FIRST SATELLITE RANGING RESULTS USING A DUAL-PULSE RUBY LASER

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1. Introduction

It has been demonstrated, that the simple passive Q-switched ruby laser may produce pulses of a few nanoseconds width [1],[2]. The new laser constructed for the Potsdam station transmits a diffraction limited TEMoo beam, but usually operates at two adjacent longitudinal modes. As a special feature, it may be adjusted so, that the modes oscillate at different times separated by 0 to 100 ns [3].

In this paper we report on first experiments directed to the use of both the pulses at low signal levels.

2. Hardware Description

The Potsdam laser radar system is based on a 4-axes camera mount modified for automatic tracking using an on-line computer. The main specifications are given in the station report contained in the proceedings.

The new ruby laser is a compact oscillator/preamplifier design with two rubies in the same pumping cavity (Fig. 1).

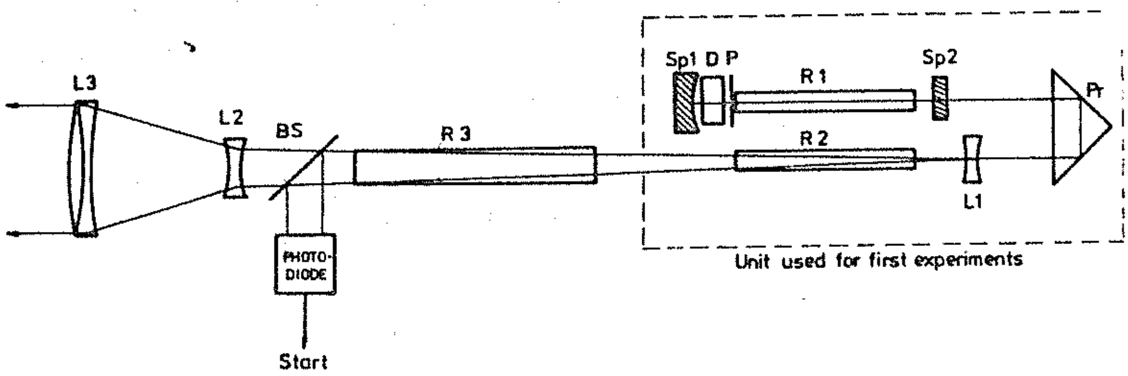

Fig. 1 Optical Scheme of the Laser

For the experiments described here only the 1st laser head producing double pulses of 5ns width, 40 to 80 ns separation, and 20 to 30 mJ energy has been used. The main specifications of the laser without the second amplifier stage are collected in Table 1. Using a beam expander of 5cm aperture only, a divergency of less than 30 arcsec is easily obtained.

To use both pulses it has been found necessary to measure their time separation for each shot, because the second pulse delay is fluctuating about 10%. For this purpose a pulse stretcher/ counter assembly has been designed giving a resolution of 0.1 ns. The real accuracy has been 1ns as yet. This pulse delay measurement system is the main modification of the electronics. Single stop time of flight method is used as before, the first laser pulse starts the counter in any case.

To minimize the noise of the time of flight measurements, both the start and stop trigger have been matched to 5ns pulses. The time walk effect of the stop trigger is now within 1ns for the full dynamical range from 1 to 10000 photoelectrons.

Table 1: Laser Parameters (Oscill.+Preamp.)

Ruby size	(6x120)mm, Czochralski
Resonator length	205mm (physical)
Q-switch	DDI* in methanol (45% SST)
Mirrors	100% dielectric, 51m curvature 15% single glass etalon, flat
Pinhole	0.8mm diam.
Pulsewidth	5ns (2 pulses)
Output energy	20-30 mJ
Repetition rate	10/min

3. Experimental Results

3.1 Calibration Target Ranging

For the single stop system the second laser pulse is occuring in the range data for very low signal levels near to 1 photoelectron only. On the other hand this is the most interesting case, because for strong signals we have a sufficient amount of data even if the first pulse is used only.

Fig.2 is a histogram of calibration target results at single photoelectron level. The attenuation was chosen so, that the return rate was about 50%. For an amplitude ratio of the 1st to 2nd pulse of 3:1, we obtained about 20% second pulse returns. Note that in Fig.2 the second peak is plotted with 5 times enhanced amplitude. In Fig.2a (uncorrected data), the second peak has significantly greater spread in time than the first because of pulse delay fluctuations. In Fig.2b corrections are applied using the pulse separation data.

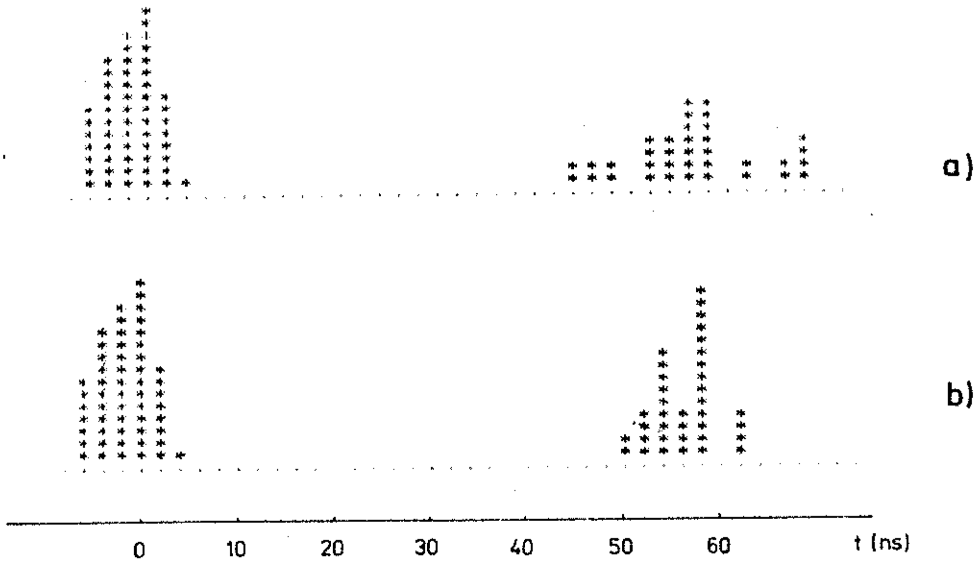

Fig. 2 Histogram of Calibration Target Results

As a result both peaks have the same rms width of about 3ns.

For signal levels of about 100 photoelectrons the first pulse returns are dominating strongly. The rms noise of individual measurements is about 0.5 ns in this case.

3.2 Satellite Ranging

During August 1981 successful satellite ranging of all interesting satellites has been obtained using a 50 to 70 arcsec laser beam. Unfortunately, difficulties with the pulse delay measurement system have prevented the use of the second pulse returns as yet. Therefore the satellite ranging has been focused on satellites giving strong signals to test the ultimate precision. LAGEOS ranging will be continued as soon as the pulse separation can be measured reliably.
Table 2 is a summary of satellite ranging results. In the 4th column of this table the numbers of unambiguously identified returns from the second laser pulse are given. Their percentage is relatively low because of the strong signals.

To determine the rms noise of the individual measurements, each pass has been treated separately. After subtracting predicted ranges the remaining differences have been fitted by a low degree polynomial. The maximum and minimum range noise, determined in this way, are given in the table. The last column contains the averages over all passes, weighted by the number of points of individual passes.

Table 2: Ranging Accuracy Summary

satellite	passes	returns	returns	range noise/cm		
		1st pulse	2nd pulse	max	min	av.
7603901	2	15	2			<50
7502701	17	434	9	42	11	20
7501001	7	172	3	21	12	18
8107501	6	99	2	44	21	30

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(see also these proceedings)

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A Laser LockOut System Using X-Band Radar

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INTRODUCTION

A laser system designed to make high resolution ($\lesssim$ 5 cm) range measurements to satellites (Lageos, Geos and Starlette) in earth orbit will be installed at the Royal Greenwich Observatory during 1982. The laser to be used in this system will allow 30 mJ 150 psec pulses to be transmitted via the 10 cm aperture telescope at up to 10 hz in the green part of the spectrum at 532 nm. This corresponds to peak powers of 200 megawatts with average powers of 300 milliwatts.

One cause for concern is the possibility of aircraft flying through the laser beam during ranging operations. Under certain circumstances the optical energy density in the beam where it is intersected by the aircraft could exceed the Maximum Permissable Exposure. In this context it should be noted that the Gatwick International Airport is about 46 km from the Royal Greenwich Observatory. To prevent the occurrence of such an event it is proposed to design, install and operate a laser lock-out system. This will consist of an aircraft detection sensor, whose output is coupled directly to a control element in the laser. The objective here is to cause the laser to be effectively switched off in the event that an aircraft is detected, before the aircraft path intersects the laser beam pattern and puts the eyes of its passengers and crew at risk. This can be achieved by using an active microwave radar system to detect aircraft, and by designing the radar antenna beam pattern to have a significantly larger spread in solid angle than the laser beam. In addition, the radar dish should be positioned close to the optical telescope, through which the laser beam is transmitted, and aligned such that the laser beam pattern passes up the centre of the radar beam pattern. Then, if the radar dish is slaved to track with the optical telescope, it is possible to detect an aircraft in the field of view of the radar dish before it is illuminated by the laser. This is illustrated in Figure 1(a). The radar receiver will be linked to a status monitor, and in parallel to an electro-mechanical shutter which, when activated will terminate laser oscillation (in about 10 milliseconds) by closing off the optical path within the laser resonator. A schematic of the proposed system is shown in Figure 1(b).

Minimum Eye Safe Range

In this context 'eye-safe range' is defined as the range at which the laser energy density drops to the level of maximum permissable exposure (MPE) defined by British Standard BS4803 (1). According to this standard, the range eye safe R_s from a laser emitting E joules per pulse at a repetition rate of p pulses per second at 532 nm, with a pulse duration τ ($< 10^{-9}$ sec) via a telescope of diameter D, producing a divergence θ is given by,

$$\frac{E}{\frac{\pi}{4}(R_s\theta+D)^2} < \frac{5 \times 10^6}{p} . \tau \qquad (1)$$

For our case E = 30 mJ, τ = 150 psec, p = 10 Hz D = 0.1 m, so we have

$$R_s\theta < 12.5 \qquad (2)$$

with R_s in metres and θ in radians. Evaluation of equation (2) for a 'worst case' value of $\theta = 10^{-4}$ radians yields the eye safe range R_s = 125 km.

Although it is clear that this in no way represents a range at which actual eye damage will occur since the MPE is considerably below the damage threshold, nevertheless it does indicate that to comply with BS4803, some technique for the detection of aircraft at all reasonable altitudes is required.

X-Band Radar Detection System

The geometry of the laser lock-out system is illustrated in Figure 2, which shows a laser beam of angular divergence ω tracking co-axially with the X band antenna, whose main lobe has an angular spread of Ω. We consider an aircraft flying horizontally at an altitude of h and at velocity V into the beams patterns. The maximum time T_{LO} available to shut down the laser assuming a successful radar detection is given by

$$T_{LO} = (h/2v \sin \theta) \ (\Omega - \omega) - \tau$$

where τ is the time taken to activate the electro mechanical shutter. T_{LO} is plotted against aircraft altitude for a range of speeds and elevation angles in Figure 3. The plots show that there is adequate time to achieve lockout for all likely combinations of aircraft altitude and speed, given that $\tau < 50$ m sec.

System Hardware

The lockout system to be installed at RGO will employ a 150 cm diameter X-band antenna dish mounted on an alt-az mount, slaved to the optical tracker telescope. The X-band transceiver is a commercial Marine Radar Unit manufactured by Racal-Decca. It produces 25 kW pulses at 9400 MHz, a pulse duration of 1 µsec and a repetition rate of 865 Hz. The receiver is fitted with a low noise (< 4db noise figure) front end and has a 5 MHz IF bandwidth.

Radar range equation calculations yield a received signal to noise ratio (single pulse case) dependence on range and radar cross section as indicated in Figure 4. However, because the time available for detection increases with range, one can use a cumulative probability of detection based on multiple pulses and a sliding window type integrator to improve the probability of detection, with a threshold level which will yidle an acceptably low false alarm rate and a high probability of detection at relevant ranges.

It is planned to complete installation of the lock-out system during 1981 and to carry out task and calibration procedures during early 1982.

Reference

(1) Radiation Safety of Laser Products and Equipment, Manufacturing Requirements, Ureis finde and Classification, British Standard, BS4803.

