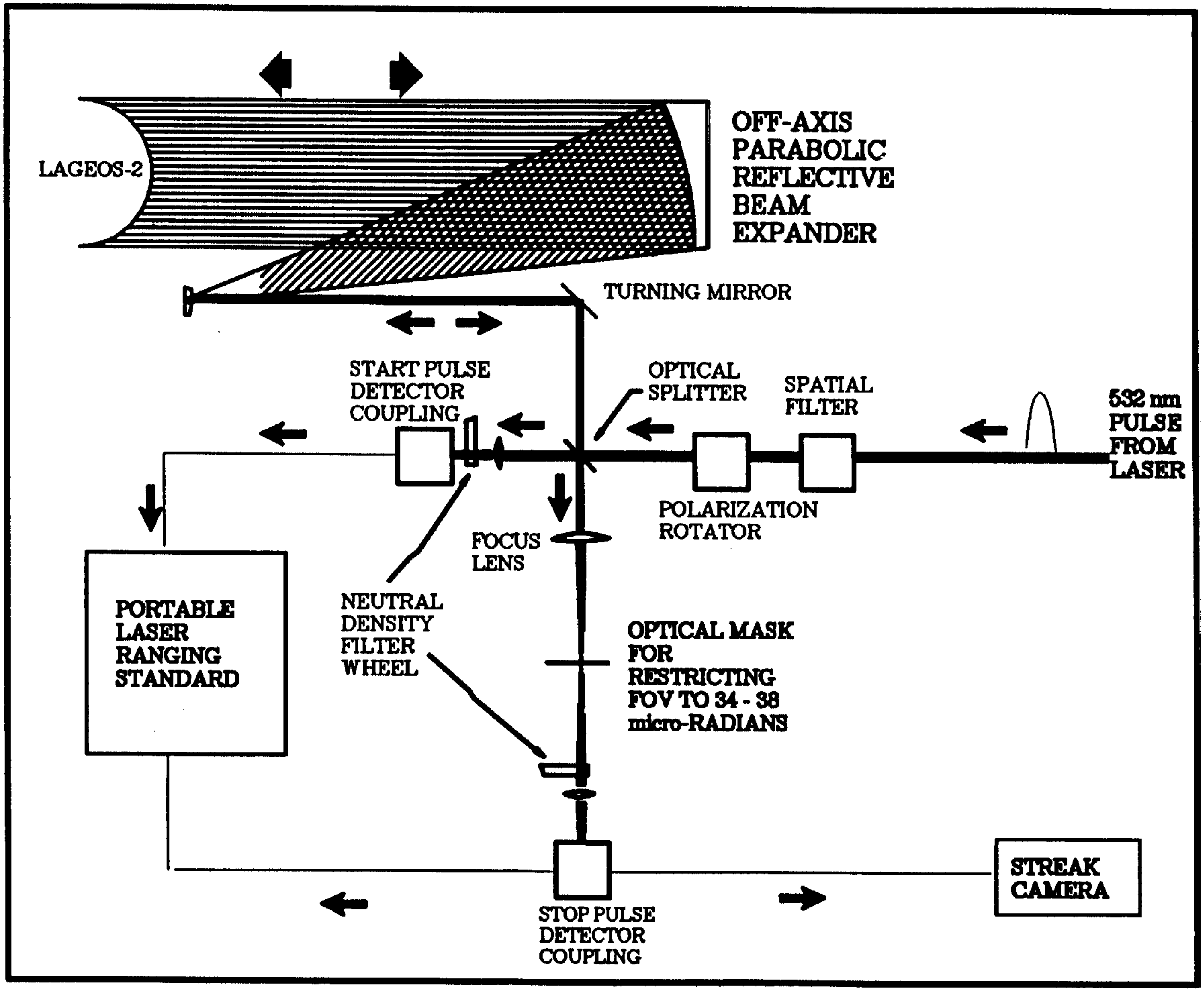
- **Peak and half max. detection produced increased range corrections (1-2mm) for shorter pulses; at longer pulsewidths, an asymptotic value of ≈ 251mm is reached.**
- **Experimental data on constant fraction discrimination showed decreased range correction for shorter pulses in good agreement with theroretical predictions.**
- **Range correction to center of mass is 250.8mm (gaussian, 200ps pulsewidth, 532 nm, average orientation, plane polarized light, centroid detection/constant fraction detection).**
- **Range correction is a function of orientation, wavelength, pulse length, detection method, coherent effects, and location within the far field diffraction pattern (FFDP).**

WAVELENGTH EFFECT:

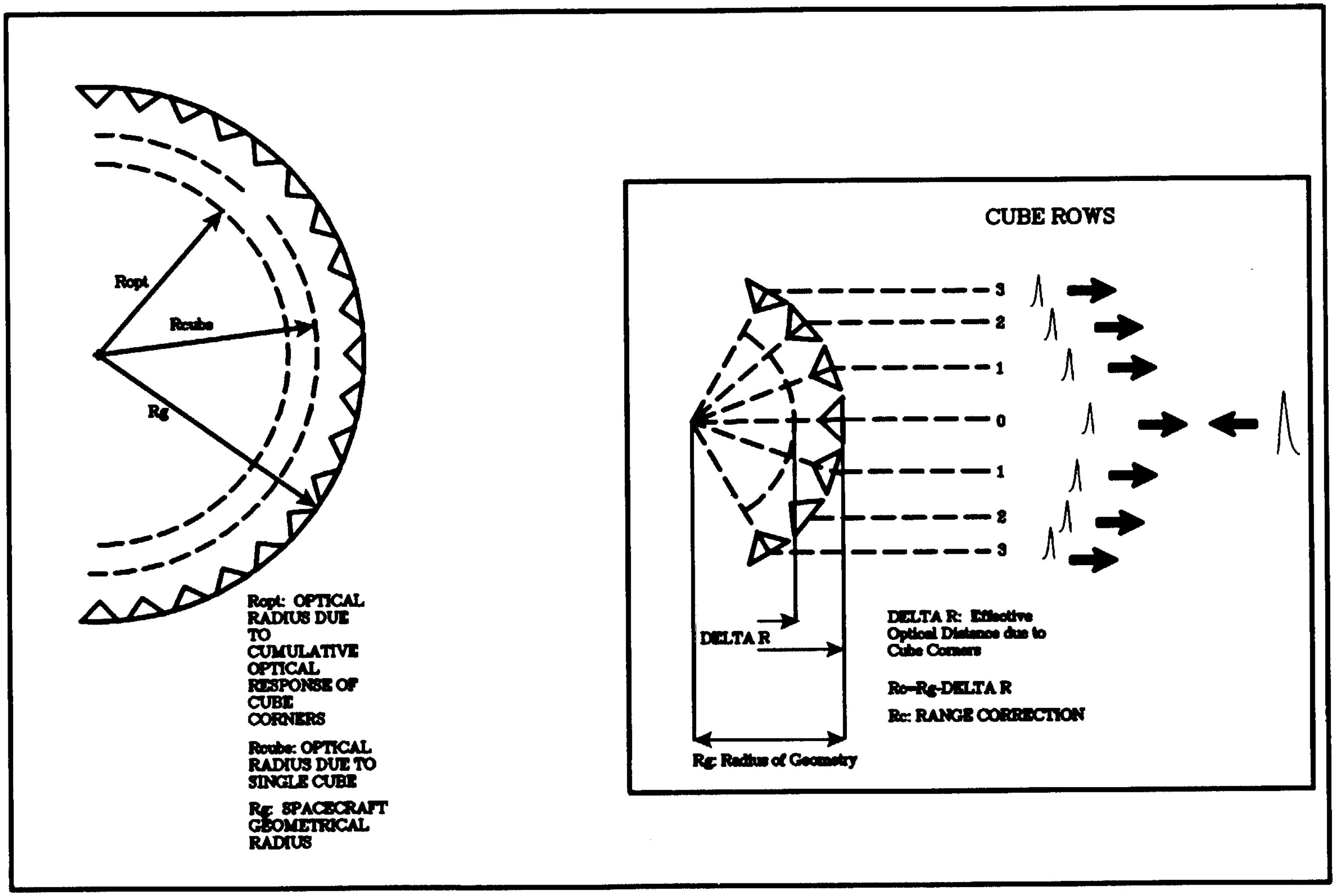
- **Range correction is maximum at 532 nm and showed a decrease with increase in wavelength (355 - 1064).**
- **Detuning of the FFDP which is optimized for 532 nm and near-normal incidence; affects longer and shorter wavelengths; cube corners farther from normal incidence contribute more and shift the range correction towards the center of the satellite.**

SUMMARY

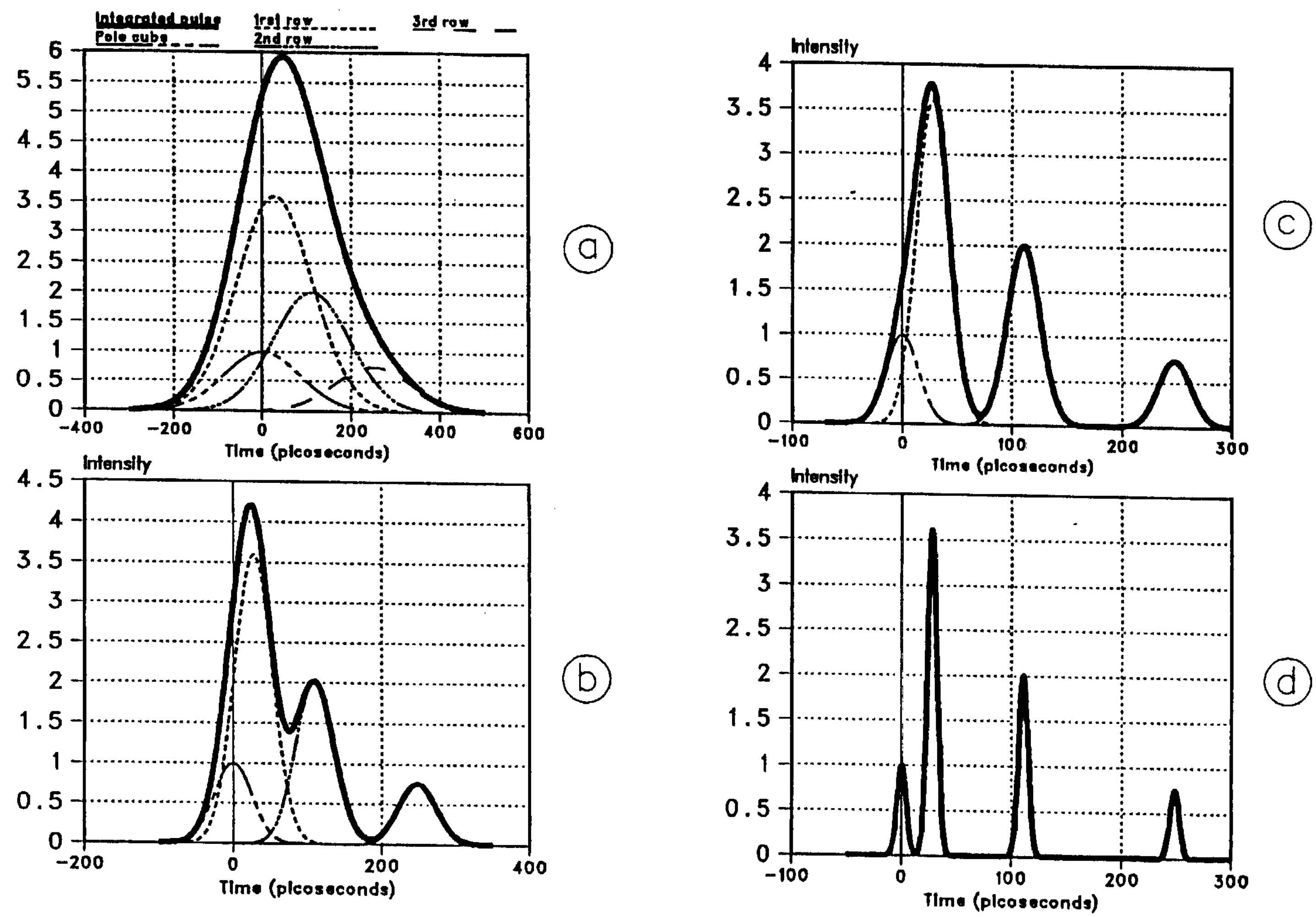
- **Detailed investigation of LAGEOS-2 optical characteristics has been completed, algorithms for RC to CM of the satellite have been derived to apply any SLR scenario.**
- **The small departure of LAGEOS-2 results from LAGEOS-1 is currently believed to be due to calibration/instrumentation errors in LAGEOS-1 measurement.**
- **Current estimates of the satellite-limited ranging accuracy is estimated to be < 3mm for the best multi-photoelectron (MPE) SLR station; accuracy approaching 1mm can be obtained with shorter pulses (<15ps) and streak cameras.**