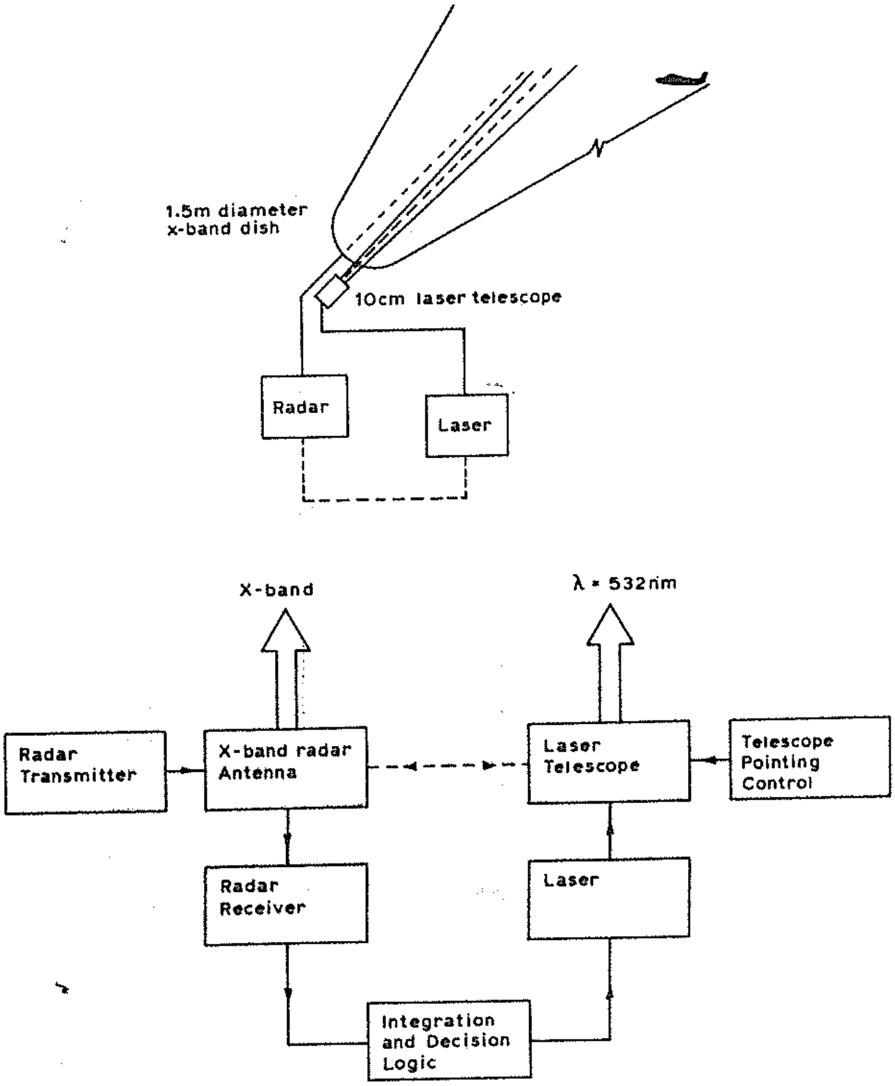

Fig. 1 Schematic of X-band Radar System for Aircraft Detection and Laser Lockout.

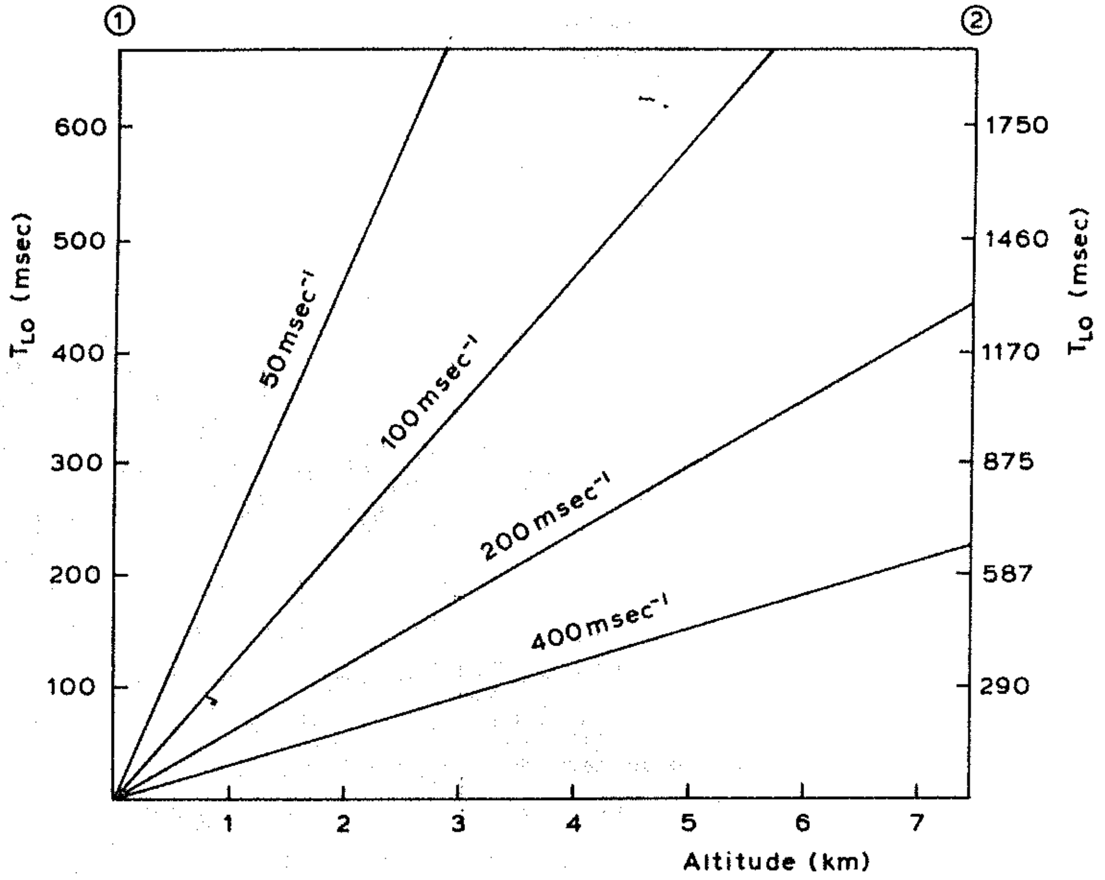

Fig. 3 Time Available for Aircraft Detection and Laser Lockout

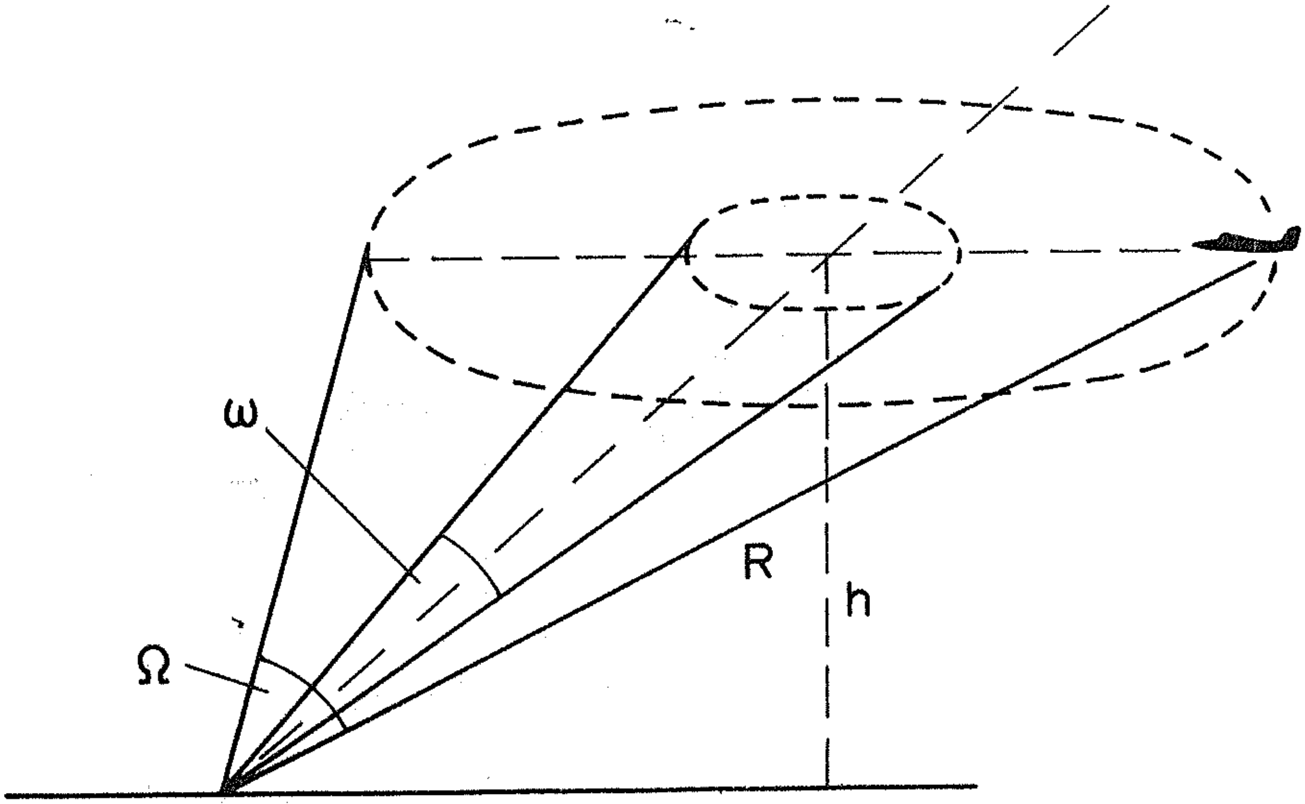

Fig. 2 Aircraft Detection Geometry

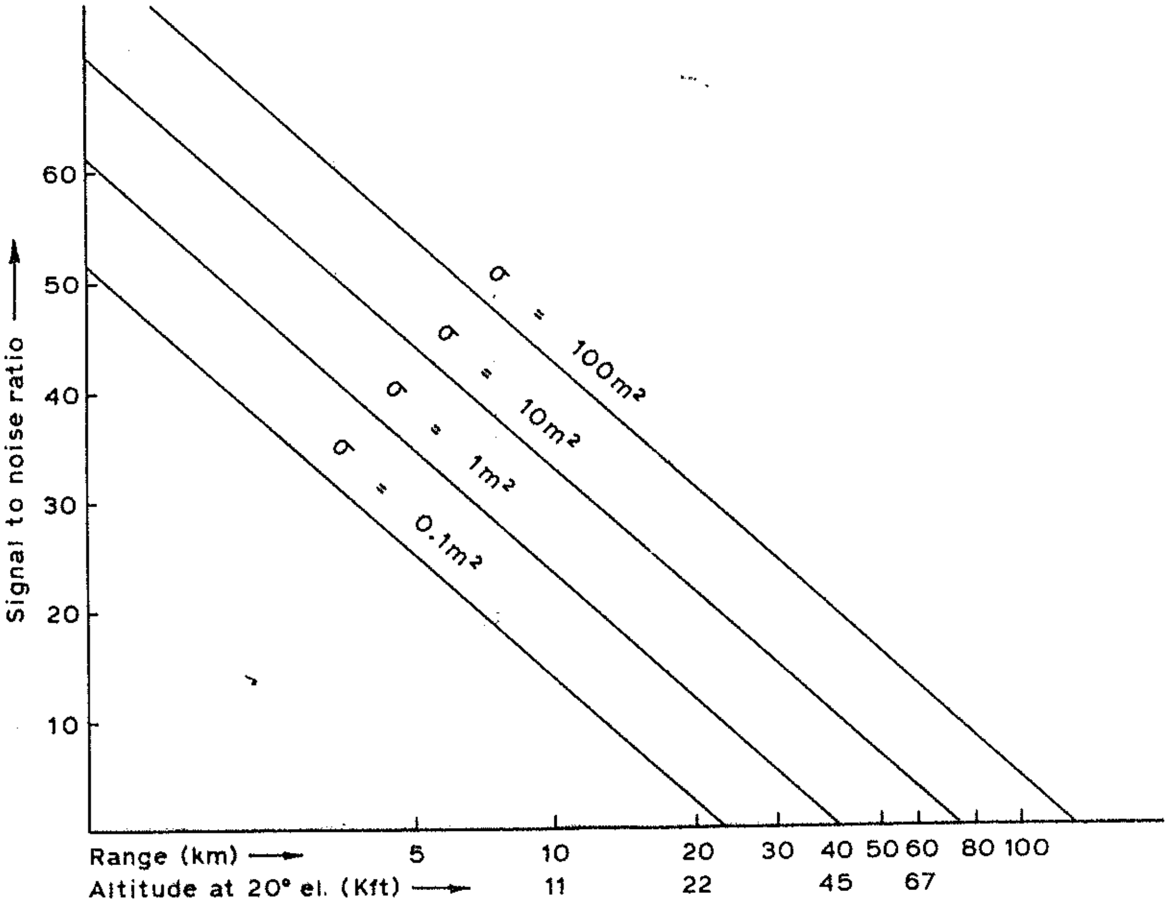

Fig. 4 Dependence of Received Signal-to-noise ratio on Target Cross-section and Range.

A FILTER FOR LAGEOS LASER RANGE DATA

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ABSTRACT

A simple filter for the Lageos range data is described. The basis of the technique is that the second time derivative of range should be constant over short time intervals. The method is well suited for use at observatory sites and as a means of cleaning the data prior to compressing it into normal points.