LAGEOS-2 EXPERIMENT OPTICAL SET-UP

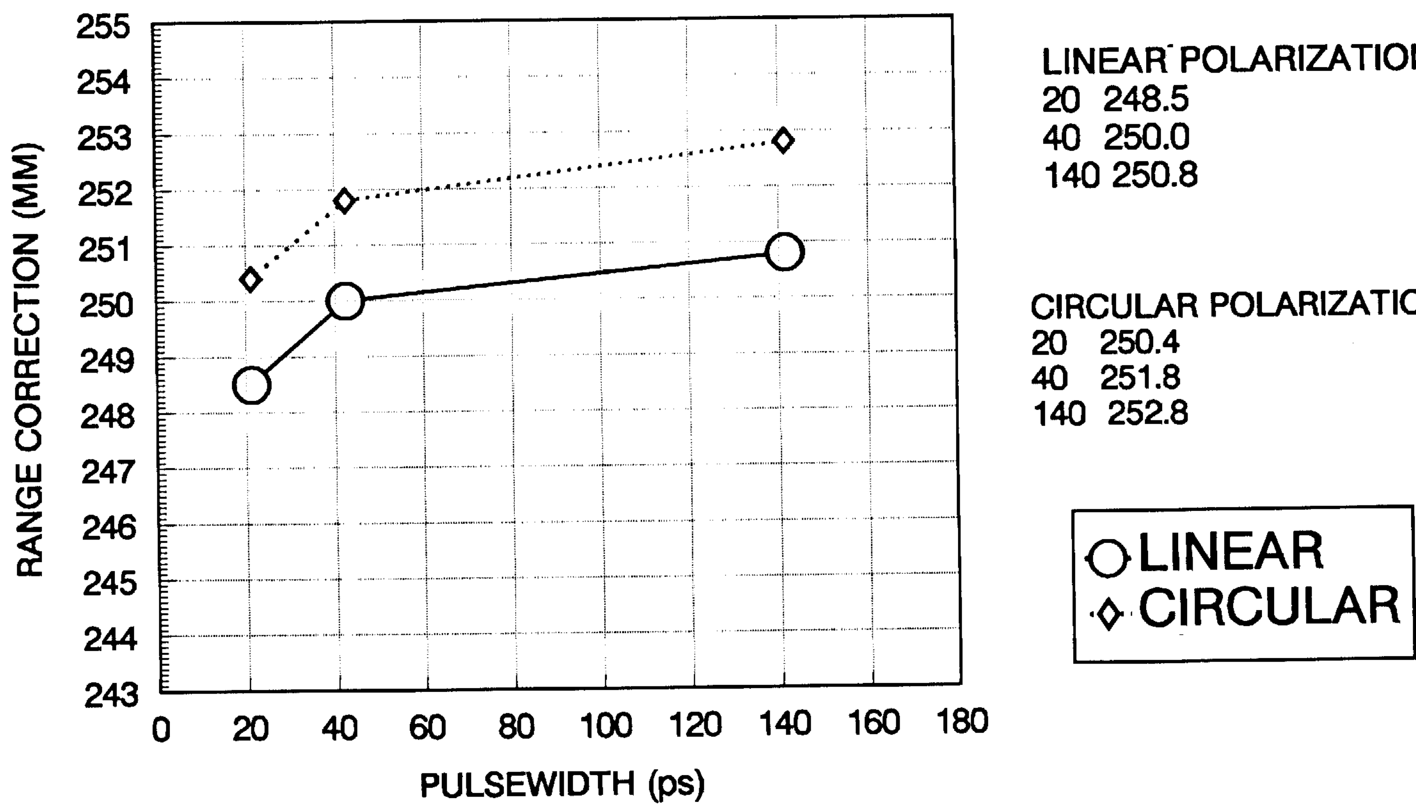


SCHEMATIC OF CUBE CORNER LAYOUT



SIMULATION SHOWING INCOHERENT SUPERPOSITION OF THE CONTRIBUTION FROM INDIVIDUAL CUBES IN THE POLAR REGION OF THE LAGEOS-2 SATELLITE AS A FUNCTION OF PULSEWIDTH. THE SIGNATURE OF THE SATELLITE GETS PROGESSIVELY TIME RESOLVED AS THE PULSEWIDTH IS REDUCED FROM APPROXIMATELY 200 PS (a) TO 10 PS (d).

RC-VS-PULSEWIDTH FOR LINEAR AND CIRCULAR POLARIZATION



LINEAR POLARIZATION

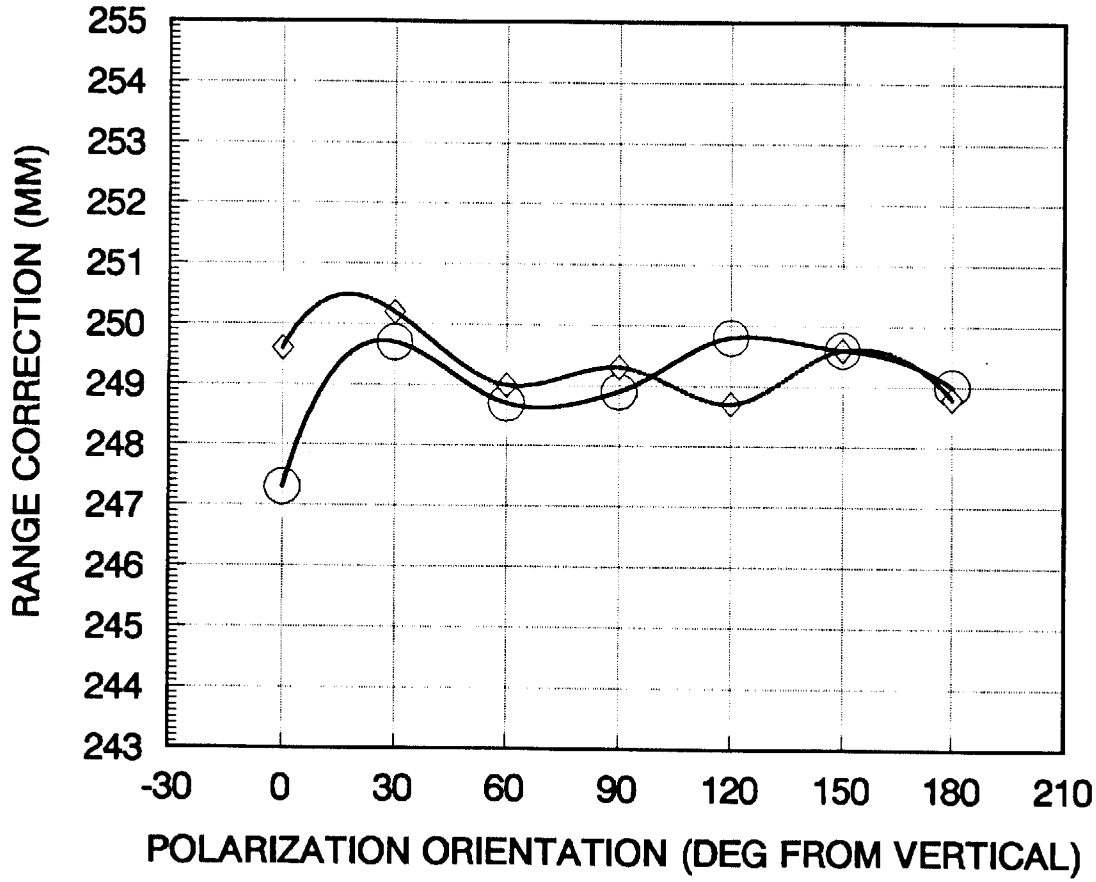
20	248.5
40	250.0
140	250.8

CIRCULAR POLARIZATION

20	250.4
40	251.8
140	252.8

Plot illustrating the Range Correction difference between circularly polarized and linearly polarized laser beams for various pulsewidths. An offset of ~2mm was consistently observed in each case.

RC -VS- POLARIZATION DIRECTION



SOUTH:

0	247.3	120	249.8
30	249.7	150	249.6
60	248.7	180	249.0
90	248.9		

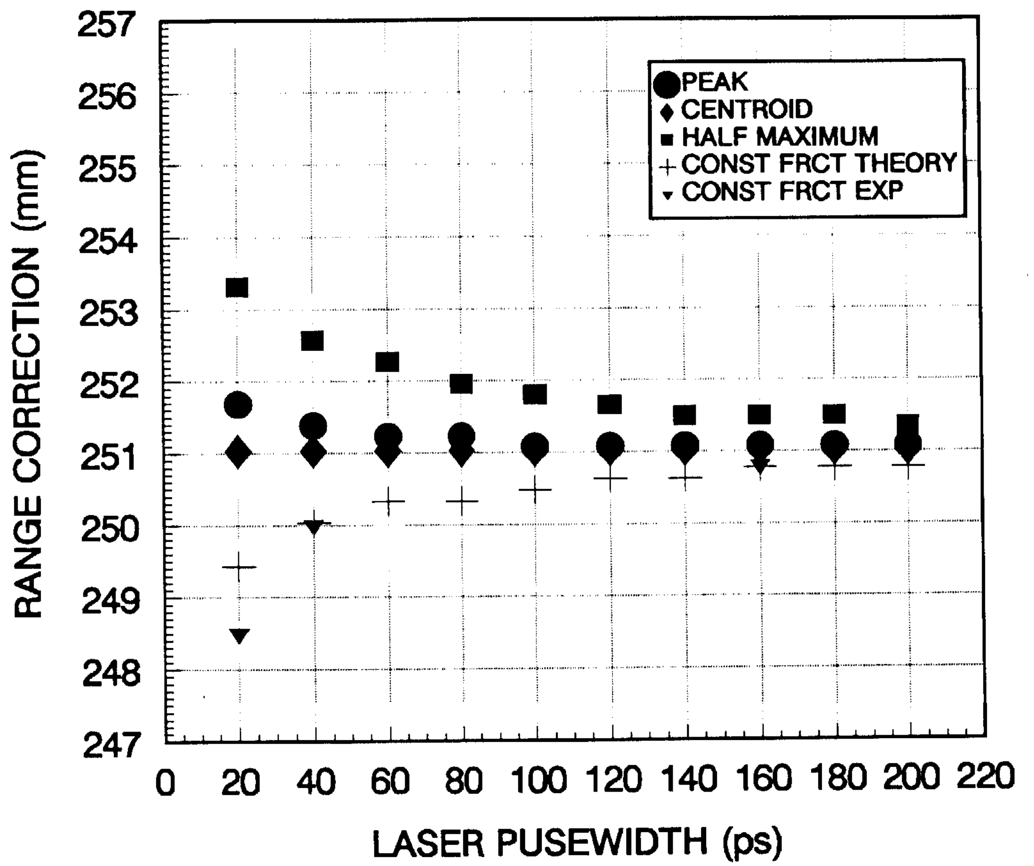
NORTH:

0	249.6	120	248.7
30	250.2	150	249.6
60	249.0	180	248.8
90	249.3		

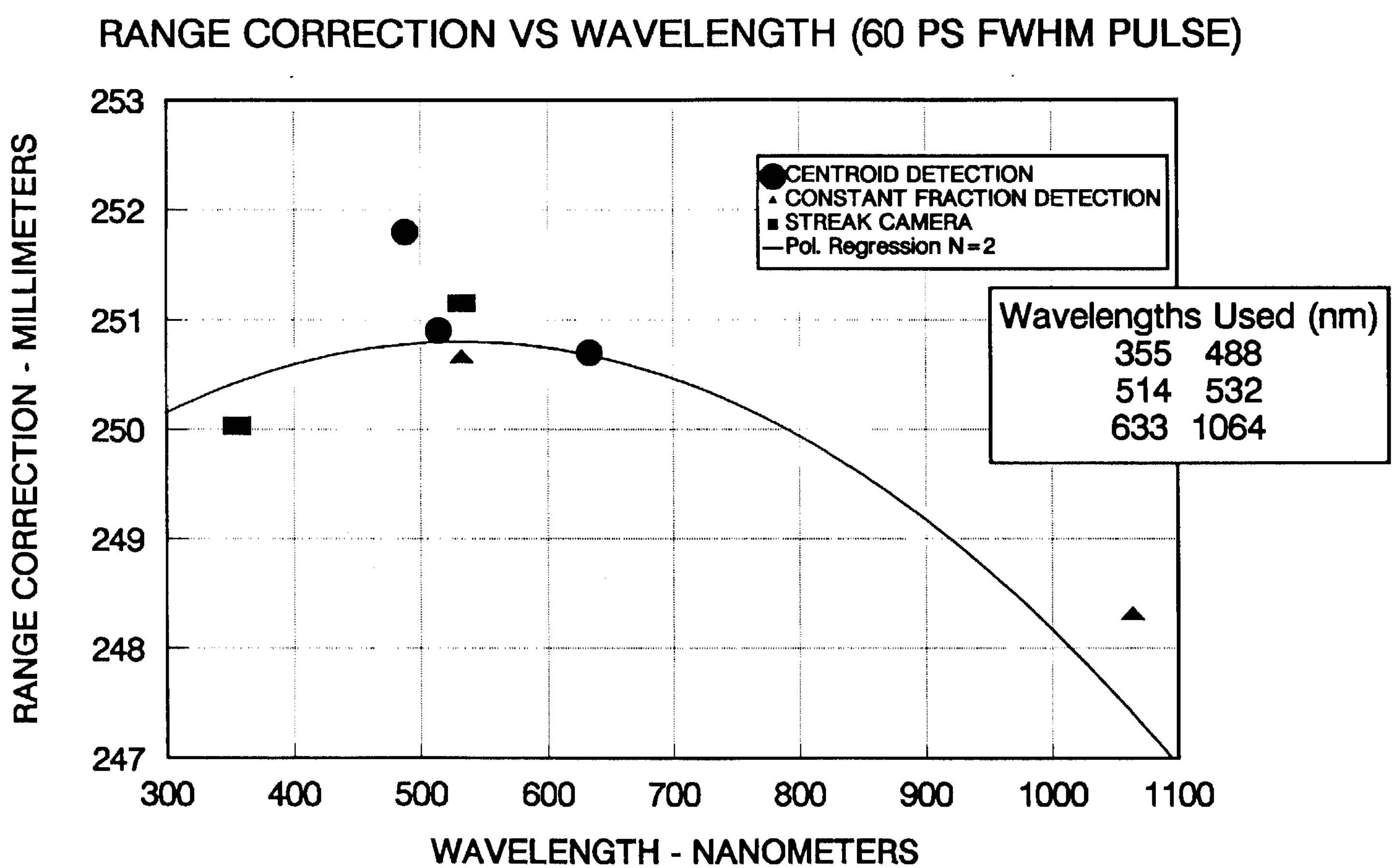
○ SOUTH POLE
◊ NORTH POLE

Plot illustrating the variation of RC as a function of orientation of the E-vector for linearly polarized light. Both polar regions of the satellite showed a similar response.

LAGEOS-2 RANGE CORRECTION -VS- LASER PULSEWIDTH



Plot to highlight the dependence of RC on laser pulsewidth as a function of signal processing technique, with special emphasis on constant fraction (CF),which is widely used in the global network. Theoretical values for peak,centroid and CF were computed by P. Minott/GSFC based on a model of the satellite.



Plot illustrating the dependence of RC on wavelength for various experimental signal processing techniques. The centroid data was computed by P. Minott/GSFC based on a model of the satellite.