INTRODUCTION

We aim to use the high-accuracy laser range measurements to the Lageos satellite, obtained at existing fixed tracking stations in the Australasian region and possibly by one or more transportable units deployed at critically selected sites to measure baselines in order to determine the relative motion between the stations (Stolz, 1981). One problem that immediately arises is that the data contain a significant proportion of outliers. These outliers are commonly removed after comparing each observation with a modelled counterpart obtained from, amongst other things, an orbit computed using all the data (Dunn, 1981). Such a scheme is inefficient and in most cases unnecessary.

We have devised a much simpler method of detecting outliers in the Lageos range data which employs the fact that, over short intervals of time, the variation of the range measurement very nearly approximates to a degree two curve. We give only an outline of the technique and two examples of its application here. For details, we refer the reader to Masters _et al_. (1981).

METHOD

For orbital arcs which do not exceed 30 seconds in length, we find that the Lageos range measurements vary with time according to a degree two curve. In Fig. 1 we plot the root mean square difference between range data and the corresponding range as modelled by a second degree curve. The data span to which the curve is fitted has been varied from 0 to 300 seconds. The truncation error exceeds the 10 cm level around the 30 second mark. This implies that, for time intervals smaller than 30 seconds, the second time derivative of range can be considered to be constant. Moreover, the difference between consecutive second time derivatives should be small and essentially proportional to the data quality. An upper bound for the departure from this condition may be obtained by applying the law of propagation of variances to the second derivative calculations. Using this technique, we are able to trace an anomolous difference of the second time derivative to two satellite range values. The outlier is then determined by means of an iterative scheme.

RESULTS

In order to demonstrate the effectiveness of the filter, we have selected two Lageos passes each containing a number of outliers. In Figs. 2a and

3a we have plotted the residuals of the raw data with respect to an orbit computed from the good data. For convenience, residuals exceeding 5 m have been assigned a value of 5 m. The same passes, after applying the filter, are shown in Figs. 2b and 3b. For this study the rejection level for the range measurements was set at 2.5 m.

Stricter conditions can of course be imposed and the level of rejection can be tightened.

CONCLUSIONS

We have developed the filter for cleaning the data prior to compressing it into normal points. The method is a simple one and could therefore be adapted for use at observatory sites. Subsequent savings of computer time are substantial. The method is better suited for use with data gathered at the Moblas sites and by TLRS-type instruments than with SAO station data. This is because with the former the acquisition rate is higher and one is therefore less likely to encounter gaps in the data bigger than 30 seconds. The filter does not remove biases and long-period signals.

ACKNOWLEDGEMENTS

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FIGURE CAPTIONS

Fig. 1

Differences (r.m.s.) between Lageos range data and the corresponding range as modelled by a degree two curve for various time spans.

Fig. 2

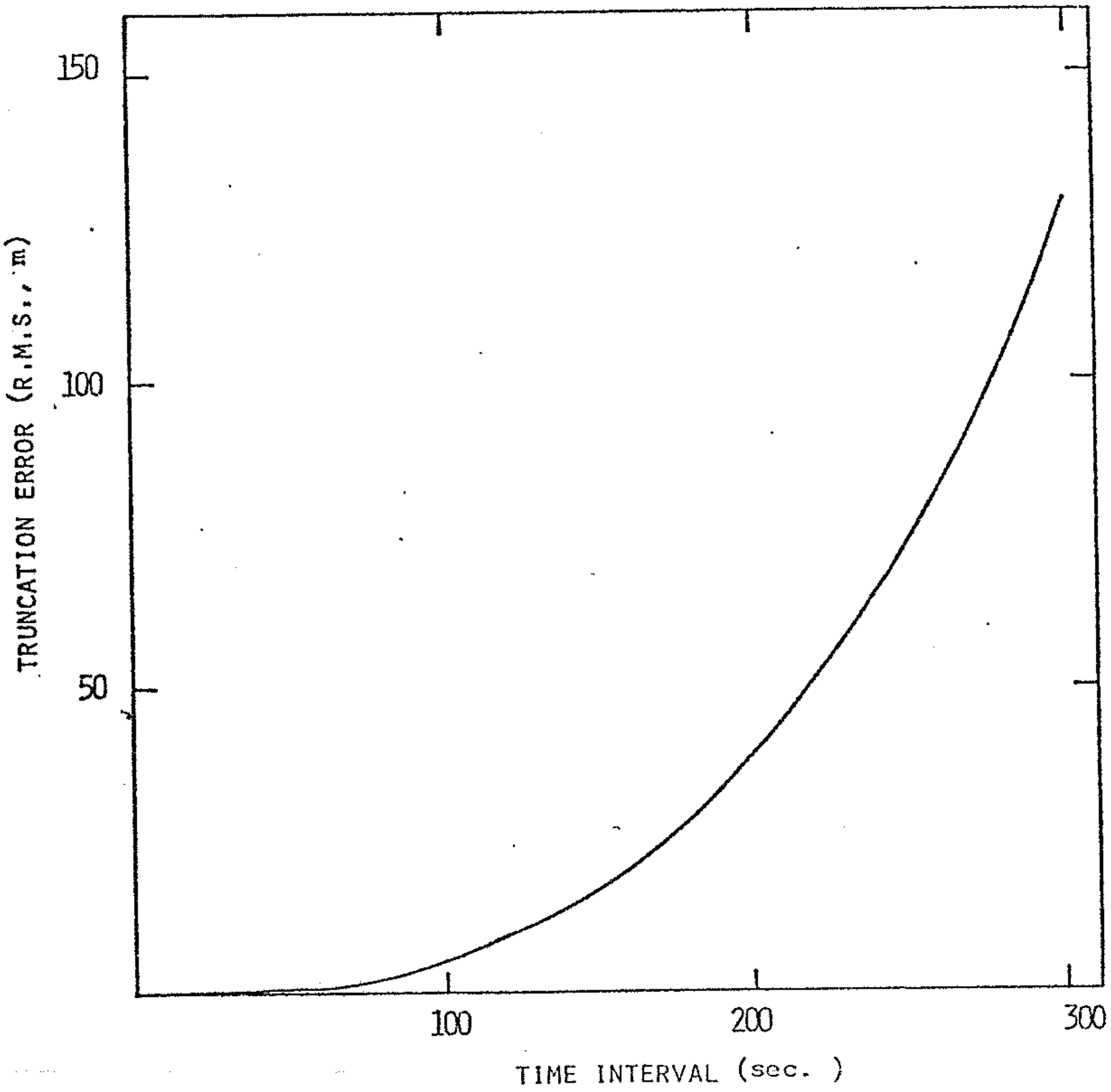
(a) Residuals of raw Lageos range data with respect to an orbit computed from good data. Residuals exceeding 5 m have been assigned a value of 5 m.

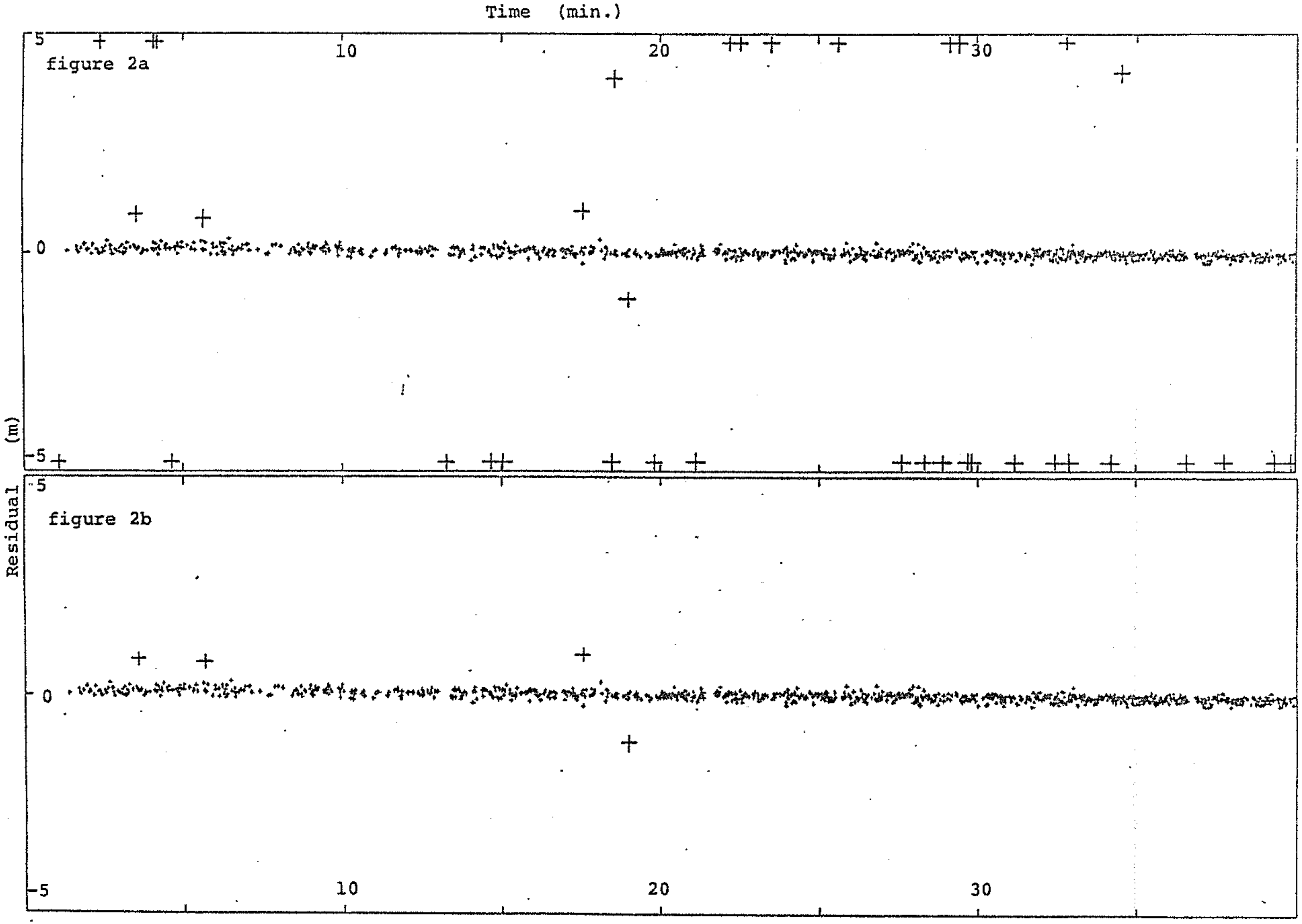
(b) Same, except that the data are filtered. The rejection-level in this example is set at 2.5 m.

Fig. 3.

Same as Fig. 2, except for a different site and time.

FIGURE 1


150
100
50
TRUNCATION ERROR (R.M.S., m)
100
200
300
TIME INTERVAL (sec.)