N94-15578

ANALYSIS OF TOPEX LASER RETROREFLECTOR ARRAY CHARACTERISTICS

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Abstract:

The joint U.S./French TOPEX/POSEIDON mission was successfully launched on August 10, 1992 for the study of ocean height variation using microwave altimetry. Accurate determination of the satellite orbit is paramount to the determination of the above phenomenon. To accomplish this, using laser ranging, the satellite is equipped with a laser retroreflector array (LRA) around the altimeter antennae. The goal of laser ranging is to obtain precision orbits with a radial accuracy of 13 cm to the Center of Mass of the Satellite. This requires the laser range correction to the LRA reference be known at the sub-cm level and is quite a challenge considering the geometry of the LRA. Detailed studies were initiated by the TOPEX project office (Christensen) under the auspices of the CDP/DOSE project (Degnan) at Goddard Space Flight Center.

The studies included the following:

(1) Theoretical Modelling of the LRA using FFDP data and computation of Centroid tables: P. Minott/GSFC; D. Arnold/SAO

(2) Experimental measurement of the LRA trays using CW techniques: P. Minott/GSFC; Carl Gliniak/EER

(3) Pulsed experimental measurement and modelling: T. Varghese/Bendix

(4) Range Correction tables for Global SLR Tracking Configurations: T. Varghese/Bendix

(5) Data Compression using Fourier Analysis and Satellite Range Correction: A. Marshall/GSFC

This paper provides an overview of items (3) and (4).

c-4

TOPEX LRA OPTICAL CHARACTERIZATION

- **LIDAR CROSS SECTION:** To determine optical link and therefore the photo electron yield for various tracking strategies, detection configurations.
- **TARGET SPREAD FUNCTION:** To study impact on ground ranging hardware configurations, calibration corrections, etc.
- **RANGE CORRECTION:** To deduce the range correction to determine the satellite range to LRA reference center.

LASER RANGING CORRECTIONS FOR TOPEX POD

DETERMINATION OF RANGE TO CENTER OF MASS INVOLVES THE FOLLOWING:

- Range from the station to LRA 'reflection plane'.
- Correction of the reflection plane to the LRA reference center.
- Co-ordinate transformation from LRA reference center to space-craft body-fixed coordinate system origin.
- Center of mass position co-ordinates with respect to the body fixed co-ordinate system origin.

LASER RANGING CORRECTIONS FOR TOPEX POD

FACTORS AFFECTING LASER RANGING CORRECTION

- Satellite elevation angle with respect to the ranging station
- Satellite velocity normal to the line of sight and therefore the location within the FFDP.
- Ranging hardware configuration

  a) Laser wavelength and pulsewidth
  b) Type of detection (peak, leading edge, centroid, CFD)
  c) Detector bandwidth and skew
  d) Detection threshold (spe, mpe, low/high threshold)

Very accurate determination of each of these parameters is required to obtain a laser ranging correction to 0.5 cm (1 sigma).

TOPEX CHARACTERISTICS PERTINENT TO LASER RANGING

- Circular orbit of 1336 km
  - Maximum Range ~ 2700 KM (20° Elevation)
  - Minimum Range ~ 1336 KM (90° Elevation)
- Range of velocity aberration 28-48μr
- Nadir pointing LRA - orientation of the array changes as a function of elevation angle
- LRA consist of 192 hexagonal cubes in a conical ring configuration with 128 cubes in the lower row and 64 cubes in the upper row. There are 16 trays each with 12 cubes
- Lower row diameter - 826.3mm
- Upper row diameter - 852.9mm
- Height of lower row from reference center - 88.6mm
- Height of upper row from reference center - 66.3mm
- Center of mass is away from the LRA reference center by a known distance and varies as a function of expended fuel

TOPEX CUBE CHARACTERISTICS

- **EACH HEXAGONAL CUBE HAS THE FOLLOWING FEATURES:**
  - Material - Corning fused silica #7958
  - Aperture - 38mm
  - Depth - 27.25mm
  - Dihedral Offset - 1.75 $\pm$ 0.25 arc sec
  - Refractive Index - 1.4606
  - Antireflection coating (Mg F2) for the entrance face
  - Protected silver coating for all other sides; total transmission 82%

PULSED LASER MEASUREMENT

- **OBJECTIVE: MEASURE FFDP IN THE ANNUAL REGION USING LINEARLY POLARIZED 60ps LASER PULSES AT 532 nm**
- **MEASUREMENT TECHNIQUES:**
  - Range measurements using portable standard similar to LAGEOS-2
  - Temporal mapping using:

    (a) High speed photodiode (<10ps rise time) and a 4.5 GHz Oscilloscope
    (b) MCP-PMT and 4.5 GHz Oscilloscope
  - Spatial intensity mapping using a CCD Camera and a Frame Grabber
- **MEASUREMENT CONFIGURATION:**
  - Single trays and individual cubes
- **ORIENTATIONS:**
  - Elevation from 0° to 40° in steps of 20°
  - Azimuth from 0° to 45° in steps of 11.25°

The elevation and azimuth here refer strictly to the laboratory setup for mounting the tray

TARGET SPREAD FUNCTION

- Although the leading edge is fairly sharp, the trailing edge is skewed and very long.
- The pulse shape is a function of elevation angle, and the position in the FFDP annulus.
- The presence of two rows of cubes arranged in the form of a conic section produces a skewed return pulse; for the leading edge the skew diminishes monotonically until the elevation reaches 40° at which time the trailing edge picks up the contribution from the upper row of cubes.
- Simulations show that if the predicted contribution from each cube is altered by a process such as thermal gradient, the resulting pulse can have significantly different temporal characteristics.
- The temporal envelope of the pulse affects the range accuracy.

SUMMARY

- Optical characterization of the LRA has been completed and a model has been established to derive the LRA optical parameters such as a Lidar Cross Section, target spread function and range correction to the LRA reference center.
- Range correction is profoundly impacted by type of detection. It is also a function of the input pulse width and the number of photo electrons used for signal definition.
- Since the range varies considerably (3-6cm) within the FFDP, the range correction has to be applied to the satellite data with the knowledge of the satellite velocity and orientation.
- Current efforts to incorporate velocity aberration and ranging instrumentation features into the data correction algorithms should provide data accuracy better than 1 cm.

Acknowledgements

The author acknowledges his deep appreciation to the following colleagues for technical assistance during the course of this project. In strictly alphabetical order, they are Steve Bucey, Christopher Clarke, Brion Conklin, Tony Mann, Tom Oldham, and Mike Selden. He is also indebted to John Degnan for various technical discussions and P. Minott for providing the far field diffraction data of the individual cubes for various orientation of the LRA.

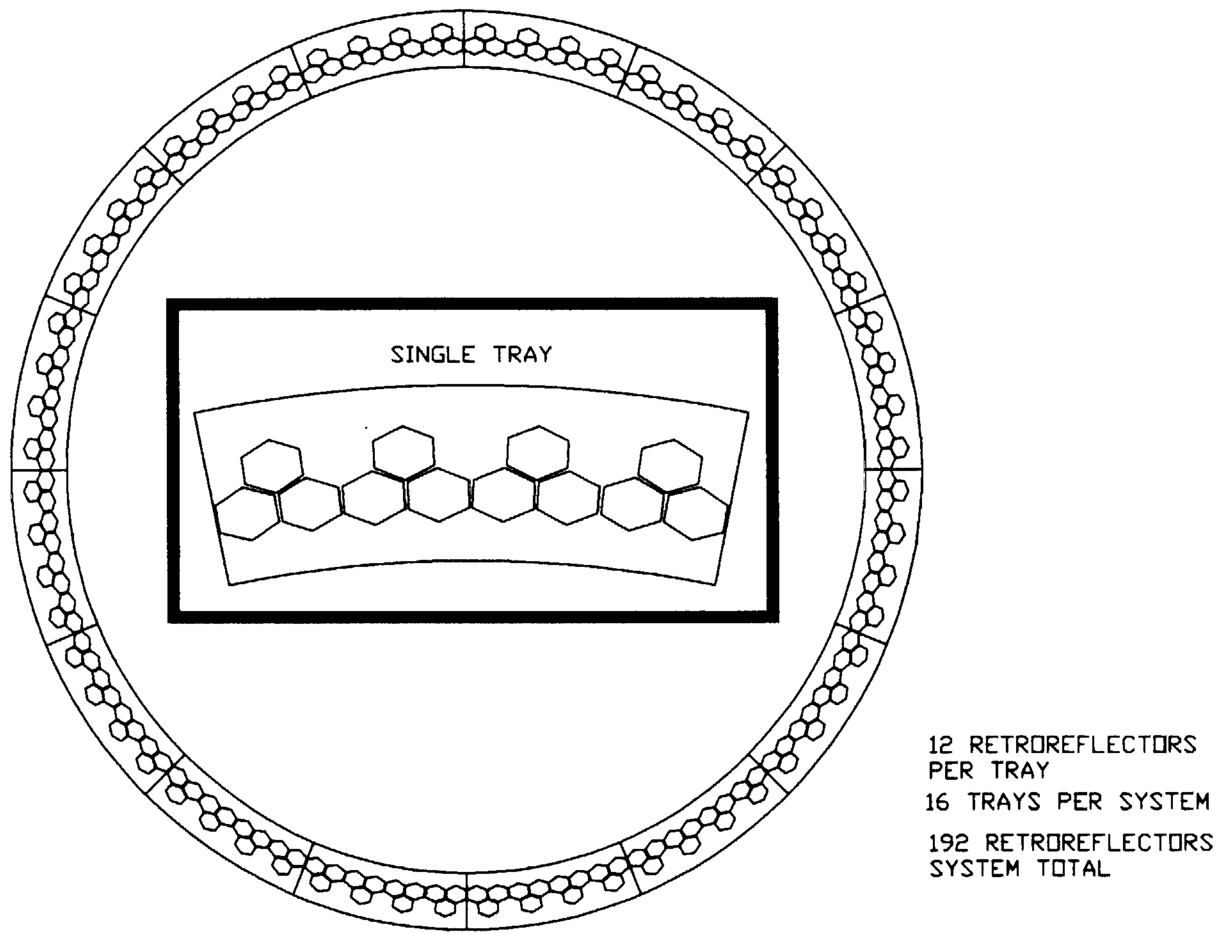


Fig. 1 ILLUSTRATION OF TOPEX LRA AND SINGLE TRAY.

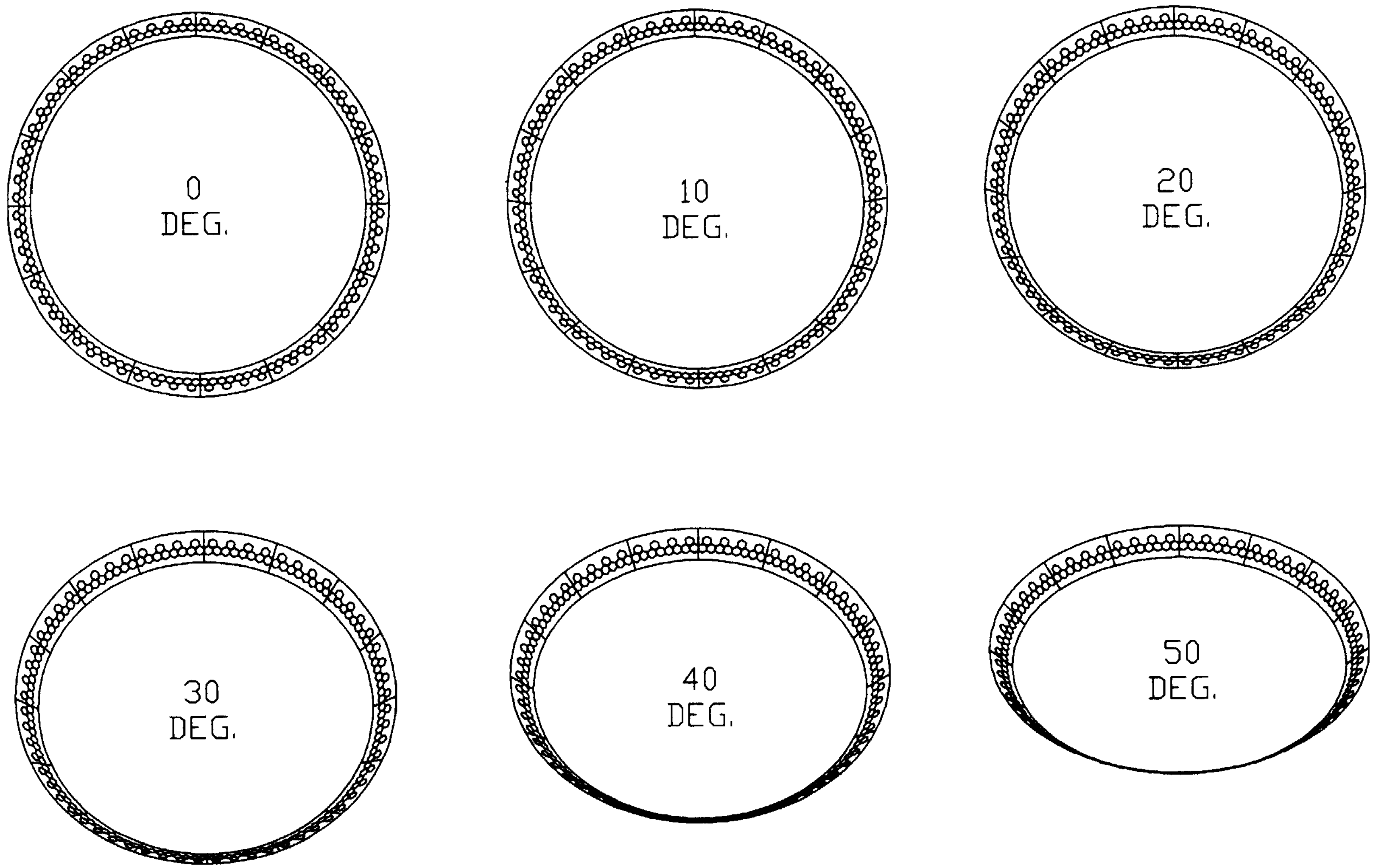
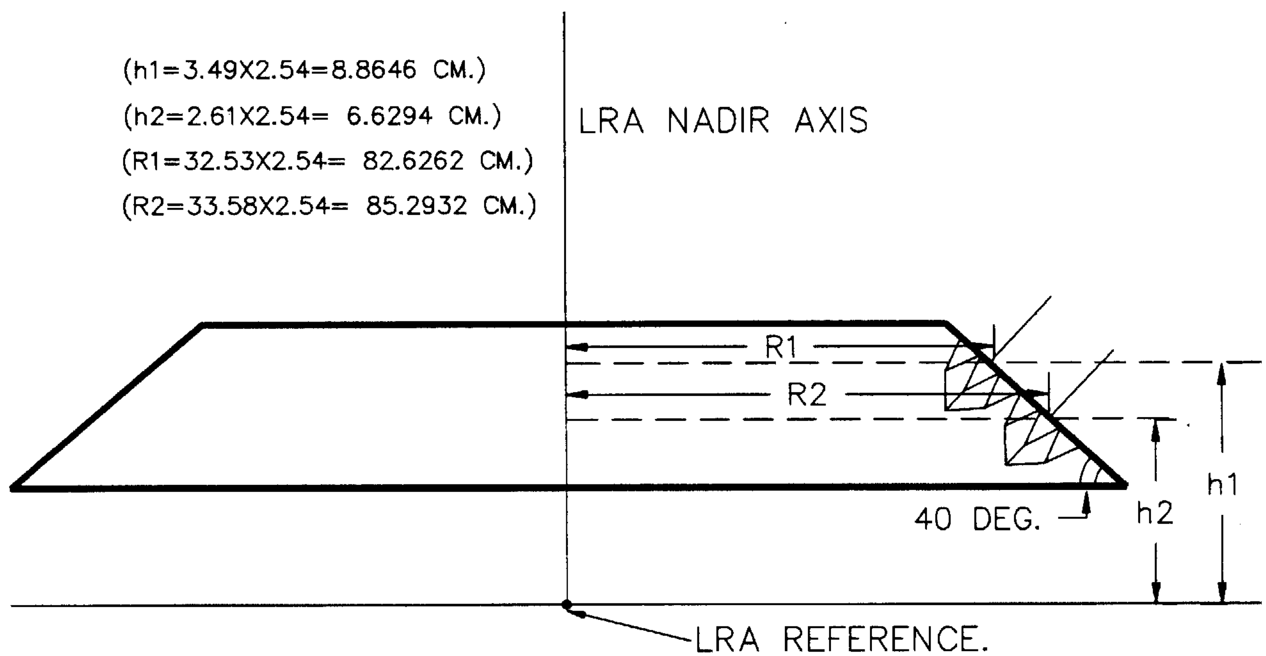


Fig. 2 LRA ORIENTATION AS A FUNCTION OF NADIR ANGLE.



h1=HEIGHT FROM THE CENTER OF THE FRONT FACE OF THE CUBE (LOWER RING; 128 CUBES) TO THE LRA REFERENCE PLANE.

h2=HEIGHT FROM THE CENTER OF THE FRONT FACE OF THE CUBE (UPPER RING; 64 CUBES) TO THE LRA REFERENCE PLANE.

R1=RADIUS (TO THE FRONT FACE OF THE CUBE) OF THE LOWER RING.

R2=RADIUS (TO THE FRONT FACE OF THE CUBE) OF THE UPPER RING.

Fig. 3 TOPEX LRA REFERENCE COORIDINATE SYSTEM.

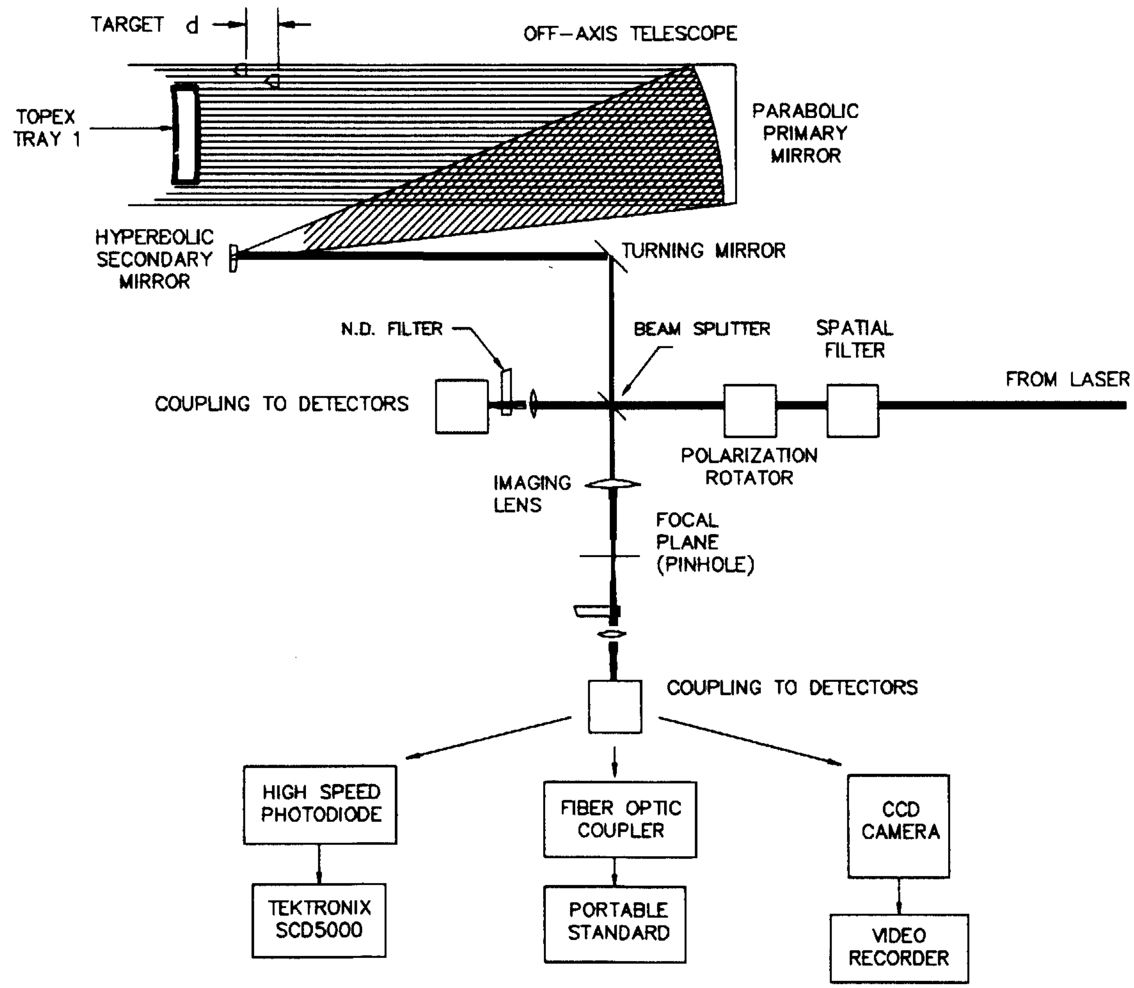


Fig. 4 OPTICAL SCEMATIC FOR TOPEX TRAY MEASUREMENT

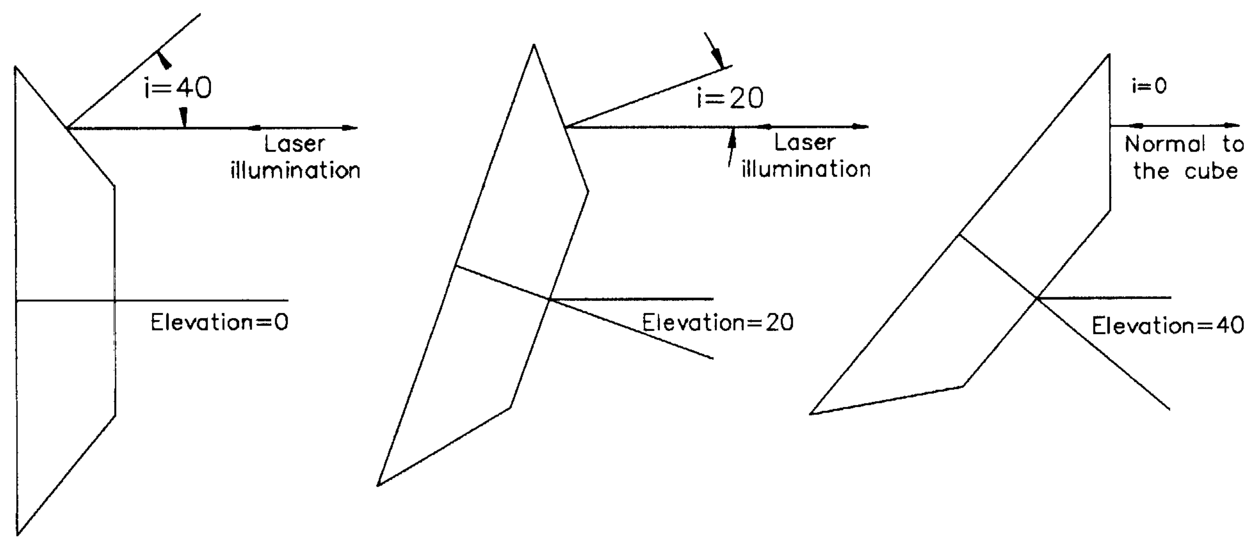


Fig. 5 LABORATORY MEASUEMENTS FOR ORIENTATIONS OF THE TOPEX TRAYS.

T/P LRA RANGE CORRECTION (RC): CFD=1250ps

INCIDENCE ANGLE=20.0; RC MIN=285.3mm; RC MAX=310.6mm

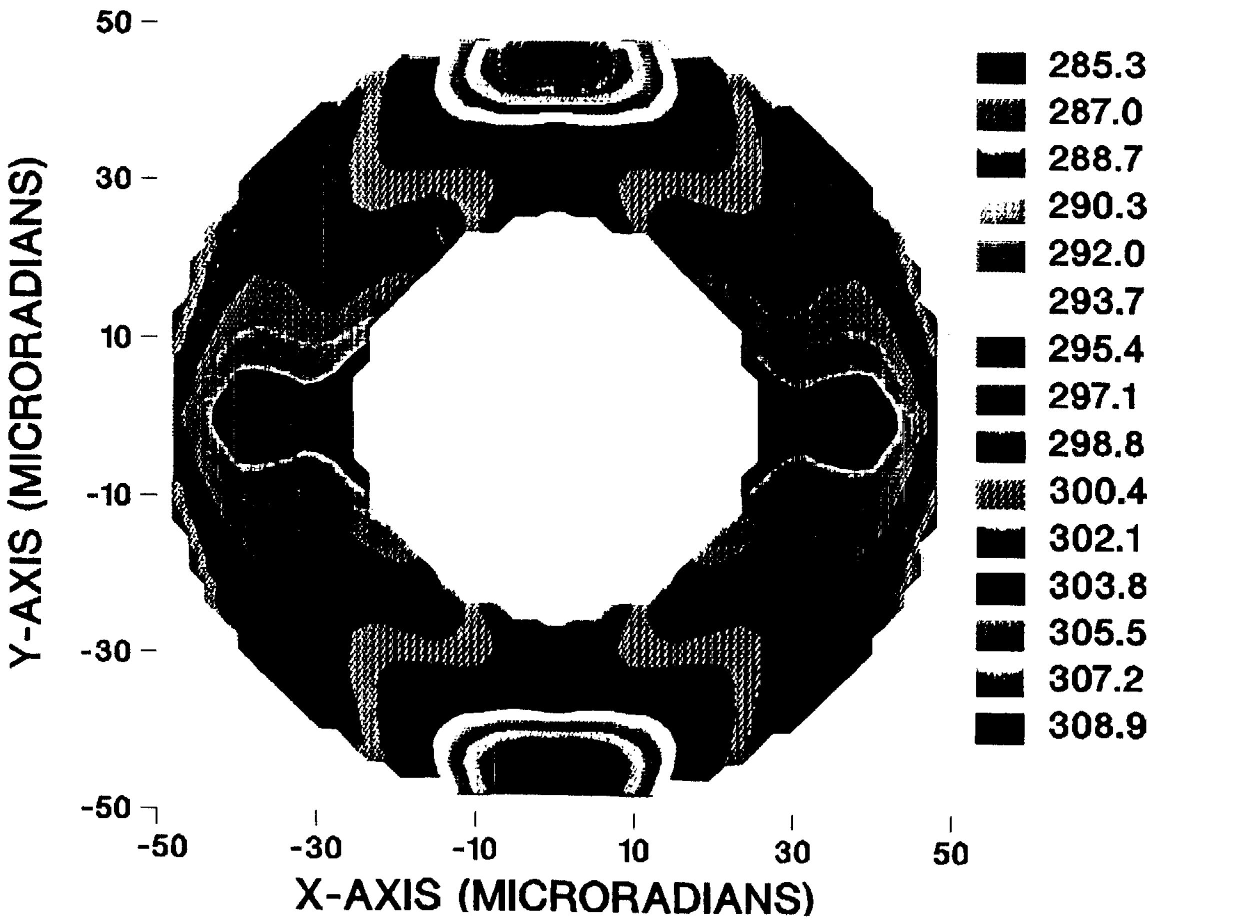


ILLUSTRATION OF THE TOPEX/POSSEIDON LRA RANGE CORRECTION FOR AN INCIDENCE ANGLE (ANGLE BETWEEN LASER LINE OF SIGHT AND NADIR) OF 20 DEGREES FOR CONSTANT FRACTION DISCRIMINATOR BASED SYSTEM. THE RANGE CORRECTION PLOTTED AS A FUNCTION OF THE VELOCITY ABERRATION SPACE SHOWS A COMPLEX PATTERN WITH A MINIMUM VALUE OF 285 MM AND MAXIMUM VALUE OF 311MM.

N94-15579

HISTORICAL MOBLAS SYSTEM CHARACTERIZATION

Van S. Husson

Abstract – This paper is written as a direct response to the published NASA LAser GEOdynamic Satellite (LAGEOS) orbital solution SL7.1 [*Smith et al.*, 1991], in order to close the data information loop with an emphasis on the NASA MOBile LAser Ranging System's (MOBLAS 4,5,6,7,8) LAGEOS fullrate data since November 1, 1983. A preliminary analysis of the supporting information (i.e. satellite laser ranging system eccentricities and system dependent range and time bias corrections) contained in SL7.1 indicated CentiMeter (cm) level discrepancies. In addition, a preliminary analysis of the computed monthly MOBLAS range biases from SL7.1 appear to show cm level systematic trends, some of which appear to be "real", particularly in the 1984 to 1987 time period. This paper is intended to be a reference document for known MOBLAS systematic errors (magnitude and direction) and for supporting MOBLAS information (eccentricities, hardware configurations, and potential data problem periods). Therefore, this report is different than your typical system characterization report [*Pearlman*, 1984], but will be more valuable to the user. The MOBLAS error models and supporting information contained in this paper will be easily accessible from the Crustal Dynamics Data Information System (CDDIS).