Time (min.)
figure 2a
figure 2b
Residual (m)
5
10
20
30
5
0
-5
5
0
-5
10
20
30

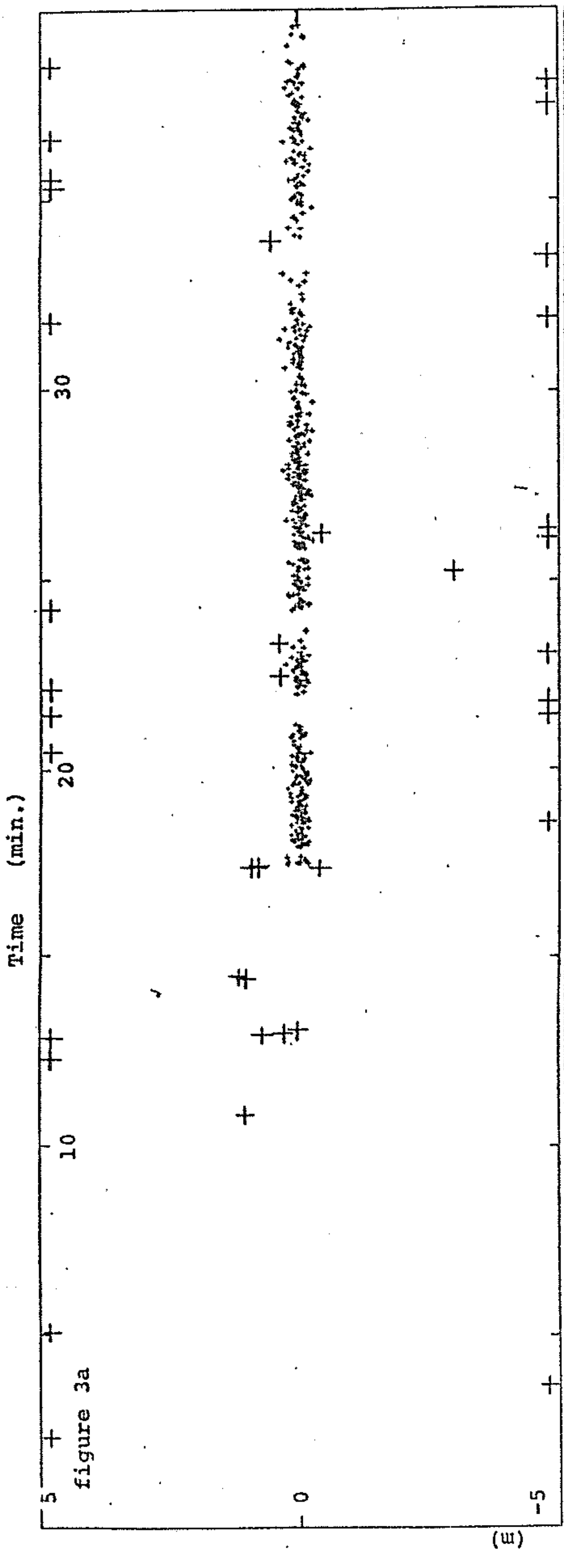


figure 3a

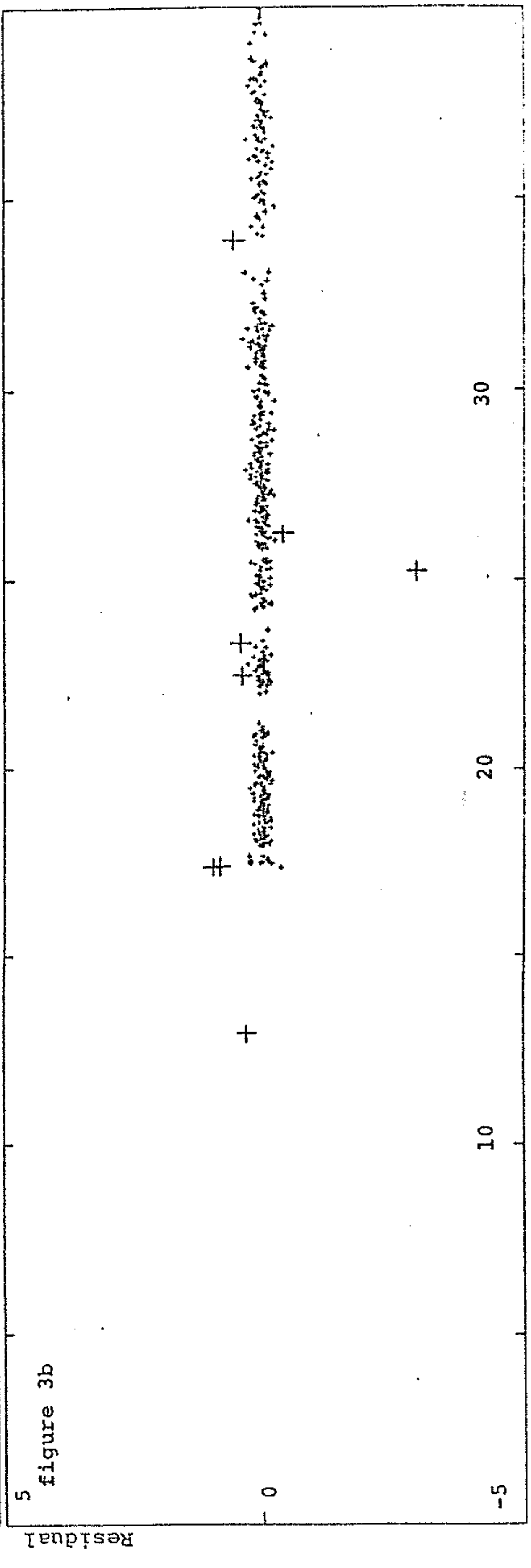


figure 3b

SCIENTIFIC GOALS OF LASER RANGE MEASUREMENTS

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ABSTRACT

Two of the most important areas of geodynamics to which laser ranging appears capable of making fundamental contributions are discussed. These are worldwide plate tectonic motion measurements and the monitoring of the longer wavelength crustal movements in seismic zones. In both areas, the accuracy and reliability of the results are of great importance, since a factor 2 improvement in accuracy can reduce the time necessary for detecting anomalous motions by the same factor. The capabilities of other techniques are discussed briefly, and it is argued that laser ranging to satellites is likely to make major and unique contributions to geodynamics if it succeeds in demonstrating higher measurement accuracy than radio techniques. A strong emphasis on improving the measurement accuracy thus appears to be needed during the next two years.

INTRODUCTION

Accurate laser range measurements to satellites like LAGEOS can provide valuable and exciting new scientific information in geodynamics, as well as important information in several other fields. Rather than trying to cover most possible applications of laser ranging results, the next section will concentrate on discussing what I believe are the two most important scientific problems where laser ranging to satellites is likely to have a major impact in the 1980's. These are the measurement of present worldwide plate tectonic motion rates and the monitoring of the longer wavelength features of strain accumulation patterns in seismic zones.

An additional reason for focusing attention on these two topics, besides their intrinsic scientific importance, is that laser ranging may have a unique advantage in these cases. Other techniques are being developed which can address the same scientific problems, including particularly very long baseline radio interferometry (VLBI) for worldwide measurements and the use signals from the Global Positioning System (GPS) satellites for geodetic measurements in seismic zones. However, for both worldwide plate motions measurements and determining the longer wavelength strain changes in seismic zones, obtaining the highest possible accuracy is of great importance. The potential unique advantage of laser ranging is that its sensitivity to the water vapor content of the atmosphere is lower than for radio techniques. Thus, there appears to be very strong reason for the continued vigorous development of laser ranging, provided that the systematic measurement errors can be reduced to or below the level of uncertainties due to the dry part of the atmosphere.

In view of the importance of achieving high accuracy in laser ranging, some additional discussion of this topic will be given in the third section. Some of the capabilities of the radio techniques will then be reviewed in the fourth section, in order to encourage further discussion of the kinds of scientific problems for which laser ranging is most suitable.

The scientific returns expected from laser ranging and the other techniques include new information on the earth's rotation and polar motion. However, I won't say much about these topics because the network of stations needed for determining crustal movements is likely to produce very good results for earth rotation and polar motion also. Lunar ranging won't be discussed either, although it is likely to make important contributions both to determining the earth's rotation and nutation and to other important scientific questions such as the secular deceleration of the moon, lunar structure, and the validity of present gravitational theories.

SCIENTIFIC GOALS IN CRUSTAL DYNAMICS

One of the most important questions which laser ranging is likely to play a major role in answering is whether the rates of motion of the larger tectonic plates are within roughly 1 cm/yr of the presently estimated rates. Agreement with the estimates is likely if recent studies of the average motion rates over roughly the last 3 million years are correct and if variability over shorter times can be neglected. However, short-term variability appears to be a plausible possibility.

Over periods of up to roughly a thousand years it is possible to think of models where the back part of a plate moves quite uniformly away from a spreading center, but the front or sides of the plate move considerably less because of the lack of large earthquakes at the boundaries. Buildup of stress within the plates over such a period would not necessarily be sufficient to trigger large earthquakes, and substantial distortion within the plate could occur. In looking for such internal distortions, one prime candidate is the Pacific plate, which is very large and also quite rapidly moving. Another candidate is the Australian plate, which might show distortion between India and Australia because of the episodic nature of crustal movement along the boundary between the Indian subcontinent and the Eurasian plate.

On the other hand, the present ideas of most geophysicists about the viscosity and thickness of the asthenosphere, which underlies the plates, would not permit such distortion away from the boundaries of even large and rapidly-moving plates. The reason is that the calculated time constant for the effect of a major earthquake at the boundary to propagate out into the plate is quite long. For this reason, the effects of changes in the boundary conditions for the plate motion would not have much effect beyond perhaps 300 kilometers from the boundary over periods characteristic of the recurrence times for large earthquakes, such as perhaps 100 or 200 years. Thus, according to this picture, the main part of the plate would continue to move quite uniformly, with earthquakes around the boundary causing episodic strain changes only near the edge. However, we should keep in mind that quite a bit of our present information on the viscosity of the asthenosphere comes from post-glacial rebound studies in Canada and Fennoscandia, which are continental areas. Thus our information concerning the asthenosphere under oceanic plates may be less reliable.

For periods of time longer than roughly 1,000 years, the main question is whether the forces driving plate tectonic motions are likely to be fairly constant. At present, the three types of forces which generally are believed to be the largest ones for a plate such as the Pacific plate are: the gravitational force associated with sliding of the back of the plate off the East Pacific rise; the negative buoyancy force on the down-going slab at the front of the plate because of its higher density; and the resistance of the mantle to the downward motion of the front of the plate. The last two forces may roughly cancel each other for a given rate of motion, with the gravitational sliding pushing on the main part of the plate to keep it pressing against the back of the down-going slab. If these forces really are the dominant ones, it seems unlikely that they would change dramatically over periods of less than perhaps a million years. However, measurements which give direct information on these questions would certainly be valuable. If the present motions of the major plates are not within roughly a centimeter per year of the presently estimated rates, this would require a substantial change in our picture of how the plate motions occur.

Direct measurements of present plate motion rates also will be important for other reasons. For some minor plates, there is not enough information available to determine the long-term average rates. Also, in order to interpret measurements of the apparent motion of a plate, it is necessary to check on the basic stability of a major part of the plate interior. Otherwise, internal distortions within the plate could lead to errors in the deduced plate motion rate. The measurements of crustal movements in plate interiors will be important also for determining how tectonic forces modify the plates. However, the rates of distortion expected are generally very small, and accuracies of 2 or 3 mm/yr are needed for studying most questions of interest.

A second major question concerns the nature of the larger wavelength crustal movements in and near seismic zones. In this case, there are strong differences of opinion about what measurement accuracy is needed. A substantial number of scientists believe that large displacements occur fairly frequently in some major seismic zones, such as the uplifts characteristic of the reported Palmdale bulge and the horizontal displacements given by the initial interpretation of earlier VLBI mobile station data. On the other hand, it has been suggested that atmospheric refraction or other effects had an important influence on the leveling data used to deduce the existence of the Palmdale bulge, and it seems possible that the reported motion of roughly 20 centimeters for JPL with respect to Owens Valley was due to a combination of ionospheric, tropospheric, and instrumental systematic errors. Thus other scientists would say that the probability of learning about strain accumulation in seismic zones isn't increased much by making measurements more frequently than a characteristic time T, which depends on the accuracy of the measurements and the baselines of interest. T would be roughly the time required at the average strain accumulation rate for the area to accumulate displacements equal to the accuracy for measuring displacements. For the San Andreas fault system, the average rate is typically about 2 parts in 10^7 per year.

It seems to me that the strategy for measuring crustal movements by space techniques needs to be "robust" in the statistical sense. Namely, the strategy should be designed so that it is likely to lead to useful results, whichever of the two opinions about the nature of the motion we are looking for turns out to be correct. Thus, a major part of the effort should be devoted to making the measurements as accurately as possible. But there also is a need for making other measurements rapidly, even if the accuracy is somewhat lower, in case large motions actually are occurring or might occur a short time before a large earthquake.

Laser range measurements seem likely to contribute mainly through the monitoring of a moderate number of sites with as high accuracy as possible. In California, for example, the accurate monitoring of 15 to 20 sites once per year can provide valuable new information on strain accumulation out to large distances from the main fault system. These sites will be coordinated with the accurate trilateration networks of the U.S. Geological Survey so that they provide both ties between the networks and intercomparison lines across the networks.

For measurements in major seismic zones in other countries, the ways in which laser ranging can contribute the most will vary. In

Japan, where excellent ground measurement networks already exist and frequent measurements are made in special study zones, the role of laser ranging may be similar to that expected in California. In areas such as western South America, sites monitored by laser ranging are more likely to serve as reference points for measurements made using other types of instruments, such as GPS geodetic receivers. Such combined networks could provide quite high accuracy, at relatively low cost, for monitoring long-term strain accumulation patterns in areas where extensive ground measurement networks do not exist at present. They also would give valuable initial epoch measurements at an early date, so that coseismic and postseismic displacements after a large earthquake could be determined effectively.

A third type of seismic zone investigation is represented by proposed measurements in the Hellenic Arc, where substantial chances of a major earthquake in this century appear to exist, and other tectonically active areas of southern Europe and the Near East. Another application in the future might be to determine where the relative motion between the Indian subcontinent and central Asia is being accommodated. Ground measurements in the USSR have indicated relative motions of about 2 cm/yr between two mountain ranges in the region near Garm, but it is not known where the rest of the expected motion is occurring. Other important applications may be in New Zealand, where a major strike slip fault system can be studied relatively easily, and in the major seismic zones in China, India, Pakistan, and the USSR.