1. INTRODUCTION

In the late 1970's, NASA developed five, second generation mobile laser ranging systems in support of the SEa Altimeter SATellite (SEASAT) mission. The goal of the SEASAT mission was to map the surface of the oceans using the onboard satellite altimeter. Satellite Laser Ranging (SLR) data was used to calibrate the SEASAT altimeter. During the 1980's, the MOBLAS systems underwent an extensive upgrade program that improved the data accuracy and precision an order of magnitude, from the 100 MilliMeter (mm) to the 10 mm level. Since the mid-1980's, LAGEOS data has been compressed into 2 minute bins (normal points), which statistically reduces the single shot precision level [*Smith et al.*, 1985]. MOBLAS LAGEOS normal point precision levels have been at the 1-2 mm level since the late-1980's.

During the 1980's, cm level systematic biases were discovered through special and collocation analysis techniques developed by Bendix in support of the Goddard Laser Tracking Network (GLTN) and the Crustal Dynamics Satellite Laser Ranging (CDSLR) mission contracts. When centimeter level systematic errors were discovered in NASA SLR data, the NASA management philosophy was to identify the source of the bias; to eliminate or model the bias; and to document the nature of the bias. Due to cost considerations, historical NASA SLR data were not repaired (in most cases) to remove known cm level systematics. In addition, the documentation of these bias problems was not maintained in a central database and had a limited distribution. The intent of this paper is to provide one reference source for known uncorrected MOBLAS (LAGEOS) systematic errors that will be available from the CDDIS.

The original MOBLAS major hardware components were the General Photonics (GP) q-switched laser, the Amperex dynode-chain PhotoMultiplier Tube (PMT), the Ortec 934 discriminator, and the Hewlett Packard (HP) 5360 time interval counter. In the 1983-1984 time frame, the largest systematic unrecoverable error source, the GP laser, was replaced with a Quantel mode-locked laser. The HP5370 counter was usually incorporated as part of the Quantel laser upgrade. In the 1986-1987 timeframe, the largest systematic error source, the Amperex 2233B and Ortec discriminator, was replaced with the ITT F4129 gated three-stage Micro-Channel Plate (MCP)PMT and Tennelec TC454 discriminators. The systematic error sources associated with the hardware components mentioned above are discussed in *Degnan* [1985] and *Varghese* [1985].

It is virtually impossible to recover any hardware related systematic errors in the GP laser era due to the domination of "wavefront-distortion" errors [*Degnan*, 1985]. In the Quantel laser pre-MCPPMT era, the largest recoverable systematic hardware related error source was signal strength (0-30mm) of the returning pulse [*Heinick*, 1984]. Discriminator and PMT "timewalk" characteristics, coupled with calibration signal strengths not distributed the same as LAGEOS signal strengths induced a systematic bias. The magnitude and direction of the bias was system dependent, and decreased in magnitude as calibration methods improved. A model has been developed to recover this error based on the review of historical calibration and LAGEOS "timewalk" curves. Unfortunately, only a small sample of these curves ever existed. Signal strength effects did vary from pass-to-pass and within a pass. The MCPPMT and dual Tennelec discriminators package developed by *Varghese*, coupled with proper calibration techniques essentially eliminated signal strength as a bias source at the mm level.

In 1988, another recoverable hardware systematic error source was discovered by *See and Sneed*. They discovered the measurement of the laser transmit delay (TDEL) was in error, because the TDEL electronics did not measure the cable delay ($\leq$0.5 microseconds) between the time code generator and the system computer. In addition, they and *McCollums* discovered that the TDEL electronics had other TDEL sub-microsecond accuracy ambiguities, which would have masked this bias. In the 1989-1990 timeframe, the TDEL electronics were modified to remove these sub-microsecond ambiguities. The cable delay has been measured in MOBLAS-4,7,8 and is being modelled in the pre-processing. As of this writing, the MOBLAS-5 and 6 cable delays have not been measured.

Other mm level hardware errors are known to exist in the current MOBLAS hardware (i.e. HP5370 [*Selden*, 1992] and optical path changes as a function of pointing angle [*McCollums*, 1986]), but are presently unrecoverable. Not all systematic error sources in SLR systems are hardware related. Survey of ground targets, survey of monument offsets, atmospheric modelling, data pre-processing, and orbital modelling are other SLR error sources. Fortunately, many of these errors sources can be recovered to the 10-20mm level, using historical processing results.

In the GP laser era, calibration targets were large boards at distances of 2-3 KiloMeters (Km). These boards were mounted on metal poles which were guyed. The height of these poles was system dependent. Cube corners also existed and were mounted on various structures and in most cases were in close proximity (a few meters) to the calibration boards. The reason calibration boards were used versus cube corners was to average the "wavefront-distortion" effects of the GP laser. Historical ground tests results [*Brogdon et. al.*] indicated up to 20cm and 60cm differences in system delay between the board and cube corner, and as a function of pointing angle, respectively. When the mode-locked (Quantel) lasers were installed, ground tests results were dramatically improved, and for the first time, 10-20mm survey errors to the ground targets and 10-20mm ground target movement could be detected [*Wroe et. al.*]. Within a few months of the MCPPMT's (1986-1987) being installed, the primary calibration targets became the original cube corners. In the 1988-1989 timeframe, long (2-3Km) Nelson piers became the primary calibration targets. In the 1991-

1992 timeframe, the primary targets became short (100-200 meters) Nelson piers with the advent of the translator and the short target ranging electronics [*Eichinger et. al.*, 1990].

In the early to mid 1980's, cm level movement of the original targets, coupled with survey uncertainties and infrequent surveys, severely limited the absolute accuracy of MOBLAS data. "Average" target movement and survey uncertainties, in most cases, is recoverable to the 10-20mm level using historical ground test results. In the mid-1980's, surveying equipment and frequency of surveying was improved, but the problem still existed with unstable targets. In the late-1980's, the target stability problem was minimized to the millimeter level, when the current day target calibration structure, the Nelson pier, were used as the primary calibration target.

The MOBLAS eccentricity measurement techniques were improved in the mid-1980's [*Nelson*, 1986]. The infrequency of eccentricity surveys was a mm level systematic error source, because long term temporal changes in the eccentricity data were at this level. Some of these errors are traceable based on MOBLAS log records or special analysis techniques.

Neutral Density (ND) filters have always been used during calibration to attenuate the signal. During satellite ranging the filters were removed, thus inducing a difference in the "effective" calibration and satellite optical paths [*Crawford*, 1985]. This difference was not modelled, but is recoverable to the 1mm level. In 1991-1992 the Optical Attenuation Mechanisms (OAM) [*Silva et. al.*, 1991] were installed in the MOBLAS, which minimizes the use of ND filters. The ND filter bias is currently being modelled in the pre-processing.

Prior to January 1, 1988, the tropospheric range correction applied to the fullrate data was computed based on the MOBLAS elevation encoder measurements. These measurements could be in error by a few millidegrees and would thus induce a systematic error in the tropospheric refraction correction [*Husson et. al.*, 1987]. This correction could be in error up to 20mm. The error was system and satellite dependent, but is fully recoverable to the sub-mm level. To remove this error in pre-1988 MOBLAS data, the applied tropospheric refraction must be removed and reapplied using the computed elevation angle. All MOBLAS data taken after January 1, 1988, were pre-processed using the computed elevation angle from a short arc fit to the ranges.

LAGEOS orbital modelling errors have improved significantly over the last 12 years along with the quality of SLR data [*Smith et. al.*, 1991]. Orbital modelling is limited by the quality and distribution of the global SLR dataset, but in some instances, is the only hope for recovering the "net" historical SLR biases.

In the remainder of this article, each MOBLAS system is addressed individually. Each system's eccentricities and recoverable bias sources are discussed and summarized in tables, which are contained at the end of this article. The bias model tables include the major system configuration changes (laser, PMT, discriminators, counter) and important pre-processing information (i.e. calibration target and calibration range). The tables and this article will be available from the CDDIS.

2. MOBLAS-4

2.1 MOBLAS-4 Eccentricities

Since August 15, 1983, MOBLAS-4 has only occupied one monument/marker (7110). Prior to August 1983, 7110 was occupied by MOBLAS-3. There exists 5 sets of MOBLAS-4 eccentricities and 10 MOBLAS-4 Site Occupation Designators (SOD's) at 7110. SOD's 71100402, 71100403, and 71100410, each have two sets of eccentricities.

The 3mm change in the Up ecc., between the 1985 and 1988, surveys could be caused by settlement of the pad and monument [*Nelson*, 1988]. There were no measurements of the eccentricities between 1985 and 1988. The MOBLAS-4 mount was releveled twice in 1988 (June 16 and December 13), but apparently there was no change in eccentricities, based on the April 1988 and November 1989 surveys. In February 1992, the eccentricities were remeasured prior to the removal of the mount. There was a 2mm unexplained change in the North ecc. In March 1992, the MOBLAS-4 mount was removed from system to be refurbished, and in April 1992, the refurbished mount was re-installed and the ecc. were remeasured. Table 1 contains the recommended set of MOBLAS-4 eccentricities with their corresponding SOD(s) and effective starting dates.

2.2 MOBLAS-4 LAGEOS Biases

The net MOBLAS-4 recoverable biases (range and time) are presented in Table 2. To correct MOBLAS-4 LAGEOS data, the known range and time biases (in Table 2) should be subtracted from the LAGEOS range and timetags, respectively. Any time there is the potential for a change in the bias(es), even though the bias(es) did not change, a new entry has been added. A component breakdown of the biases is presented, followed by a section describing known problem data, and followed by a section describing potential problem data.

2.2.1 MOBLAS-4 ND filters

MOBLAS-4 LAGEOS data was biased short by 3mm ± 1 and 1mm ± 0mm from August 15, 1983 through January 17, 1992, and from January 18 through May 31, 1992, respectively, due to ND filters. On January 18, 1992, the OAM was installed in MOBLAS-4 reducing the ND filter bias. After June 1, 1992, this bias has been removed through modelling.

2.2.2 MOBLAS-4 signal strength

MOBLAS-4 LAGEOS data was biased long by 20mm ± 10, 10mm ± 5, 6mm ± 3, and 4mm ± 2 from August 15, 1983 through June 30, 1984; July 1, 1984 through August 31, 1984; September 1, 1984 through July 31, 1985; and August 1, 1985 through November 19, 1986; respectively, due to signal strength. This bias would vary from pass-to-pass and would have a slight elevation dependence. Low elevation data would be biased longer by several mm than high elevation data. Signal strength effects were reduced as the MOBLAS-4 calibration techniques improved, and were eliminated when the MCPPMT package was installed on November 20, 1986.

2.2.3 MOBLAS-4 elevation angles

Prior to January 1, 1988, the tropospheric range correction applied to the fullrate data was computed based on the MOBLAS-4 encoder measurements. To remove this error in pre-1988 MOBLAS-4 data, the applied tropospheric refraction must be removed and reapplied using the computed elevation angle.

2.2.4 MOBLAS-4 calibration targets/distances

MOBLAS-4 has used 4 different calibration targets (1 board and 3 cube corners) at marker 7110. From August 15, 1983 through December 31, 1987; from January 1, 1987 through January 28, 1988; from January 29 through April 29, 1988; from April 29, 1988 through December 5, 1991; and from December 6, 1991 to the present; the MOBLAS-4 primary calibration targets were the 2Km board, the 2Km cube corner, the 2Km board, the 2Km Nelson pier, and the 200m Nelson pier, respectively.

MOBLAS-4 has been surveyed 5 times (1983, 1985, 1988, and twice in 1992) at marker 7110. Sometime between the 1983 and the 1985 surveys, vandals removed the bracing support of the MOBLAS-4 calibration board tower [*Nelson*, 1985], which could explain the 13mm difference between the 1983 and 1985 calibration board distances. When the new calibration board values were used in data processing, there would be an automatically induced 13mm discontinuity in the MOBLAS-4 range bias. The new board values were used with all data taken after June 20, 1985. Data just prior to June 20, 1985 would have been biased longer by 13mm than data after June 20, 1985 (This 13mm change does not appear in the range bias model, because the exact date of the change is unknown). The cube corner became the operational target in January 1987 (The exact day is unknown at this time).

The distance (2Km) and the design/stability of the original MOBLAS-4 targets (a calibration board mounted on a tower and a cube corner mounted on wooden posts) were limiting factors to surveying accuracy and MOBLAS-4 data accuracy. The survey accuracy of these original targets was at the 10-15mm level [*Nelson*]. Historical ground test results indicate up to 20mm differences in "apparent" system delays between the MOBLAS-4 calibration board and the cube corner, which indicates both targets could move at least 10mm in either direction from month-to-month and from day-to-day. LAGEOS orbital analysis appears to be the only viable means for recovering the "true" average MOBLAS-4 monthly target distance to better than 20mm in the October 1983 to April 1988 timeframe.

Between November 1, 1987 and January 28, 1988, the MOBLAS-4 operational calibration target, cube corner, was very unstable, which caused unusual changes (up to 90mm) in the "apparent" system delay. Individual MOBLAS-4 LAGEOS passes could be biased long (up to 90mm) during this period. *Eanes* [1987] originally discovered this data problem. The bias could change (up to 30mm) from pass-to-pass and from day-to-day. The problem was eliminated when the previous calibration target (board) was used starting January 29, 1988. On April 30, 1988, the MOBLAS-4 calibration target became the 2Km Nelson pier.

2.2.5 MOBLAS-4 TDEL

All MOBLAS-4 data between January 5, 1990 and May 31, 1992 contains a time bias of -0.4 microseconds. To correct this time bias, add +0.4 microseconds to each observation's timetag. This correction is only valid after January 5, 1990, because on this date, the MOBLAS-4 TDEL electronics were modified to eliminate other TDEL sub-microsecond accuracy ambiguities, which would have masked this bias. This bias has been eliminated through modelling, effective June 1, 1992.

2.2.6 MOBLAS-4 known problem data

Between April 12, 1984 and May 24, 1984, individual MOBLAS-4 passes contained discontinuities (100mm up to 600mm) due to the range gate window being changed during the pass. The magnitude of the discontinuities depends upon where the return occurred in the range gate window [*Varghese*, 1985]; therefore, data during this period should not be used. This problem was originally detected by *Eanes* [1985] and was resolved when the system adhered to standard tracking procedures.