RELATED QUESTIONS CONCERNING MEASUREMENT ACCURACY

In view of the necessity of achieving high measurement accuracy and reliability for the scientific problems considered above, some additional discussion of accuracy seems desirable. Some useful methods for evaluating accuracy are as follows: (a) construction of systematic error budgets, (b) investigation of the stability and reasonableness of results, (c) comparisons with other laser ranging systems over short baselines, and (d) consistency of global solutions. While all of these methods have some advantages, none of them is sufficient by itself. For example, important effects can be left out of systematic error budgets, and the stability and reasonableness of experimental results over some period of time would not show up errors which correlate strongly with the azimuth or elevation angle of the observations, since they would produce consistent effects in the apparent station position. Also, consistency of global solutions cannot be established until after systems with high accuracy have collected data for a substantial period, such as a year or so. It thus seems necessary to proceed using all four of these approaches.

The confidence level for measuring crustal movements has to be high if the results are to influence geophysicists. Some prior information exists on long-term plate motions plus reasonable theoretical reasons for suspecting constancy of motion over long times, as discussed earlier. Thus, geophysicists aren't likely to change their ideas based on discrepancies which have only 70% confidence limits, which really constitute "just another opinion." Testing hypotheses at the 95% confidence level is widely accepted in biology, medicine and other areas of science. It seems essential to reach the same level of confidence in deciding whether anomalous motions have been detected. This is particularly true for conclusions about whether the present rates of plate motion disagree with the long-term average rates.

It should be emphasized that dealing with 95% confidence intervals is substantially different than taking 70% confidence intervals and then roughly doubling them. That procedure would work for Gaussian error distributions or any other error distributions for which the tails cut off rapidly. But with some systematic error sources, the error level for 95% confidence may be 4 or 5 times larger than for 70% confidence. For example, wavefront corregation errors may average out fairly well at the 70% confidence interval because of changes in the pointing error during the course of a run or over a couple of days. However, at the 95% confidence level it is much harder to be sure that correlated effects aren't present, such as the pointing being considerably better later in the run than early in the run, coupled with smaller wavefront corregation errors in the center of the beam. This could give an apparent offset in the station position. It seems necessary to make up separate systematic error budgets at the 95% confidence level, rather than assuming that the ratio of 95% and 70% confidence estimates for different error sources is the same.

One particularly disturbing thing about systematic errors is associated with the fact that they can vary systematically with time during a pass so that they cause an error in the station position. The magnitude of the station error can then drift roughly linearly over long periods of time because of gradual changes in the instrumental errors. Thus, one could remeasure a baseline many times over a period of 2 or 3 years and see a roughly linear change in length. However, the confidence level for being able to say that a real change in length occurred may be little better than if most of the intermediate measurements hadn't been done. This is because, at the 95% confidence level, the magnitude of the systematic errors could indeed have changed roughly linearly 5% of the time. Additional intermediate measurements still are valuable, of course, in giving consistency checks.

The approach of constructing careful error budgets and publishing a discussion of how the individual error magnitudes were estimated has been used very widely in connection with measurement of the fundamental constants in physics. Realistic error estimates are needed so that the results of experiments measuring different combinations of the fundamental constant can be combined. While the degree of over-determination in the available experiments is not very high, it is sufficient to show how consistent the results are. Discrepancies certainly occur, but historically the number of experiments which have turned out to be in error by considerably more than the quoted uncertainties has been fairly small.

As an example of the extent of accuracy improvement which is needed, the error budgets for the NASA stations given in the Laser Ranging System Development Plan (NASA, 1980) are shown in Table 1. The error contribution due to the dry part of the atmosphere has been reduced to 0.7 cm to correspond to the results obtained by Gardner (1976) at 20° elevation from radiosonde data without any correction for horizontal gradients in the atmospheric density. Fortunately, at least one of the MOBLAS stations currently is being substantially upgraded in accuracy, as discussed in another paper, and it is planned to upgrade three of these stations to 1 to 2 cm accuracy at the 70% confidence level by 1983. However, further accuracy improvements certainly are needed in the next 2 years.

Table 1

Current Error Budgets* for the GSFC Satellite Laser Ranging Systems

Error Source	STALAS	MOBLAS 1-3	MOBLAS 4-8
Transmitter	0.5 cm	2.5 cm	6.0 cm
Atmosphere	0.7	0.7	0.7
Satellite (LAGEOS)	0.2	0.2	0.2
Receiver	1.5	4.0	8.0
Timing	0.7	0.7	0.7
Calibration	1.0	1.0	1.0
Total (RSS)	2.1 cm	4.9 cm	10.1 cm

*Normal point accuracy, 100-point average.

CAPABILITIES OF OTHER TECHNIQUES

In discussing the scientific contributions which laser ranging is likely to make, it is important not to underestimate the capabilities of other methods. Some of the capabilities demonstrated by VLBI measurements for determining baselines are listed in Table 2. The subcentimeter demonstrated accuracy and repeatability over a 1.24 kilometer baseline and the 3 centimeter repeatability over 4 years for a 3,929 kilometer baseline are accomplishments which laser ranging has not yet equaled. Also, actual measurement times as short as 1 day at a site have been demonstrated by the mobile 4 m ARIES VLBI station.

For measurements with either VLBI or GPS signals, the uncertainty in the tropospheric correction due to water vapor seems likely to be the most serious limitation. Even with water vapor radiometers in operation at each site, the uncertainty in the water vapor correction is likely to be about a centimeter, as discussed elsewhere (see e.g. Resch, 1980; Guiraud _et al._, 1979; and other references given in Bender, 1980). However, the situation is really too complicated to

Table 2

VLBI Baseline Measurements

Length (km)	Precision, Repeatability, or Accuracy (cm)	
1.24	0.3, 0.5, 0.7 (three components)	Repeatability (15 mo)
	≤0.6	Accuracy
42*	10	Accuracy
3929	3	Repeatability (4 yrs)
5600 to 7914†	6 to 8	Precision

*Difference of 353 and 387 km baselines measured by mobile station.

†U.S. to Sweden baselines; precision estimated from effects of different assumptions in analysis.

be described by a single number. In addition to the calibration errors of the water vapor radiometers, the effects of uncertainties in the effective emission temperature of the atmosphere and in the distribution of droplet sizes in clouds also have to be considered. Radiometer calibration errors are not likely to introduce azimuth-dependent measurement errors, so horizontal coordinates may be affected relatively little by this source of error. On the other hand, the one centimeter water vapor correction error estimate mentioned above has not yet been demonstrated experimentally, and the effect of such an error on the vertical coordinate of a station may be larger by as much as a factor 2.

The level of uncertainty in the range due to horizontal gradients in the dry part of the atmosphere also is uncertain. Since such uncertainties affect laser ranging as well as radio methods, the potential accuracy advantage of laser ranging would be small if the dry part of the atmosphere should turn out to introduce as much uncertainty as the water vapor does. Hopefully some reduction in the horizontal gradient error below the 0.7 cm value at 20° elevation angle found by Gardner (1976) can be achieved by using airport radiosonde data or other meteorological information, since much of the effect comes from gradients at the higher elevations. Such gradients may exist over fairly large areas and be stable over periods of a number of hours, except near frontal systems. However, Pearce et al. (1981) have raised the question of whether gradients with shorter wavelengths than those studied by Gardner may give larger uncertainties for an observation campaign of limited duration. Such questions certainly need to be resolved.

While the size of the effects discussed above is considerably more uncertain than we would like, it still seems fairly likely to me that the errors for laser ranging will be a factor 2 smaller than those for radio techniques. Thus, if we can make the other sources of systematic error for laser ranging small enough, I believe that the overall accuracy may be better than for any other technique.

The crustal dynamic problems for which an accuracy advantage would be particularly important are those discussed in Section 2; i.e. measurements of plate tectonic motions and of the longer wavelength distortions in seismic zones. For plate tectonic motions, in particular, the total number of measurements needed per year is limited, so the overall cost hopefully can be kept at a reasonable level. A factor 2 difference in accuracy will have a major impact scientifically, as mentioned earlier, because it reduces the time necessary to compare present motions with the expected rates by about the same factor. If this means obtaining new scientific information in 5 years which otherwise would have taken 10 years of measurements, then the probability of affecting the work done in a considerable area of geodynamics over a substantial period of time is considerably enhanced. For determining where large-scale distortion is taking place in plate interiors, the advantage of improved accuracy is equally strong.

There are important types of problems, however, for which laser ranging from mobile ground stations does not seem likely to be the most efficient approach. This includes, particularly, cases where large numbers of measurements need to be made per year, either with moderate times between measurements at a high density of points in seismic zones, or at very short repetition times for a lower density of points. In cases of this kind the cost per measurement is a very important factor, as well as the accuracy. It now appears likely that measurements using GPS receivers can be made with 1 or 2 centimeter accuracy in times as short as half an hour or less if the Global Positioning System is completed as planned. If not, VLBI measurements with highly mobile stations will still be quite competitive because of the considerable cloud cover problems for laser ranging, and the fact that one doesn't have to wait for a LAGEOS pass to make observations. While the cost of high mobility laser ranging stations is likely to be less than that for their VLBI counterparts, the operating budgets probably will be the most important factor over long times. However, if new information on the relative accuracies achievable by optical and radio methods favors laser ranging, the use of a larger number of high density satellites in lower orbits needs to be considered (Wilson et al., 1978). The launch of a second LAGEOS satellite also might be desirable in that case.

In addition to the measurements discussed above, a few words should be said about the possible future capabilities of airborne laser range measurements. NASA has been involved in investigating the accuracy achievable by pulsed laser range measurements from aircraft to ground reflectors. This approach might well be competitive for frequent repeat measurements in seismic zones with the use of high mobility VLBI stations and possibly also with GPS receivers if higher accuracy can be achieved. In addition there is a possibility that airborne measurements using a line crossing method with microwave modulated cw lasers would be desirable in the future. The potential advantage would be high measurement accuracy, with the two-wavelength approach used to correct for atmospheric refraction. However, the vertical coordinate would not be determined well with this approach.

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Status of the networks for global and regional laser ranging

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1. Introduction - System review

A telescope count of all laser ranging equipment known to exist or to be under construction at this time (and to be fully operational by 1984) gives approximately 50 units. These systems differ widely in their capabilities and operate in the framework of one or more of the international networks.

Only four of the systems have been designed for relatively high mobility and of these only one, TLRS I, is currently in the field; a second, TLRS II, will follow shortly. The remaining two systems, a German and a Dutch, are undergoing construction and will be identical. Both systems will be handed over for field testing in 1983 and will go into full operation in 1984. All four systems will produce data of similar quality, characterised here by 1-3 cm normal points.
Details of all of these will be discussed in succeeding presentations.

There is some prospect that TLRS III and TLRS IV will be procured in the time-frame 1984-85, but this will depend upon a number of factors which are currently not predictable.

It is anticipated that there will be 4 further MOBLAS type stations plus some 8 permanent stations world-wide of the same ultimate quality in operation by 1984. Of these the stations at Herstmonceux (UK), Lustbühel (Austria), Mc Donald Observatory - MLRS - (U.S.A) and

Orroral - NATMAP - (Australia) are under construction and Simosato (Japan) is just about to be installed. Haleakala, MOBLAS 4,5,6,8 and Wettzell have been in operation with more or less success for some time. MOBLAS 7 has recently replaced STALAS as the Goddard reference, STALAS having been de-commissioned.

At a somewhat lower level of accuracy (2-5 cm normal points) there will then be 8 further systems available, of which the deployment of the SAO systems from Mt. Hopkins (U.S.A.), Natal (Brazil), and Orroral (Australia) is as yet uncertain. The remaining 5 are the systems at Arequipa (Peru), Kootwijk (Netherlands) and MOBLAS 1,2,3.

The system at Dionysos (Greece) is being upgraded with a Nd:YAG short-pulse laser, but the definitive plans and the time-table for completion of the work is not yet known. However it can be presumed that it will ultimately fit into one of the preceding categories and may reach 1-3 cm accuracy by 1983-84. Similarly, the accuracy for the systems at the Plateau de Calerne (France) and Dodaira (Japan) until the end of this period and for the recently upgraded system at San Fernando (Spain) are not known, but again there is some hope that there too, results will be sufficient to give at least the equivalent of 4-8 cm normal points if not better.

No attempt has been made to assess the remaining systems, but the majority will be inadequate for making significant contributions to satisfy current requirements, unless they undergo major upgrading in order to give Lageos ranging capabilities to one of the preceding levels.

The preceding discussion leads to the conclusion that only about 50 % of the systems in operation by 1984 will have the capacity to deliver data of adequate quality for use in MERIT and the ongoing Crustal Dynamics and Earthquake Research Program.

2. The Networks

Historically four networks of laser ranging instrumentation and a few individual systems have been operating. The networks were:

- the NASA network,
- the SAO network,
- the EROS network,
- the Interkosmos network.

In recent years, as the result of a number of influences, the co-operation between the networks has been improved to the point where nowadays there are essentially only two major network operations, each of which is addressing a multitude of tasks such as earth rotation, gravity field improvement and crustal dynamics. The NASA and SAO groups have continued to bear the brunt of the observational task during the years since the last Workshop, but with the anticipation of a closer international co-operation, the European (EROS) network for example is under pressure to make a more effective contribution to ongoin programs. This leads inevitably towards the integration of the first three of the aforementioned into one consolidated network.