2.2.7 MOBLAS-4 potential problem data

Between December 29, 1988 and January 27, 1989, MOBLAS-4 LAGEOS data is questionable due to a bad time interval unit (HP5370). The RMS scatter of this data was cyclic and dependent upon the LAGEOS range [*Heinick et. al.*, 1989]. The data is <u>believed</u> to be unbiased and just systematically noisy. This problem was resolved by replacing the HP5370.

3. MOBLAS-5

3.1 Eccentricities

Since July 1, 1979, MOBLAS-5 has only occupied one monument/marker (7090). There exists only 3 unique sets of MOBLAS-5 eccentricities and 12 MOBLAS-5 SOD's at 7090. SOD 70900508 has 2 sets of eccentricities.

The MOBLAS-5 mount was releveled on September 5, 1985. No survey was performed after the releveling til 1987. The 8mm change in the Up ecc., between the 1979 and 1987 surveys, remains unexplained. It is not known how far back the 1987 Up ecc. can be backdated. The MOBLAS-5 mount was also releveled on August 5, 1989, but the eccentricities were not remeasured. In January 1992, the mount was re-installed and the eccentricities were remeasured. Table 3 contains the recommended set of MOBLAS-5 eccentricities with their corresponding SOD(s) and effective starting dates.

3.2 MOBLAS 5 LAGEOS Biases

The net MOBLAS-5 recoverable biases (range and time) are presented in Table 4. To correct MOBLAS-5 LAGEOS data, the known range and time biases (in Table 4) should be subtracted from the LAGEOS range and timetags, respectively. Any time there is the potential for a change in the bias(es), even though the bias(es) did not change, a new entry has been added. A component breakdown of the biases is presented, followed by a section describing known problem data, and followed by a section describing potential problem data.

3.2.1 MOBLAS-5 ND filters

Prior to June 1, 1992, MOBLAS-5 LAGEOS data was biased short by 3mm $\pm$ 1 due to ND filters. After June 1, 1992, this bias has been removed through modelling.

3.2.2 MOBLAS-5 signal strength

MOBLAS-5 LAGEOS data was biased short by 3mm $\pm$ 2 from July 27, 1983 through April 22, 1987, due to signal strength. This bias would be fairly constant from pass-to-pass. This bias was eliminated when the MCPPMT package was installed in MOBLAS-5 on April 23, 1987.

3.2.3 MOBLAS-5 elevation angles

Prior to January 1, 1988, the tropospheric range correction applied to the fullrate data was computed based on the MOBLAS-5 encoder measurements. To remove this error in pre-1988 MOBLAS-5 data, the applied tropospheric refraction must be removed and reapplied using the computed elevation angle.

3.2.4 MOBLAS-5 calibration targets/distances

MOBLAS-5 has used 4 different calibration targets (2 boards and 2 cube corners) at marker 7090. From August 1, 1979 through June 7, 1980; from June 8, 1980 through May 31, 1987; from June 1 through July 31, 1987; from August 1 through August 25, 1987; and from August 26, 1987 through June 30, 1992; the MOBLAS-5 primary calibration targets were the 2Km calibration board, the 3Km calibration board, the 1Km cube corner, the 3Km calibration board, and the 3Km Nelson pier, respectively.

MOBLAS-5 has been surveyed only 3 times in 13 years (1979/80, 1987, & 1992) at marker 7090. Between the 1979/80 and 1987 surveys, the 1Km cube corner and the 3Km board ranges changed by +30mm and -9mm, respectively. The 2Km board was never resurveyed and the 3Km board blew away in August 1987. In early January 1992, the mount was replaced and a new survey was performed.

The system delay differences obtained from the 1Km cube corner and the 3Km board in historical minico tests since June 1985 were 39mm $\pm$ 5 and 0mm $\pm$ 5 [*Husson and Wroe,* 1987] using the 1980 and 1987 surveys, respectively. Therefore, the 1987 survey values can be backdated to at least June 1985, which means MOBLAS-5 data between June 1985 through May 31, 1987 (all board calibrated data) was biased long by 9mm $\pm$5mm. All data since June 1, 1987, until the mount replacement in 1992, was processed with the 1987 surveyed ranges and should be bias free. Research into minico results prior to June 1985 still needs to be performed.

3.2.5 MOBLAS-5 TDEL

The MOBLAS-5 cable delay causing this bias has not been measured as of this writing. On January 30, 1990, the MOBLAS-5 TDEL electronics were modified to eliminate other TDEL sub-microsecond ambiguities.

3.2.6 MOBLAS-5 PMT Gating

Prior to June 8, 1980, MOBLAS-5 LAGEOS data was biased short by 20mm$\pm$5 due to calibration data falling in a non-linear region of the Amperex 2233B PMT gate. This bias was characterized by *Varghese* [1985]. This bias was eliminated, effective June 8, 1980, when a longer calibration board (>3Km) was used.

3.2.7 MOBLAS-5 known problem data

Between December 19, 1991 and January 3, 1992, MOBLAS-5 data quality was degraded due to a stuck bit. The bit was stuck low (100 picosec.) for LAGEOS. It does not appear that this data is recoverable, because of it's unknown effect on calibration data.

3.2.8 MOBLAS-5 potential problem data

Between August 12, 1988 and January 31, 1989, MOBLAS-5 system delays and pre-to-post calibration shifts were erratic [*Heinick et al.*, 1989]. Therefore, the uncertainty in the system delay is increased during this period; however, this should be a random error than should average over several passes. This problem disappeared during February 1989.

4. MOBLAS-6

4.1 MOBLAS-6 Eccentricities

Since March 3, 1983, MOBLAS-6 has only occupied one monument\marker (7122). There exists 4 sets of MOBLAS-6 eccentricities and 9 MOBLAS-6 SOD's at 7122. SOD 71220604 has two sets of eccentricities.

The May 1988 survey sheet had the <u>wrong sign</u> for the East ecc. It should be negative, not positive. Based on the 1991 survey, there was no apparent change in the eccentricities when the MOBLAS-6 mount was releveled on August 5, 1989. Table 5 contains the recommended set of MOBLAS-6 eccentricities with their corresponding SOD(s) and effective starting dates.

4.2 MOBLAS-6 LAGEOS Biases

The net MOBLAS-6 recoverable biases (range and time) are presented in Table 6. To correct MOBLAS-6 LAGEOS data, the known range and time biases (in Table 6) should be subtracted from the LAGEOS range and timetags, respectively. Any time there is the potential for a change in the bias(es), even though the bias(es) did not change, a new entry has been added. A component breakdown of the biases is presented, followed by a section describing known problem data, and followed by a section describing potential problem data.

4.2.1 MOBLAS-6 ND filters

All MOBLAS-6 LAGEOS data was biased short by 3mm ± 1 due to ND filters.

4.2.2 MOBLAS-6 signal strength

MOBLAS-6 LAGEOS data was biased long by 12mm ± 4, 10mm ± 3, and 4mm ± 2 from May 1, 1984 through March 31, 1986; from April 1 through August 31, 1986; and September 1, 1986 through January 27, 1987; respectively, due to signal strength. This bias would vary slightly (several mm) from pass-to-pass and would have a slight elevation dependence. Low elevation data would be biased longer than high elevation data. Signal strength effects were reduced as system calibration techniques improved, and were eliminated when the MCPPMT package was installed in MOBLAS-6 on January 28, 1987.

4.2.3 MOBLAS-6 elevation angles

Prior to January 1, 1988, the tropospheric range correction applied to the fullrate data was computed based on the MOBLAS-6 encoder measurements. To remove this error in pre-1988 MOBLAS-6 data, the applied tropospheric refraction must be removed and reapplied using the computed elevation angle.

4.2.4 MOBLAS-6 calibration targets/distances

MOBLAS-6 has used 4 different calibration targets (1 board and 3 cube corners) at marker 7122. From May 1, 1983 through March 26, 1987; from March 27, 1987 through August 16, 1988; from August 17, 1988 through October 3, 1989; and from October 4, 1989 through April 30, 1991; the MOBLAS-6 primary calibration targets were the 2Km calibration board, the 2Km cube corner, the first 2Km Nelson pier, and the second 2Km Nelson pier, respectively.

MOBLAS-6 was surveyed 4 times in 8 years (1983, 1988, 1989, & 1991) at marker 7122. In October 1983, several months after the first survey, a hurricane passed through the site. Between the 1983 and 1988 surveys, the ranges to the 2Km cube corner and the 2Km board changed by +6mm and -17mm, respectively. The system delay differences obtained from the these two targets in historical minico tests, since the Quantel laser installation (July 1984), were 33mm ± 15 and 10mm ± 15 [*Husson and Wetzel,* 1987] using the 1983 and 1988 surveys, respectively. The 1988 surveyed target ranges for the cube corner and the board are only accurate to the 10mm level. The 10mm difference which remains in the historical minico results can be attributed to survey. Making this assumption and distributing the 10mm difference equally to both targets, the 1988 survey (with adjustment) can be backdated to the hurricane (October 1983). This means MOBLAS-6 data from October 1, 1983 through March 26, 1987; from March 27, 1987 through May 2, 1988; and from May 3 through August 16, 1988; is biased long by 22mm ± 10, short by 11mm ± 10, and short by 5mm ± 10, respectively.

In 1988, the first Nelson pier was built; however, the pier foundation was not built to specifications. The pier moved 14mm between 1988 and 1989 due to a poor foundation and being on a steep slope [*Nelson*, 1989]. *Nelson* believes this movement would have been linear over the 13 months between the 1988 and 1989 surveys. MOBLAS-6 data between August 17, 1989 and June 23, 1989, was biased long by 4mm $\pm$ 1mm/month. On October 4, 1989, the primary MOBLAS-6 calibration target became the second Nelson pier, which eliminated target movement as a MOBLAS-6 systematic bias source.

4.2.5 MOBLAS-6 TDEL

The MOBLAS-6 cable delay causing this bias has not been measured as of this writing. On January 11, 1990, the MOBLAS-6 TDEL electronics were modified to eliminate other TDEL sub-microsecond ambiguities.

4.2.6 MOBLAS-6 known problem data

All MOBLAS-6 satellite RMS's between February 1 and March 1, 1984, were high caused by a bad distribution amplifier [*Oldham*]. Data during this period should not be used. On March 2, 1984, the distribution amplifier was replaced which eliminated the problem.

4.2.7 MOBLAS-6 potential problem data

All MOBLAS-6 data between February 8 and May 12, 1989, was affected by a bad Setra barometer. Setra barometric data was in error by up to 30 millibars. All MOBLAS-6 data during this interval was corrected and believed to be accurate to at least 3 millibars.

All MOBLAS-6 calibration data between April 1 and September 26, 1990, was unusually noisy (twice the normal RMS). The LAGEOS data during this period is suspected to be bias free. The calibration data returned to normal when some adjustments were performed on the HP5370 in late September [*MOBLAS-6*, 1990].

5. MOBLAS-7

5.1 MOBLAS-7 Eccentricities

Since January 1, 1981, MOBLAS-7 has only occupied one monument/marker (7105); however, two other laser systems (TLRS-2, 71051206, and MOBLAS-2, 71050207) have been referenced to marker 7105. There exists 14 sets of MOBLAS-7 eccentricities and 21 MOBLAS-7 SOD's at 7105.

The reason for the 5mm change in the east ecc. between the 1981 and 1984 survey is assumed to be caused by movement of the survey monument to the East or by movement of the MOBLAS support pad to the West [*Nelson*, 1984].

During the 1985 pre-collocation survey of MTLRS-1 and MOBLAS-7, a 2 cm discrepancy was found in the 7105 Up eccentricity [*Nelson*, 1985]. The original determination of the Up eccentricity is suspected to be in error [*Nelson*, private communication]; and therefore, the 1985 Up eccentricity can be backdated to Jan 1, 1981.

Prior to the TLRS-1 and MOBLAS-7 collocation in 1986 [*Nelson*, 1986], MOBLAS-7 eccentricities were measured on three different occasions, once in December 1985 and twice in January 1986 (before and after the MOBLAS-7 mount was releveled on January 18, 1986). There were millimeter level changes between these surveys. This would give SOD 71050709 five unique sets of eccentricities.

During October 1989, a 1-2 cm bias existed between MOBLAS-7 and TLRS-3 [*Varghese and Husson*, 1989] and a follow-up survey indicated cm level movement of the MOBLAS-7 reference point. Polyquick collocation analysis revealed that the movement appeared to have occurred in August 1989; therefore, the October 12, 1989 survey can be backdated to August 25, 1989.

MOBLAS-7 was down for approximately 6 months in early-1990 due to a major slip ring failure. During this period that the slip rings were being repaired, MOBLAS-7 was removed from it's pad in order that the pad could be reinforced. Prior to ranging and after MOBLAS-7 re-occupied marker 7105, the eccentricities were remeasured. Table 7 contains the recommended set of MOBLAS-7 eccentricities with their corresponding SOD(s) and effective starting dates.

5.2 MOBLAS-7 LAGEOS Biases

The net MOBLAS-7 recoverable biases (range and time) are presented in Table 8. To correct MOBLAS-7 LAGEOS data, the known range and time biases (in Table 8) should be subtracted from the LAGEOS range and timetags, respectively. Any time there is the potential for a change in the bias(es), even though the bias(es) did not change, a new entry has been added. A component breakdown of the biases is presented, followed by a section describing known problem data, and followed by a section describing potential problem data.

5.2.1 MOBLAS-7 ND filters

All MOBLAS-7 LAGEOS data was biased short by 3mm ± 1,1mm ± 1,3mm ± 1, and 1mm ± 1 from January 1, 1981 through July 9, 1991; from July 10 through 23, 1991; from July 24 through October 17, 1991; and from October 18, 1991 through May 31, 1992; respectively, due to ND filters. The OAM was installed on July 10, 1991, removed on July 24, 1991, and reinstalled on October 18, 1991. After June 1, 1992, this bias has been removed through modelling.

5.2.2 MOBLAS-7 signal strength

MOBLAS-7 LAGEOS data was biased long by 30mm ± 15, 4mm ± 2, 7mm ± 3, 30mm ± 10, 5mm ± 3, 3mm ± 2, and 4mm ± 2 from August 22, 1983 through February 29, 1984; from March 1 through July 31, 1984; from August 1 through September 30, 1984; from October 1, 1984 through January 25, 1985; from January 26, 1985 through March 31, 1985; from April 1, 1985 through March 30, 1986; and from February 1, 1988 through April 30, 1988; respectively, due to signal strength. This bias would vary slightly (several mm) from pass-to-pass and would have a slight elevation dependence. Low elevation data would be biased longer than high elevation data. Signal strength effects were reduced as system calibration techniques improved, and were eliminated when the MCPPMT package was installed in MOBLAS-7 on March 31, 1986.

5.2.3 MOBLAS-7 elevation angles

Prior to January 1, 1988, the tropospheric range correction applied to the fullrate data was computed based on the MOBLAS-7 encoder measurements. To remove this error in pre-1988 MOBLAS-7 data, the applied tropospheric refraction must be removed and reapplied using the computed elevation angle.

5.2.4 MOBLAS-7 calibration targets/distances

MOBLAS-7 has used 3 different calibration targets (1 board and 2 cube corners) at marker 7105. From January 1, 1981 through September 19, 1986; from September 20 through December 5, 1986; and from December 6, 1986 to the present; the MOBLAS-7 primary calibration targets were the 3Km board, the second 3Km cube corner, and the 200m Nelson pier, respectively.

MOBLAS-7 has been surveyed at least once per year since January 1984. The February 1981 and the June 1981 surveyed board ranges were incorrect, causing all MOBLAS-7 data from March 1 through June 30, 1981 and from July 1 through December 31, 1981 to be biased long by 49mm $\pm$ 20 and 22mm $\pm$ 20, respectively.

Between the 1984 and 1985 surveys, the board range changed by 17mm, however; historical minico results support the 1984 survey value [*Heinick*, 1985] for the board range (not the 1985 value). On February 7, 1986, the guy wires were tensioned on the calibration board before the board was resurveyed (12mm change); however, the new surveyed calibration board range was not used until March 2, 1986. Therefore, all MOBLAS-7 LAGEOS passes from August 1, 1985 through February 6, 1986, and from February 7 through March 1, 1986, is biased long by 17mm $\pm$ 20 and short by 12mm $\pm$ 20, respectively, except for the LAGEOS passes in Table 9. Occasionally due to ground fog conditions, the board could not be ranged, so the secondary calibration target, the 3km cube corner, was used. All passes in Table 9 were calibrated using the original 3Km cube corner and are believed to have the correct calibration distance. Between the January and October 1989 surveys, the Nelson pier target range changed by 15mm due to movement of the MOBLAS-7 reference point. Apparently, the MOBLAS-7 reference point moved around August 25, 1989 based upon intercomparison with TLRS-3 [*Varghese and Husson*, 1989]. All MOBLAS-7 data from August 25 through October 11, 1989 is biased short by 15mm.

5.2.5 MOBLAS-7 TDEL

All MOBLAS-7 data from July 13, 1989 through September 27, 1990, and from September 28, 1990 through May 31, 1992 contains a time bias -0.5 and -0.3 microseconds, respectively. This correction is only valid after July 13, 1989, because on this date, the MOBLAS-7 TDEL electronics were modified to eliminate other TDEL sub-microsecond accuracy ambiguities, which would have masked this bias. On September 28, 1990, the cable length causing this bias was shortened, which caused a decrease in the magnitude of the bias. This bias has been eliminated through modelling, effective June 1, 1992.

5.2.6 MOBLAS-7 known problem data

All MOBLAS-7 data between January 13 through January 17, 1986, has a reference frequency problem and should not be used. The HP5370 frequency was on internal frequency during this period of time.

5.2.7 MOBLAS-7 potential problem data

All MOBLAS-7 LAGEOS data between June 7 and June 13, 1984 was noisy (100-130mm) and should be used with caution. The cause of the high noise is unknown.

All MOBLAS-7 LAGEOS data between September 25 and October 5, 1984 was noisy (80-120mm) and should be used with caution. The cause of the high noise is unknown.

6. MOBLAS-8

6.1 MOBLAS-8 Eccentricities

Since October 1, 1981, MOBLAS-8 has only occupied one monument/marker (7109). In July 1982, the MOBLAS-4 and MOBLAS-8 moms vans were switched. There exists 9 sets of MOBLAS-8 eccentricities, and 15 MOBLAS-8 SOD's at 7109.

On August 4, 1982 the system was releveled, but there was not a follow-up survey until 1984, which indicated a 17mm change in the Up ecc. *Nelson* [1984] recommends that the 1984 survey be backdated to 1982. There was a 4mm change in the Up ecc between 1985 and 1988, possibly due to settlement of the laser support slab [*Nelson* ,1985]. Table 10 contains the recommended set of MOBLAS-8 eccentricities with their corresponding SOD(s) and effective starting dates.

6.2 MOBLAS-8 LAGEOS Biases

The net MOBLAS-8 recoverable biases (range and time) are presented in Table 11. To correct MOBLAS-8 LAGEOS data, the known range and time biases (in Table 11) should be subtracted from the LAGEOS range and timetags, respectively. Any time there is the potential for a change in the bias(es), even though the bias(es) did not change, a new entry has been added. A component breakdown of the biases is presented and followed by a section describing known problem data.

6.2.1 MOBLAS-8 ND filters

All MOBLAS-8 LAGEOS data was biased short by 3mm $\pm$ 1 and 1mm $\pm$ 1 from September 1, 1981 through April 7, 1992, and from April 8, 1992 through May 31, 1992, respectively, due to ND filters. On April 7, 1992, the OAM was installed in MOBLAS-8 reducing the ND filter bias. After June 1, 1992, this bias has been removed through modelling.

6.2.2 MOBLAS-8 signal strength

MOBLAS-8 LAGEOS data was biased long by 5mm $\pm$ 3, 10mm $\pm$ 5, 6mm $\pm$ 3, and 3mm $\pm$ 2 from August 4, 1982 through December 31, 1983; from January 1 through March 31, 1984; April 1 through July 31, 1984; and from August 1, 1984 through September 25, 1986; respectively, due to signal strength. This bias would vary slightly (several mm) from pass-to-pass and would have a slight elevation dependence. Low elevation data would be biased longer than high elevation data. Signal strength effects were reduced as system calibration techniques improved, and were eliminated when the MCPPMT package was installed in MOBLAS-8 on September 26, 1986.

6.2.3 MOBLAS-8 elevation angles

Prior to January 1, 1988, the tropospheric range correction applied to the fullrate data was computed based on the MOBLAS-8 encoder measurements. To remove this error in pre-1988 MOBLAS-8 data, the applied tropospheric refraction must be removed and reapplied using the computed elevation angle.

6.2.4 MOBLAS-8 calibration targets/distances

MOBLAS-8 has used 5 different calibration targets (2 boards and 3 cube corners) at marker 7109. From September 1, 1981 through August 19, 1985; from August 20, 1985 through December 31, 1986; from January 1, 1987 through March 22, 1989; from March 23, 1989 through April 7, 1992; and from April 8, 1992 to the present; MOBLAS-8 primary calibration targets were the original 2Km board, the second 2Km board, the second 2Km cube corner, the 2Km Nelson pier, and the 200m Nelson pier, respectively.

MOBLAS-8 was surveyed 7 times (1981, 1982, 1984, 1985, 1988, and twice in 1991) at marker 7109. During August 1985, new calibration targets (a 2Km board and 2Km cube corner) were built to replace the vandalized 2Km board and 2Km cube corner [*Nelson*, 1985]. The guy wires had been cut on both targets. The newly constructed board became the operational target, effective August 20, 1985. The preliminary board range and the final surveyed board range published in the November 1985 survey sheet were different by 10mm. It is not known at this writing when the "official" number was used for fullrate data processing. Sometime between October 1986 and January 1987, the cube corner became the operational target. In December 1988, these targets were resurveyed along with a newly constructed 2Km Nelson pier. Between the 1985 and 1988 surveys, the board and cube corner ranges changed by 14mm and 11mm, respectively. Historical minico results, since January 1987, suggest that 1985 and 1988 cube corner surveyed ranges were in error by -20mm and -9mm, respectively. Therefore, MOBLAS-8 data was biased long by 20 ± 15 and 9 ± 10mm from January 1, 1987 through December 11, 1988, and from December 12, 1988 through March 22, 1989, respectively. More research is needed into data processing results prior to January 1987.

6.2.5 MOBLAS-8 TDEL

All MOBLAS-8 data from November 22, 1989 through May 31, 1992, contains a time bias of +0.3 microseconds. This correction is only valid after November 22, 1989, because on this date, the MOBLAS-8 TDEL electronics were modified to eliminate other TDEL sub-microsecond accuracy ambiguities, which would have masked this bias. This bias has been eliminated through modelling, effective June 1, 1992.

All MOBLAS-8 data from August 4, 1982 (the date of the moms van swap with MOBLAS-4) through October 26, 1986 was biased late depending on the interval of a second the laser was fired [*MOBLAS-8 crew and Heinick*, 1986]. The transmit delays (TDEL) on the .0, .2, .4, .6, .8 second intervals were reading high by 0.0, 3.2, 6.4, 9.6, and 11 microseconds, respectively, due to a wiring problem. Since MOBLAS-8 data was equally distributed in these different time intervals, a mean offset of 6.0 microseconds can be post-applied to the data. The TDEL wiring problem was fixed on October 27, 1986.

6.2.6 MOBLAS-8 known problem data

All MOBLAS-8 data between January 1 through March 4, 1982, exhibited very high RMS's (300-600mm) due to poor hardware performance. This data probably contains significant biases and should not be used. The hardware was repaired on March 5, 1982, and the RMS's returned to nominal levels.

7. CONCLUDING REMARKS

The present article has been the first attempt to characterize known biases contained in historical MOBLAS LAGEOS data; however, more research into historical ground test results and calibration processing information is needed to resolve potential biases. These bias models and eccentricity information should improve the quality of the historical MOBLAS LAGEOS dataset. We encourage other global data producing centers to characterize their historical biases.

In the 1980-1983 timeframe, the laser was the dominant MOBLAS systematic error source. In the 1984-1986 timeframe, target stability, survey related issues, and signal strength effects were the dominant error sources. In the 1987-1988 timeframe, target stability and survey related issues were the dominant error sources. In the 1989-1992 timeframe, the HP5370 counter and ND filters appear to have been the dominant error sources. Some of the above mentioned systematic errors are recoverable (to some level) using historical processing results; however, orbital analysis may be the only way to unravel the "net" biases in the global SLR dataset to the 10mm level. These bias models will evolve as historical SLR data is better understood by close cooperation of the data producer and the data user.

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Table 1. MOBLAS-4 Eccentricities for SOD 711004xx

Occ. No.	Start Date	North (M)	East (M)	Up (M)	Revis. Date	Comments
2	08/15/83	-0.033	-0.015	3.209	01Aug92	First survey
2-3	06/20/85	-0.033	-0.015	3.210	01Aug92	1mm change in Up
3-10	04/27/88	-0.033	-0.016	3.213	01Aug92	1 & 3mm change in East and Up
10	02/01/92	-0.031	-0.016	3.213	01Aug92	2mm change in North, no survey sheet published
11	04/21/92	-0.026	-0.019	3.189	01Aug92	Mount replacement

Table 2. MOBLAS-4 LAGEOS Biases at 7110

Time Span	Range Bias(mm)	Time Bias(us)	Revis. Date	Comments
08/15/83 - 04/11/84	17	0	01Aug92	Quantel, 2233B, 5370, Ortec, & board (1954.6037m)
04/12/84 - 05/24/84	17	0	01Aug92	Gating problem causing discontinuous data, see 2.2.6
05/25/84 - 06/30/84	17	0	01Aug92	Data quality returned to normal
07/01/84 - 08/31/84	7	0	01Aug92	Improvement in amplitude modelling
09/01/84 - 06/19/85	3	0	01Aug92	Improvement in amplitude modelling
06/20/85 - 07/31/85	3	0	01Aug92	New target range (1954.5910m), see 2.2.4 para. 2
08/01/85 - 11/19/86	1	0	01Aug92	Improvement in amplitude modelling
11/20/86 - 12/31/86	-3	0	01Aug92	MCP & Tennelec disc. installed
01/01/87 - 10/31/87	-3	0	01Aug92	Cube corner (1955.469m)
11/01/87 - 12/31/87	-3	0	01Aug92	Unstable cube corner, see 2.2.4 para. 4
01/01/88 - 01/28/88	-3	0	01Aug92	Computed angles used, see 2.2.3, unstable cube corner, see 2.2.4 para. 4
01/29/88 - 04/29/88	-3	0	01Aug92	Cal. board (1954.5910m)
04/30/88 - 12/28/88	-3	0	01Aug92	Long Nelson pier (1955.2677m)
12/29/88 - 01/27/89	-3	0	01Aug92	Questionable data, bad counter, see 2.2.7
01/28/89 - 11/06/89	-3	0	01Aug92	New counter installed
11/07/89 - 11/11/90	-3	0	01Aug92	New range (1955.2682m), cube replaced
11/12/90 - 01/04/90	-3	0	01Aug92	Cube vandalized and replaced (1955.2600m)
01/05/90 - 12/05/91	-3	-0.4	01Aug92	Transmit delay modification see 2.2.5
12/06/91 - 01/17/92	-3	-0.4	01Aug92	Translator installed, short Nelson pier (186.9920m)
01/18/92 - 04/20/92	-1	-0.4	01Aug92	OAM installed
04/21/92 - 05/31/92	-1	-0.4	01Aug92	Mount replaced, new target range (186.9986m)

Table 3. MOBLAS-5 Eccentricities for SOD 709005xx

Occ. No.	Start Date	North (M)	East (M)	Up (M)	Revis. Date	Comments
1-8	08/01/79	0.003	0.011	3.185	01Aug92	First survey
8-10	10/15/87	0.003	0.010	3.177	01Aug92	1mm & 8mm change in East and Up
11-12	01/12/92	-0.011	0.020	3.181	01Aug92	Mount replaced