Despite an apparent dependence on the SAO satellite ephemerides which are supplied to the centres in Prague and Moscow every week by telex via CNES in Toulouse, the Interkosmos network operates autonomously. Little is known of the real priorities set by this group in the way of scientific objectives, but from the literature it would appear that perhaps polar motion and the improvement of the gravity field model take pride of place. In any case it would be worthwhile to obtain more information on this topic in the course of the meeting.

3. Network response to project activities

Since the last workshop in 1978 three projects of world-wide interest have been addressed:

- SEASAT,
- Lageos,
- MERIT (preliminary campaign).

The - MERIT (long campaign)
and a program for - Crustal Dynamics and Earthquake Research

are in the course of preparation. The Lageos Project and the Crustal Dynamics Project were each conceived as long-term, on-going activities (the two will run jointly until expiration of the Lageos Project at the end of 1982) and MERIT as a co-ordinated, interdisciplinary effort of 3 + 12 + ... months observation in 1980, 1983-84 and ....

The network response to each of the projects addressed to date has served to show up the individual and collective weaknesses to which international co-operative efforts of this magnitude are susceptible. Problems of weather, maintenance, system-deployment, communication, standardisation of procedures, formatting, calibration and global coverage are just the first that come to mind from the catalogue of headaches that surfaced during the last three years.

Whereas the overall laser-ranging contribution to the success of the short-lived SEASAT project can only be described as disappointing - weather, system deployment, to some extent ephemerides and the sudden power failure onboard the satellite brought things to a halt before the observational campaign had fully atuned to the project in hand - the succeeding efforts for Lageos and MERIT have shown a vast improvement, both in the quality and quantity of data. Some problems still remain. After years of campaign oriented operations for which a few months of concentrated observation could be followed by a prolonged period of spasmodic activity interspersed between the times devoted to system improvement, the Lageos activities were the first for which the systems were to be put to a prolonged period of observation. Only SAO could respond immediately to this challenge, this having long been the cornerstone of their operational policy. NASA followed on, but the remaining portions of the network have been slow to respond. Perhaps a reason for this lies in the fact that too little emphasis has been placed on the on-going characteristic of the Lageos Project and on the need for continuity in observations, two items which should receive more emphasis in encouraging contributions to the forthcoming Crustal Dynamics programme.

With a similar limitation,the preliminary MERIT campaign proved to be an outstanding success - both for the observers and the analysts. Again the observational contribution from European stations was disappointing, but the overall campaign opened up new and until then untried, possibilities for exploiting the quick-look data normally supplied to maintain the satellite ephemerides.

Generally, it can be said that 1979 proved to be the year in which a significant improvement in the data being submitted - quality and to some extent also quantity - became apparent. As a result:

- the quality of both the Lageos and Starlette orbits has improved considerably;
- the gravity model has been refined, both by the addition of altimeter data and the improved tracking;
- tuned gravity models are now available for both Lageos and Starlette;
- improved earth rotation parameters and earth and ocean tidal models are available for the analysts.

Still, more care is needed in the recording of reliable meteorological data - systematic ranging errors of up to 5 cm have been reported as a result of faulty data - and reliable calibration at the 2 cm level is evidently creating more problems than had been anticipated. Furthermore, despite the use of sophisticated measuring techniques, such as that shown previously for TLRS, the old problem of recording unambigvous measurements to a reference ground marker (for which more redundancy is required in the observations) has appeared for both SLR and VLBI stations. Each of these problems should be addressed in ensueing discussions.

4. Data exchange

Since 1978 there has been a great improvement in the readiness to exchange data between participating agencies and the analysts.

Quick-look data is made available to those requesting it (e.g. SAO and the University of Texas) immediately "after the event". The turn-around for pre-processed data during SEASAT and MERIT was of the order of 90 days, with some data being dispatched to the data centre within 28 days of its taking.

Whereas this schedule caused some difficulties during the SEASAT campaign, the data submissions for MERIT were prompt and effective. Increasing attention is being paid to the use of GE-Mk. III for transferring pre-processed information between data banks and some stations are also arranging to be connected to the system.

No information is available on data exchange within the Interkosmos community. Some Interkosmos stations expressed interest in participating in MERIT and e.g. a request to the IfAG for MERIT data was answered promptly and positively in accordance with the agreements reached for the project. Again, it would be helpful to have some comment on this from the Interkosmos participants.

5. Outlook

As we approach MERIT and enter the Crustal Dynamics programme the outlook is reasonably good. Whereas about 50 % of the existing systems will be in a position to deliver valuable, high quality data for the project by 1984, it must be anticipated that the knowledge of the Lageos orbit will be sufficient to justify a considerable cut-back in the global support network used to maintain it and a shift in emphasis towards a stronger support for regional investigations can be predicted, mainly resulting in an increased observational load for the highly mobile systems. At that time it can be anticipated that it may be unnecessary to occupy a station/site for longer than one week, if weather conditions are favourable.

Significant improvement in relative accuracy may also result from a more effective and concentrated use of mobile equipment in regional investigations. This is particularly important in the light of the time span over which we are forced to make our projections for Crustal Dynamics. New reduction techniques are currently being investigated for these problems.

A practical problem of some concern is to develop data compaction procedures applicable to all requirements. Proliferation of a number of differing techniques for this would put an unnecessary burden of work on stations reporting data. We already have too many formats for data exchange and there is no need to generate the same problem for reporting normal points.
Finally it is suggested that laser ranging suffers from a lack of standardisation of equipment and procedures. As the transition from the experimental to the operational era is made more effort is needed to ensure that the cm the analyst and the geophysicist is wanting to sec results from something external to the measuring system and not a systematic resulting from it. If this cannot be guaranteed the laser ranging community will lose its support in favour of other contenders. In a few words - we need results - we need high quality results - but we need guaranteed results. This workshop can contribute to attaining them.

Country	Station	Latitude	Longitude	Height	Normal point accuracy				Remarks
		(LSC 80.11)			1981	1982	1983	1984	
Australia	Natmap	35 38S	148 57E					1-3	Lunar/Lageos
	Orroral-SAO IV	35 37S	148 57E	949	8-12	2-5	2-5		SAO
	Yarragadee	29 03S	115 21E	245	4-8	4-8	2-5		NASA (MOBLAS 5)
Austria	Lustbühel	47 04N	15 28E			1-3	1-3	1-3	EROS
Bolivia	Patacamaya	17 15S	292 06E		100				Interkosmos
Brazil	Natal-SAO I	5 56S	324 50E	39	8-12				SAO
Bulgaria	Plana				100				Interkosmos
China	Shanghai	31 12N	121 12E		60	60	8-12	8-12	
	Yunnan	25 01N	102 47E		100	100	100	100	
Cuba	Santiago de C.	20 01N	282 14E		100				Interkosmos
Czechoslovakia	Hradec Kralowe	50 13N	15 50E		100				Interkosmos
	Ondrejov	49 55N	14 47E		100				Interkosmos
Ecuador	Quito	0 12S	281 31E		100				Interkosmos
Egypt	Helwan I	29 52N	31 21E		100				Interkosmos/SAO
	Helwan II	29 52N	31 21E		8-12				Interkosmos/SAO

Country	Station	Latitude	Longitude	Height	Normal point accuracy				Remarks
		(LSC 80.11)			1981	1982	1983	1984	
F.R. Germany	Wettzell	49 09N	12 53E	661	1-3	1-3	1-3	1-3	EROS
	MSLRS						1-3	1-3	EROS
Finland	Metsähovi	60 13N	24 24E	78	50				EROS
France	Calerne LLRS	43 45N	6 56E	1306		8-12			Lunar/Lageos/ Starlette
	Calerne SLRS	43 45N	6 56E	1306	30				EROS
German D.R.	Potsdam	52 23N	13 04E		100				Interkosmos
Greece	Dionysos	38 05N	23 56E		100				EROS
Hungary	Penc	47 47N	19 17E		100				Interkosmos
India	Kavalur	12 54N	78 49E		100				Interkosmos
Italy	Cagliari	39 13N	9 07E						EROS
Japan	Dodaira LLRS	36 00N	139 12E						Lunar
	Dodaira SLRS	36 00N	139 12E		50				
	Simosato	34 07N	135 10E			1-3	1-3	1-3	
Netherlands	Kootwijk	52 11N	5 49E	93	8-12	8-12	2-5	2-5	EROS
	MSLRS						1-3	1-3	EROS

Country	Station		Latitude (LSC 80.11)	Longitude	Height	Normal point accuracy				Remarks
						1981	1982	1983	1984	
Peru	Arequipa-SAO II		16 28S	288 30E	2492	8-12	2-5	2-5	2-5	SAO
Poland	Borowiec		52 17N	17 04E		100				Interkosmos
Switzerland	Zimmerwald		46 53N	7 28E		100				EROS
Spain	San Fernando		36 28N	353 48E						EROS
United Kingdom	Herstmonceux		50 52N	0 20E			1-3	1-3	1-3	EROS
U.S.A.	Mc Donald		30 40N	255 59E		2-5				UT/NASA
	MLRS		30 40N	255 59E	1965		1-3	1-3	1-3	UT/NASA
	TLRS I					1-3	1-3	1-3	1-3	UT/NASA
	TLRS II						1-3	1-3	1-3	NASA
	Haleakala		20 43N	203 44E		2-5	1-3	1-3	1-3	UH/NASA
	MOBLAS 1	Mayi	20 42N	203 45E	3071	2-5	final plans uncertain			NASA
	MOBLAS 2	Boulder				2-5	2-5	2-5	2-5	NASA
	MOBLAS 3	Monument Peak				2-5	2-5	2-5	2-5	NASA
	MOBLAS 4	GSFC	39 01N	283 10E	21	4-8	4-8	2-5	1-3	NASA
	MOBLAS 6	GSFC	39 01N	283 10E	21	4-8	4-8	2-5	1-3	NASA
	MOBLAS 7	GSFC	39 01N	283 10E	21	1-3	1-3	1-3	1-3	NASA
	MOBLAS 8	Quincy	39 58N	239 04E	1064	4-8	4-8	2-5	1-3	NASA
	SAO 3						2-5	2-5	2-5	SAO

Country	Station	Latitude	Longitude	Height	Normal point accuracy				Remarks
		(LSC 80.11)			1981	1982	1983	1984	
U.S.S.R.	Riga	56 57N	24 04E		100				Interkosmos
	Simeis	44 24N	34 00E		100				Interkosmos
	Zvenigorod	55 42N	36 47E		100				Interkosmos

A CRITICAL ANALYSIS OF SATELLITE LASER RANGING DATA

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Abstract

The goals for satellite laser ranging, set forth in several international geodynamics programs establish challenging requirements on the observation accuracy, continuity in the observation program and geographical distribution of the laser tracking stations. The NASA Crustal Dynamics Project and the IAU/IUGG Program to Monitor Earth Rotation and Intercompare Techniques (MERIT) are two current programs which impose the most demanding requirements. In this discussion, the characteristics of the Lageos laser ranging data collected since its launch in May 1976 are reviewed. In particular, the quality of the data obtained during the last two years is contrasted with the pre-1980 data. A comparison of the precision of both the quick-look and full-rate data is presented. Finally, current limitations of the data base from the analyst point of view are noted.

Introduction

In recent years, laser ranging to near-earth satellites has been used for the determination of precise satellite orbits, the earth's gravity field, the earth's polar motion and rate of rotation, solid earth and ocean tide parameters, tectonic plate motion and crustal deformation [NRC Committee on Geodesy, 1978]. Further enhancement of results achieved in these applications will require a concentrated effort to ensure that the data set collected has adequate geographic and temporal distribution and small random and systematic errors. In particular, the goals set forth in several current international global earth dynamics programs, including the NASA Crustal Dynamics Project [NASA Office of Space and Terrestrial Applications, 1979], the San Andreas Fault Experiment [Smith, et al., 1976] and the IAU/IUGG MERIT Campaign [Wilkins, 1980], impose requirements on the observation program which are at the limit of the laser network observation efficiency and accuracy. Table 1 summarizes the geophysical measurement accuracy required for the Crustal Dynamics Project [NASA, 1979]. These requirements present a significant challenge to the laser ranging community. A dedicated effort in both the data analysis and the observation program will be required to achieve satisfactory results.

The following discussion reviews both the quick-look and full-rate Lageos laser ranging data and notes both the improvement in data quality and some of the current limitations on the data use for geophysical applications. In addition, the relative precision and productivity of the various systems which constitute the global laser tracking network are considered.

The Laser Range Measurement

Figure 1 illustrates the various elements in the laser range measurement. The primary measurement is the flight-time, Δt, between the laser pulse transmission and the return of the satellite reflected energy to the optical receiver at the tracking station. With appropriate corrections for atmospheric refraction and instrument delays, the measured time of flight can be used to give (with sufficient accuracy for this discussion) the range from the first non-moving point in the optical path of the laser (the reference point) to the average satellite corner-cube position at the time the pulse is reflected at the satellite. That is,

$$\rho = \frac{1}{2} c\Delta t - \eta_r - \eta_e - b + \varepsilon \qquad (1)$$

where

ρ is the range from the laser reference point to the average corner-cube reflector position,

Δt is the round-trip flight time,

c is the speed of light in a vacuum,

η_r is the atmospheric refraction correction,

η_e is the effect of systematic and random measurement errors,

b is the system delay as determined by calibration measurements, and

ε is the unmodeled observation error.