Table 4. MOBLAS-5 LAGEOS Biases at 7090

Time Span	Range Bias(mm)	Time Bias(us)	Revis. Date	Comments
08/01/79 - 06/07/80	-23	0	01Aug92	GP laser, 2233B, 5360, Ortec, & board (2065.491m), gating problem see 3.2.6
06/08/80 - 07/26/83	-3	0	01Aug92	New board (3100.2532m) used
07/27/83 - 05/31/85	-6	0	01Aug92	Quantel & 5370 installed
06/01/85 - 04/22/87	3	0	01Aug92	Suspect 9mm error in target range, see 3.2.4
04/23/87 - 05/31/87	6	0	01Aug92	MCP & Tennelec disc. installed
06/01/87 - 07/31/87	-3	0	01Aug92	Cube corner (1257.9630m) used
08/01/87 - 08/25/87	-3	0	01Aug92	Board (3100.2442m) used
08/26/87 - 12/31/87	-3	0	01Aug92	Long Nelson pier (3116.8969m) used
01/01/88 - 08/11/88	-3	0	01Aug92	Computed angles used, see 3.2.3
08/12/88 - 01/31/89	-3	0	01Aug92	High cal. shifts, see 3.2.8
02/01/89 - 01/29/90	-3	0	01Aug92	Cal. shifts return to normal
01/30/90 - 07/22/90	-3	0	01Aug92	Transmit delay modification, see 3.2.5
07/23/90 - 12/18/91	-3	0	01Aug92	New range (3116.8974m), cube replaced
12/19/91 - 01/03/92	-3	0	01Aug92	Bad data, stuck bit see 3.2.7
01/04/92 - 01/11/92	-3	0	01Aug92	Stuck bit repaired
01/12/92 - 05/31/92	-3	0	01Aug92	Mount replaced, new survey (3116.9047m)

Table 5. MOBLAS-6 Eccentricities for SOD 712206xx

Occ. No.	Start Date	North (M)	East (M)	Up (M)	Rev. Date	Comments
1-4	05/01/83	0.001	-0.007	3.182	01Aug92	First survey
4-7	05/03/88	0.002	-0.006	3.181	01Aug92	1mm change in all eccs., see 4.1
8-9	06/23/89	0.002	-0.006	3.181	01Aug92	No change
9	04/30/91	0.002	-0.006	3.181	01Aug92	No change, final survey

Table 6. MOBLAS-6 LAGEOS Biases at 7122

Time Span	Range Bias(mm)	Time Bias(us)	Revis. Date	Comments
05/01/83 - 09/30/83	-3	0	01Aug92	GP laser, 2233B, 5360, Ortec, & Board (2229.1998m)
10/01/83 - 01/31/84	19	0	01Aug92	Hurricane, suspect target movement, see 4.2.4, para 2
02/01/84 - 03/01/84	19	0	01Aug92	Bad distribution amplifier, see 4.2.6
03/02/84 - 04/30/84	19	0	01Aug92	Distribution amplifier replaced
05/01/84 - 03/31/86	31	0	01Aug92	Quantel laser and HP5370 installed
04/01/86 - 08/31/86	29	0	01Aug92	Improvement in amplitude modelling
09/01/86 - 01/27/87	23	0	01Aug92	Improvement in amplitude modelling
01/28/87 - 03/26/87	19	0	01Aug92	MCP and Tennelec installed
03/27/87 - 12/31/88	-14	0	01Aug92	Cube corner used (2229.4086m)
01/01/88 - 05/02/88	-14	0	01Aug92	Computed angles used, see 4.2.3
05/03/88 - 08/16/88	-8	0	01Aug92	New cube corner range used (2229.4150m)
08/17/88 - 08/31/88	1	0	01Aug92	First Nelson pier used (2229.2215m)
09/01/88 - 09/30/88	2	0	01Aug92	Nelson pier movement, see 4.2.4 para 3
10/01/88 - 10/31/88	3	0	01Aug88	Nelson pier movement
11/01/88 - 11/30/88	4	0	01Aug92	Nelson pier movement
12/01/88 - 12/31/88	5	0	01Aug92	Nelson pier movement
01/01/89 - 01/31/89	6	0	01Aug92	Nelson pier movement
02/01/89 - 02/28/89	7	0	01Aug92	Nelson pier movement, bad barometric data
03/01/89 - 03/31/89	8	0	01Aug92	Nelson pier movement, bad barometric data
04/01/89 - 04/30/89	9	0	01Aug92	Nelson pier movement, bad barometric data
05/01/89 - 05/12/89	10	0	01Aug92	Nelson pier movement, bad barometric data
05/13/89 - 05/31/89	10	0	01Aug92	Barometer repaired
06/01/89 - 06/22/89	11	0	01Aug92	Nelson pier movement
06/23/89 - 11/16/89	-3	0	01Aug92	Second Nelson pier used (2232.7419m)
11/17/89 - 01/10/90	-3	0	01Aug92	New range (2232.7447m), cube replaced
01/11/90 - 03/31/90	-3	0	01Aug92	Transmit delay modification
04/01/90 - 09/26/90	-3	0	01Aug92	Calibration RMS's are high
09/27/90 - 04/30/91	-3	0	01Aug92	Calibration RMS's return to normal levels

Table 7. MOBLAS-7 Eccentricities for SOD 710507xx

Occ. No.	Start Date	North (M)	East (M)	Up (M)	Rev. Date	Comments
1-4	01/01/81	0.016	-0.026	3.169	01Aug92	First survey, Up was in error
5	03/22/84	0.017	-0.031	3.169	01Aug92	1 & 5mm change in North & East
8	05/07/85	0.017	-0.031	3.169	01Aug92	No change
9	07/29/85	0.017	-0.032	3.169	01Aug92	1mm change in East
9	12/13/85	0.017	-0.032	3.170	01Aug92	1mm change in Up
9	01/17/86	0.016	-0.031	3.168	01Aug92	1, 1 and 2mm changes in North, East, and Up
9	01/22/86	0.017	-0.031	3.168	01Aug92	1mm change in North
9-10	03/17/86	0.017	-0.031	3.168	01Aug92	No change
10-11	10/06/86	0.017	-0.031	3.168	01Aug92	No change
11-12	06/18/87	0.017	-0.031	3.168	01Aug92	No change
13	01/09/89	0.017	-0.031	3.168	01Aug92	No change
15-16	08/25/89	0.035	-0.040	3.162	01Aug92	System moved, 18mm, 9mm, 6mm changes in North, East, and Up
17-18	07/25/90	-0.014	-0.033	3.153	01Aug92	Relocation
19-23	12/10/90	-0.014	-0.033	3.153	01Aug92	No change

Table 8. MOBLAS-7 LAGEOS Biases at 7105

Time Span	Range Bias(mm)	Time Bias(us)	Revis. Date	Comments
01/01/81 - 06/30/81	46	0	01Aug92	GP laser, 2233B, 5360, Ortec, & board (3225.460m)
07/01/81 - 12/31/81	19	0	01Aug92	Slyvania laser installed, board (3225.433m)
01/01/82 - 01/31/83	-3	0	01Aug92	Board (3225.411m)
02/01/83 - 08/21/83	-3	0	01Aug92	HP5370 counter installed
08/22/83 - 02/29/84	27	0	01Aug92	Quantel laser installed
03/01/84 - 03/21/84	1	0	01Aug92	Improvement in amplitude modelling
03/22/84 - 06/06/84	1	0	01Aug92	New board (3225.421m)
06/07/84 - 06/13/84	1	0	01Aug92	Data suspect, high RMS's, see 5.2.7
06/14/84 - 07/31/84	1	0	01Aug92	RMS's return to normal
08/01/84 - 09/24/84	4	0	01Aug92	Increase in amplitude dependence
09/25/84 - 09/30/84	4	0	01Aug92	Data suspect, high RMS's, see 5.2.7
10/01/84 - 10/05/84	27	0	01Aug92	Increase in ampl. dependence, high RMS's
10/05/84 - 01/25/85	27	0	01Aug92	RMS's return to normal
01/26/85 - 03/31/85	2	0	01Aug92	Improvement in amplitude modelling
04/01/85 - 07/31/85	0	0	01Aug92	Improvement in amplitude modelling
08/01/85 - 01/12/86	17	0	01Aug92	New range (3225.438m), see 5.2.4 & Table 9
01/13/86 - 01/17/86	17	0	01Aug92	5370 on internal frequency, see 5.2.6
01/18/86 - 02/06/86	17	0	01Aug92	5370 put back on external frequency
02/07/86 - 03/01/86	-12	0	01Aug92	Guy wires on board tensioned, Secondary cal. target new cube corner (3482.552m)
03/02/86 - 03/30/86	0	0	01Aug92	New board range (3225.450m)
03/31/86 - 09/30/86	-3	0	01Aug92	MCP and Tennelec disc. installed
10/01/86 - 12/05/86	-3	0	01Aug92	Cube corner used (3482.547m)
12/06/86 - 12/31/87	-3	0	01Aug92	Nelson pier used (223.385m), antiparallax hardware installed
01/01/88 - 01/31/88	-3	0	01Aug92	Computed angles used 5.2.3
02/01/88 - 04/30/88	1	0	01Aug92	Amplitude dependence (+4mm)
05/01/88 - 01/08/89	-3	0	01Aug92	Elimination of amplitude dependence
01/09/89 - 06/14/89	-3	0	01Aug92	New range (223.3868m)
06/15/89 - 07/12/89	-3	0	01Aug92	New antiparallax hardware installed
07/13/89 - 08/02/89	-3	-0.5	01Aug92	Transmit delay modification, see 5.2.5
08/03/89 - 08/24/89	-3	-0.5	01Aug92	Original antiparallax hardware installed
08/25/89 - 10/11/89	-18	-0.5	01Aug92	Apparent movement of system, see 5.2.4
10/12/89 - 07/23/90	-3	-0.5	01Aug92	New range (223.4018m)
07/24/90 - 09/27/90	-3	-0.5	01Aug92	New range (223.3922m), cube replaced
09/28/90 - 12/09/90	-3	-0.3	01Aug92	TDEL cable shortened, see 5.2.5
12/10/90 - 07/09/91	-3	-0.3	01Aug92	New antiparallax hardware installed
07/10/91 - 07/23/91	-1	-0.3	01Aug92	OAM installed
07/24/91 - 10/17/91	-3	-0.3	01Aug92	OAM removed
10/18/91 - 05/31/92	-1	-0.3	01Aug92	OAM reinstalled

Table 9. MOBLAS-7 Cube Corner Calibrated LAGEOS Passes
(The range biases for these passes would be 0)

Date	Time
08/09/85	5:20
08/09/85	8:51
08/14/85	5:51
08/28/85	4:11
08/29/85	6:16
08/29/85	9:42
08/30/85	8:30
08/31/85	7:08
09/04/85	5:10
09/04/85	8:36
09/06/85	5:55
09/06/85	9:22
09/07/85	4:35
09/07/85	8:03
09/10/85	3:59
09/10/85	7:31
09/11/85	2:52
09/11/85	6:15
09/11/85	9:37
09/17/85	5:04
09/18/85	10:38
09/20/85	8:01
09/21/85	9:59
10/01/85	10:22
10/07/85	12:49
10/08/85	11:24
10/16/85	11:34
10/17/85	13:22
12/03/85	21:32
12/04/85	0:59
02/13/86	22:07

Table 10. MOBLAS-8 Eccentricities for SOD 710908xx

Occ. No.	Start Date	North (M)	East (M)	Up (M)	Rev. Date	Comments
1	09/01/81	0.012	0.011	3.225	01Aug92	First Survey
1	07/22/82	-0.029	0.011	3.124	01Aug92	M8 & M4 mom's van swap
1-2	08/04/82	-0.029	0.011	3.141	01Aug92	System releveled, 17mm change in Up, based on 84 survey
2-3	09/24/84	-0.029	0.011	3.141	01Aug92	No survey sheet
3-5	08/20/85	-0.029	0.011	3.142	01Aug92	1mm change in Up
6-11	12/12/88	-0.027	0.012	3.138	01Aug92	2, 1, & 4mm change in North, East, and Up
12	12/01/91	-0.019	0.005	3.184	01Aug92	Mount replacement
13-15	12/12/91	-0.035	-0.003	3.184	01Aug92	System releveled, 16 & 8mm change in North and East

Table 11. MOBLAS-8 LAGEOS Biases at 7109

Time Span	Range Bias(mm)	Time Bias(us)	Revis. Date	Comments
09/01/81 - 12/31/81	-3	0	01Aug92	GP laser, 2233B, 5360, Ortec, & board (2394.087m)
01/01/82 - 03/04/82	-3	0	01Aug92	Very high RMS's (300-600mm), see 6.2.6
03/05/82 - 08/03/82	-3	0	01Aug92	Hardware repaired, data nominal
08/04/82 - 12/31/83	2	+6.0	01Aug92	M4/M8 van switch, Quantel, HP5370, transmit delay problem see 6.2.5, board (2394.120m)
01/01/84 - 03/31/84	7	+6.0	01Aug92	Increase in amplitude dependence
04/01/84 - 07/31/84	3	+6.0	01Aug92	Improvement in amplitude modelling
08/01/84 - 08/19/85	0	+6.0	01Aug92	Improvement in amplitude modelling
08/20/85 - 09/25/86	0	+6.0	01Aug92	New board used (2389.506 or 2389.496m), see 6.2.4
09/26/86 - 10/26/86	-3	+6.0	01Aug92	MCP & Tennelec disc. installed
10/27/86 - 12/31/86	-3	0	01Aug92	Transmit delay wire connected, see 6.2.5
01/01/87 - 12/31/87	17	0	01Aug92	Cube corner used (2389.519m), see 6.2.4
01/01/88 - 12/11/88	17	0	01Aug92	Computed angles, see 6.2.3
12/12/88 - 03/22/89	6	0	01Aug92	New cube corner range (2389.508m)
03/23/89 - 11/06/89	-3	0	01Aug92	Nelson pier used (2401.1450m)
11/07/89 - 11/21/89	-3	0	01Aug92	New range (2401.1458m), cube replaced
11/22/89 - 11/30/91	-3	-0.3	01Aug92	Transmit delay modification, see 6.2.5
12/01/91 - 12/11/91	-3	-0.3	01Aug92	Mount re-installed, Nelson pier (2401.1392m)
12/12/91 - 04/06/92	-3	-0.3	01Aug92	Mount releveled, Nelson pier (2401.1576m)
04/07/92 - 05/31/92	-1	-0.3	01Aug92	Short range Nelson pier used (207.4742m), OAM installed