Eq. (1) suggests that the errors which corrupt the measurement of the round-trip time of flight can be separated into instrument or measurement errors and errors in the models used to correct the time of flight for atmospheric refraction and other effects [Plotkin, et al., 1973]. Corrections for these effects requires that other ancillary data, such as atmospheric pressure, temperature and reltive humidity be obtained [Marini and Murray, 1973; Rinner, 1974].

The equations of motion predict the position of the satellite's center of mass; hence, the location of the effective optical center, d_s, (Fig. 1) of the laser corner-cube array with respect to the spacecraft's mass center must be known precisely [Fitzmaurice, et al., 1977]. Since the laser reference point, O, will vary as different instruments occupy a given site, the surveyed distance, $\bar{r}$, between the laser reference point and the laser site benchmark must be precisely determined for each new site occupancy. Finally, since some applications will require intercomparison of positions and baselines determined by various techniques, the location of the laser station benchmark with respect to a specified survey mark $(\bar{s})$ must be precisely determined.

The instrument errors, η_e, include errors in the time standard, which can be separated into clock bias (relative to UTC), drift and discontinuous or anomalous time standard behavior. It is generally assumed that the transmitted pulse is symmetrical in shape. A non-gaussian pulse can lead to erroneous interpretation of time of flight for the returned signal unless corrections for this effect are included in the data pre-processing. The TLRS-1 which is based on a single-photon detection system uses a cross-correlation technique to correct for pulse distortion effects. For the systems which record the full wave-form, the two primary means of locating the returned pulse are leading edge discrimination and centroid location [Lehr, et al., 1975]. The centroid location requires integration of the total returned signal and, provided that sufficient attention is given to the process, can be made to yield a more accurate determination of the time of flight measurement. The effect of such pulse-dependent errors vary with both the laser and the detection system. For example, for

MOBLAS and SAO lasers, the far field diffraction patterns of the laser can cause systematic errors which vary with the position of the satellite in the laser beam [Fitzmaurice, et al., 1977]. However, single-photon systems like the one used for TLRS [Silverberg, et al., 1980] avoid this error source.

Another common error source occurs in the determination of the system delays from pre- and post-observation calibration measurements. Factors which influence the overall accuracy of the bias measurement are uncertainties in the measurement of the calibration target distance, d_c, background interference in ranging to the target, atmospheric instability in the calibration medium and differences in the signal strength of calibration versus satellite returns.

In most applications, the data analyst tacitly assumes that the instrument corrections have been properly modeled and that the bias and noise for the data lie within the specified accuracy bounds. If uncorrected errors remain in the data, the analysis results will be corrupted, and progress toward improving the requisite models will be slowed. Since systematic observation errors may be accommodated into adjusted parameters, such as orbit elements, gravity field coefficients and station positions, they are difficult for the analyst to confidently isolate. Consequently, the reduction of systematic errors in the observations is an essential requirement for achieving the scientific objectives of the international laser ranging programs.

The Lageos Data Set

The two fundamental requirements which the satellite laser ranging systems must satisfy to achieve the objectives of the current geodynamic programs are measurement accuracy and continuity of operation. A laser site which operates with high precision but operates over sparse time intervals will have little impact in the solution of most global geodynamic problems. At the present time, polar motion and earth rotation solutions require continuity in tracking by each station to ensure adequate temporal and spatial distribution of the data. Furthermore, the best determination of relative distance between tracking stations, which is an inherent element in regional and intercontinental baseline solutions, is obtained when the sites observe the satellite during the same time period. Because of the inability of most laser sites to track Lageos during the daylight hours, there will be extended periods during which only one or two passes per day will be observable from some sites, and weather conditions will reduce further the passes actually acquired. Consequently, to determine accurate global baselines, data must be gathered over a sufficiently long period to allow averaging of the effects of dynamical model error.

The tracking stations which have ranged to the Lageos satellite are shown in Figure 2. The laser ranging data set for the Lageos satellite for the period May 1976 to November 1981 is summarized in Table 2. The set of stations which have contributed to this data base, along with the number of observations from each station (based on samples at one-minute intervals) are tabulated. The question of the relative accuracy of the data from the various sites will be considered in the subsequent discussion. Figure 3 shows the temporal distribution of the passes for this data set, as summarized in the number of passes per five-day interval for the period up to December 1981. There are obvious time periods when substantially more data is collected than at other periods, and some stations have contributed a much larger number of observations than other stations. The five-day interval is used for the current University of Texas polar motion and earth rotation solutions [Schutz, et al., 1981] and, when the number of passes during the five-day period approaches ten or less, the accuracy of the solution is questionable. As is evident from Table 2, the contribution from the various stations is not uniform.

A number of factors influence the variation in the quantity of data collected at any given station. As an example, Figure 4 shows the number of passes contributed in each five-day interval by the Orroral tracking site. The station was not operating during the first 100 days of the Lageos mission which began in May 1976 (MJD = 42905). Note that there is an apparent periodic character to the number of passes in each five-day interval. The dominant variation is at a period of 560 days and is associated with the motion of the Lageos node relative to the sun. This effect is a function of the ratio of daytime passes to nighttime passes at each tracking site and is introduced by the limited ability of most tracking stations to range to Lageos during the daylight hours. Additional variations with an annual period may also be present due to seasonal meteorological variations and changes in the number of hours of daylight.

There are also shorter period variations in the amount of data gathered introduced by the tracking schedule adopted for the laser operation. This effect can be evaluated by considering the data set collected during the Preliminary MERIT Campaign. This data set, collected during a period of 92 days, represents the best satellite laser ranging data available with regard to quantity and global data distribution. The daily amount of tracking varies from 40 to approximately 320 minutes. The mean is 107 minutes, and the RMS about the mean is 74 minutes. Figure 5 shows the results obtained by analyzing the histogram of the data collected each day using a maximum entropy spectral analysis. Presumably the peaks at 7.0 and 3.5 days occur because the five-day work week is uniformly scheduled at most sites on Monday through Friday, leading to limited data being collected on Saturday and Sunday. Figure 6 shows the actual data collected in minutes per day for the Preliminary MERIT Campaign. Superimposed on this figure is a best fit trigonometric function containing terms with

7-day and 3.5-day periods. Note that the phase determined by the data is such that each Saturday (shown by the solid circle) is at a minimum of the data. A rotated schedule to ensure tracking by an adequate number of stations during the weekend could eliminate this schedule-induced void in the tracking data.

Figure 7 shows the number of passes obtained by the stationary laser (Stalas) operated at the Goddard Space Flight Center. While the measurements from this instrument are some of the most precise of any consistently operating laser system, the number of passes contributed is substantially fewer than those provided by the SAO sites. Because of the limited data distribution, the impact of the Stalas-gathered data on the global station coordinate solutions, orbit accuracy results and polar motion solutions is far less than the Stalas system precision would promise. Problems with weather, instrument malfunctions and the use of the system for development work are cited as the primary reasons for the sparse data collected by Stalas. The weather factor can be modulated by site location; however, the design inherent in achieving the high-accuracy range measurements must be such that reliable system operation can be achieved as well.

Accuracy Assessment for Laser Range Data

To obtain an overall assessment of the performance of the laser network, several factors should be considered. In addition to the amount of data contributed by the respective laser systems, the number of observations edited, the noise level and systematic error signals in the data are other factors which must be considered. In order to obtain relative comparisons of these quantities, the capability for computing an orbit which yields an accurate fit to the data is necessary.

In the approach presented in the subsequent discussion, a single long-arc solution for the orbit of the Lageos satellite was computed using the UTOPIA orbit computation system at the University of Texas [Schutz and Tapley, 1980]. There will be residual error in the orbit due to unmodeled orbit effects. The effects of the long-period orbit error were removed by using a smoothed solution through a set of short-arc orbit element adjustments. In this approach, the residuals from the long-arc solution were separated into five-day batches, and average orbit element corrections were determined for each of these five-day batches. The orbit element corrections were smoothed using a method proposed by Vondrak [1977], and corrections to the long-arc solution were obtained using the smoothed orbit element corrections. This corrected solution removes essentially all of the long-period orbit error. However, the residuals computed from the corrected orbit will contain measurement errors and short-period orbit error.

If the corrected long-arc orbit solution is used to obtain a computed value of the range, ρ^*_i, then the raw range residual, $\delta\rho_i$, is defined as follows:

$$\delta\rho_i = \rho_i - \rho^*_i \tag{2}$$

where ρ_i is the observed value of the range.

The raw range residual RMS for the entire set of data is given then as follows:

$$\sigma_\varepsilon = \left[\frac{1}{m} \sum_{i=1}^{m} (\delta\rho_i)^2 \right]^{1/2} \tag{3}$$

The value of σ_ε is nominally on the order of 40 cm for the 100-day fit interval used in the subsequent discussions. The raw range residuals, $\delta\rho_i$, still contain the effect of orbit error with shorter periods than those included in the orbit element smoothing, as well as the effects of inaccuracies in the station location, inaccuracies in the atmospheric refraction corrections and other measurement model errors. The systematic trend in a single pass of residuals can be mostly removed with a two parameter least squares adjustment of an apparent range bias and time bias. To achieve this effect, the following equation is used:

$$\delta\rho_i = b + \dot{\rho}_i \, \tau + \tilde{\varepsilon}_i \tag{4}$$

where b is the apparent range bias, τ is the time bias, $\dot{\rho}_i$ is the range rate, and $\tilde{\varepsilon}_i$ is the remaining error. The residuals, $\tilde{\varepsilon}_i$, will consist of random measurement noise, as well as trends not accommodated by the time bias adjustment. The RMS of the $\tilde{\varepsilon}_i$ is referred to as the range bias-time bias (RB-TB) RMS. Next, a kth-order polynomial, usually selected as a quadratic, is fit to the residuals in each pass using the following model

$$\tilde{\varepsilon}_i = \sum_{j=0}^{k} c_j \, t^j + \varepsilon_i \tag{5}$$

where c_j, $j=0,\ldots,k$ are constant coefficients whose values are to be estimated from the residuals $\tilde{\varepsilon}_i$ for any given pass and where ε_i is the remaining residual. The RMS of the ε_i is referred to as the polynomial (POLY) RMS.

The polynomial RMS is predominantly due to high frequency and random observation error and can be used as a good measure of the single-pass internal precision of the laser tracking systems. The estimates for the range bias b and time bias τ, as well as their uncertainties, can be used as a measure of the systematic errors which still remain. These errors occur due to inaccurate solutions for the orbit, the tracking station coordinates, polar motion, the various models for correcting the laser range measurements, as well as systematic measurement error with periods comparable to the duration of a pass or longer.

Comparison of the Quick-Look and Full-Rate Data

The laser range data is transmitted to the NASA Goddard Space Flight Center in two modes.

1. The quick-look data, sampled at approximately 50 points per pass, is used primarily for orbit maintenance and overall data quality checks. These data are transmitted to the Goddard Space Flight Center over the NASA Communications (NASCOM) Network from the individual Goddard laser tracking sites and from the Smithsonian Astrophysical Observatory for data collected by Telex from the SAO and participating foreign laser sites. In either case, data can be made available with delays as short as a few hours.
2. The full-rate data is the complete data set collected by the tracking sites and corrected for all known errors and stored in the National Space Science Data Center at the NASA Goddard Space Flight Center as an archival data record. This data set is used for precise orbit computation and for geodynamic parameter determinations. The full-rate data set requires substantially more computational effort and, as a consequence, is not available for a period of approximately 90 days after the data are collected at the tracking site.

Although the primary use for the quick-look data is in the preliminary orbit determination application to support tracking station acquisition predictions, there are a number of other applications which require data availability within a few days of its collection. These include the determination of rapid service polar motion and earth rotation values and preliminary accuracy assessment of TLRS site solutions. In addition, the quick-look data can be used to detect data abnormalities, such as timing anomalies, systematic bias or increased noise levels in the data from the various stations.

Since the quick-look data is the only source for satisfying these rapid response requirements, a comparison of the the quick-look and the full-rate data is of interest. Figures 8 through 11 summarize a comparison of the quick-look data gathered by the SAO Orroral laser system and the NASA Stalas system operated at the Goddard Space Flight Center during the MERIT Short Campaign from August 1, 1980, through October 31, 1980.

The complete pass statistics during this 92-day time interval are summarized into two parameters, the mean range difference and the mean time difference. These statistics are formed by identifying the measurements in the full-rate data which correspond to each quick-look observation. The differences in the associated range measurements, y_i, and the differences in the time tags, t_i, are formed for each individual quick-look measurement. That is,

$$y_i = \rho_i - \rho^*_i \quad , \qquad t_i = T_i - T_i^* \tag{6}$$

where ρ_i is the full-rate range at the time, T_i, and ρ^*_i is the quick-look range at the indicated quick-look time, T_i^*. Then, for each pass, the mean and standard deviation is computed for both the range differences and the time differences as follows:

$$\overline{y} = \frac{1}{m} \sum_{i=1}^{m} y_i \quad , \qquad \sigma_y^2 = \frac{1}{m} \sum_{i=1}^{m} (y_i - \overline{y})^2 \tag{7}$$

$$\overline{t} = \frac{1}{m} \sum_{i=1}^{m} t_i \quad , \qquad \sigma_t^2 = \frac{1}{m} \sum_{i=1}^{m} (t_i - \overline{t})^2 \tag{8}$$

where m is the number of quick-look measurements in the pass.

Figures 8 and 9 show the mean range and time differences for each pass of Stalas laser data collected during the MERIT Campaign, while Figures 10 and 11 show similar results for Orroral. The error bars indicate the pass standard deviation. From Figures 8 and 10, it can be seen that there are significant differences in the character of the mean range difference for the Goddard stations as compared with the SAO stations. The data for the Orroral station in Figure 10 have an overall mean of -0.6 cm with an RMS about the mean of 3 cm. The overall mean for the Stalas data is 3.2 cm with an RMS of 5.4 cm. The range difference between the quick-look and full-rate Stalas data is relatively constant from pass to pass, but the RMS for each individual pass is about 5 cm. On the other hand, the mean of the range difference for the Orroral data may vary from pass to pass by as much as ± 10 cm, while the scatter within a pass is less than 1 cm.

Figures 9 and 11 show that the time difference for the Stalas data is on the order of 0.8 μs and is uniform throughout the entire MERIT Campaign. For the Orroral data, the time difference varies from -3 μs at the beginning of the MERIT Campaign to about 9 μsec at the end of the MERIT Campaign. This growth in the time difference is due to a drift in the station clock which is corrected in the final processing. While a time tag difference of 9 μsec would lead to apparent range differences of only 3 cm, if this error growth continues uncorrected it could lead to non-negligible degradation in the quality of the quick-look data as compared to the full-rate data. In order to avoid this, efforts should be made to recalibrate the SAO station clocks often enough to ensure that polar motion solutions obtained using the quick-look data are not degraded.

As pointed out previously, the data obtained in the MERIT Short-Campaign is the most complete set of laser ranging data collected to date. Consequently, these data form an excellent set for evaluating the overall quality of the quick-look data. Table 3 shows the mean range and time differences for several of the stations which tracked throughout the MERIT Campaign. Note that the characteristics of the differences identified in considering Figures 8 through 11 are present in this table. That is, the mean time differences between the quick-look and full-rate data for the Goddard stations is negligibly small. On the other hand, the mean time differences for the SAO stations are larger, varying from a -0.93 μsec to 4.8 μsec with the RMS about the mean varying from 3 to 5 μsec. The range difference for the SAO stations is on the order of 0.5 cm with an RMS of the order of 3 cm. The range difference for the NASA MOBLAS stations, on the other hand, varies from station to station with a maximum mean difference of 8 cm for the Yarragadee site with RMS values which range from 3 cm to 6 cm.

From the previous comparison, it can be concluded that the precision of the quick-look data is comparable to that of the full rate data and is thus quite valuable for rapid determinations of polar motion and other geophysical phenomena. After further examination of the differences, changes might be made to improve the precision of the quick-look data.

Improvements in the Laser Range Accuracy

In addition to the need for tracking continuity and global coverage, the accuracy of geophysical parameter determinations is dependent on the accuracy with which the laser range measurements are made. Since launch of the Lageos satellite in May 1976, there have been significant improvements in the accuracy of the laser measurements. The increased accuracy has resulted from improvements in the hardware used to make the measurements and in the understanding of the error sources which influence it.

For the purposes of this discussion, errors in the range are considered to be composed of a random part which is uncorrelated from pulse to pulse and a systematic part that could vary on several time scales. There could be a bias that is constant over several passes, biases that vary from pass to pass and errors that change during the course of a pass both continuously and discontinuously. The spectrum of range errors for periods of less than about 10 minutes (about 1/4 of a Lageos pass) can be separated confidently from the geophysically interesting signal. Also, the existence of dual populations from a double laser pulse or of discontinuous range error is easily detectable when the size of the error is large compared to the internal precision of the data. Consequently, the internal precision of the range measurements in a single pass can be estimated from appropriately filtered residuals.

On the other hand, the error spectrum for periods comparable to the duration of a pass and longer is difficult to separate from signal due to gravity, station coordinate and earth rotation errors. As a result, the size of these range errors must be estimated indirectly from analysis of the deviaton of polar motion or orbit element solutions from suitably smoothed curves. Any systematic range error that can lead to errors in the polar motion and orbit elements that is correlated over more than about 40 days will be impossible to detect.

At Lageos launch, the precision of the laser systems in the SAO network was on the order of 1 m. Figure 12 shows estimates of the range precision for each pass of Lageos data collected by the SAO system at Arequipa, Peru. Note that the single-pass noise is estimated to be on the order of 1 m with occasional excursions as high as 1.4 m during the first part of the Lageos mission. In late 1978 and early 1979, the SAO laser systems were modified to include a pulse chopper which reduced the 25 nsec pulse to a width of 6 nsec. The effect of this modification is readily evident in Figure 12, where around day 900 in the Lageos mission, one can see a significant reduction in the noise level for the Arequipa laser. The noise level for the SAO systems following the pulse chopper modification is on the order of 40 cm. With the SAO pulse-repetition rate of 8 pulses per minute, the 40 cm data collected for the continuing period since November 1978 have played a significant role in the quality of the polar motion and tracking station coordinate solutions determined with the Lageos data.

The NASA Mobile Laser Ranging Systems (MOBLAS) have operated with precisions which vary from 9 cm to 30 cm during the time period since Lageos launch. One problem with a number of the MOBLAS sites is the lack of continuity in the tracking operations. Figure 13 shows the range precision estimates for the Stalas tracking station. Note that since the beginning of 1978, the noise level has been systematically below the 10 cm level.

Figures 14 through 16 show a sample of the quick-look data from a 40-minute Lageos pass taken by MOBLAS-7 at the Goddard Space Flight Center following a recent modification in which a Sylvania laser replaced the original Q-switched system. Figure 14 shows the corrected long-arc residuals with the RB-TB fit obtained using Eq. (4). The residuals from the solid curve in Figure 14 are shown in Figure 15. The solid line in Figure 15 is the quadratic polynomial fit described by Eq. (5). The polynomial residuals, which are obtained when the polynomial is subtracted from the results in Figure 15, are shown in Figure 16. The polynomial RMS, which is used to approximate the measurement noise RMS, is 3.3 cm for this 40-minute pass. Similar data collected over a 100-day interval had a measurement noise RMS of 4.8 cm, indicating that the new laser will yield routine Lageos laser ranging at the sub-5 cm level. Normal points created from the raw range measurements at the rate of one per second should approach a sub-centimeter noise level for one-minute normal points.

In an alternate development, the University of Texas McDonald Observatory has developed for NASA a Transportable Laser Ranging System, referred to as the TLRS-1, based on a single photoelectron detection design. The key design goals for this system are [Silverberg, et al., 1980]:

- air-transportable without disassembly,
- eye safe (i.e., no safety radar required),
- a 2 cm Lageos normal point precision for 3-minute averages.

Figure 17 shows the internal precision of the TLRS as a function of the number of single-shot returns in the normal points formed for three separate passes in November and December, 1980. Note that for normal points based on twenty or more returns, the precision is below 2.0 cm.

From the previous discussion, it is apparent that the precision of the laser tracking data has improved significantly since the Lageos satellite was launched. However, as pointed out in the previous discussion, continuity in tracking from the sites in the network and the geographical distribution of the stations are additional factors which influence the accuracy of geophysical parameter estimates. In addition to the improvements in the tracking precision, continuity in operation and the distribution of the tracking network have both improved significantly during the five-year lifetime of the Lageos mission. The effect of these improvements are manifested in improved geodynamic parameter recovery.

As an example, Figures 18 and 19 show the improvement in the x-component of the polar motion determined with the Lageos range observations collected during this time period. Figure 18 shows the difference between the estimate of the x-component of the polar motion using five-day values [Schutz, et al., 1981] from a smoothed curve [Vondrak, 1977] through the individual values. The RMS of the fit during the period from satellite launch through 1979 was 16 mas. Following the introduction of the pulse chopper in the SAO networks in November 1978 and early 1979 and the global deployment of the MOBLAS network in October 1979, the RMS value for the x-component of polar motion was reduced to about 6 mas.

When the 5-day arc residuals are combined into 100-day averages, the evolution of the improvement is shown in an even more dramatic fashion. Figure 19 shows the standard error of the mean x_p

residual for 100-day averages. In each point, 20 five-day arc solutions are combined into a single point. Note that the standard error for the 100-day averages at the beginning of the Lageos mission were on the order of 4 mas. The standard error was reduced to the order of 1.5 mas during the MERIT Campaign which occurred around 1600 days after satellite launch. Figure 17 also shows the degradation in the accuracy at the beginning of 1981 when a number of the NASA sites were taken out of operation for a network move. By late 1981, the lasers were re-deployed and operating, and the standard error was reduced again to the order of 1.5 mas. Note that the 1.5 mas standard error corresponds to roughly 6 mas in RMS value. It is also significant to note the reduction in the standard error which occurred around the beginning of 1979 as the SAO sites were modified to include the pulse chopper.

An important additional problem is the determination of baseline and station coordinate heights. A major factor in this determination will be the accuracy with which the Lageos satellite orbit can be determined. Figure 20 shows the improvement in the orbit inclination precision during this time period. The figure plots the difference between raw and smoothed values for independent 10-day arc determinations of the inclination. Note that the scatter about the smoothed curve is as large as .014 arcsec during the early part of the mission, while during 1980, the value is below .005 arcsec. A linear improvement with time is shown in Figure 20. The results obtained during 1980 demonstrate the potential of the laser data for geophysical parameter determinations, and if a global laser network can be operated with reasonable continuity and with the measurement precision at a level consistent with current capability, the geophysical objectives called for in the Crustal Dynamics Project can be achieved within the next half-decade.

However, at the present time, the reliability of the laser network is not uniform, the geographic coverage is not global, and there is some disparity in the accuracy with which the various systems are tracking. The following section discusses the overall quality of the data obtained from the global network.

An Assessment of Current Laser Range Accuracy

As a means of assessing the accuracy of the current laser tracking network, two sets of global laser range data were selected for detailed analysis. In the first of these, a 100-day interval spanning the period from September 23, 1980, through December 31, 1980, was analyzed using the full-rate laser range data archived in the National Space Science Data Center. In a second set, a 100-day interval of laser quick-look data spanning the period from July 17, 1981, through October 9, 1981, was analyzed.

Table 4 gives a list of the laser stations along with the station identification number for the lasers which contributed data to the full-rate and quick-look solutions. Table 5 summarizes the results obtained from the 100-day analysis of the full-rate data. Table 6 shows similar results for the analysis of the quick-look data. In addition to the data contributed by each station, these tables give the raw RMS, RB-TB RMS and POLY RMS statistics described previously. Estimates of the range bias and time bias for each station are also given.

For the full-rate data given in Table 5, the noise levels for the three SAO stations, Station No. 9907 (Arequipa), 9929 (Natal) and 9943 (Orroral), have internal precisions which vary between 33 and 36 cm. These numbers are consistent with the expected accuracy of the SAO systems following the addition of the pulse chopper. The Goddard systems, on the other hand, have noise levels in the range of 10 to 15 cm. The noise level for the TLRS-1 (7896) system was approximately 9 cm during this time period. It should be noted that the European stations, Kootwijk, Metsahovi, Grasse and Potsdam, have noise levels which vary from 23 cm to 62 cm. The Kootwijk (7833) and Grasse (7835) sites appear to be particularly important in terms of their performance levels. The range bias and time bias solutions contain both the average effects of orbit errors, polar motion errors and tracking station location errors. Since the station coordinates used for the solution are currently expected to be accurate to about 30 cm RMS, a significant portion of the range bias-time bias values can be attributed to station location error. Time bias values in excess of 100 ms are of concern, and further analysis of the data must be performed to understand the nature of these values.

In Table 6 similar results are presented for the quick-look data. In contrast to Table 5, where there were no edited observations since a previously edited data set was processed, Table 6 shows the amount of data edited for each of the stations. Note that the percent of data edited varies from approximately 2% to as high as 85%. The most significant of these statistics is the fact that, out of the 84 passes collected by Haleakala (7210), essentially 80% of the data were edited. Note that the quick-look data contains data from Wettzell (7834) and from Helwan (7831). The Helwan data have an internal precision of 70 cm, while Wettzell is operating at 20 cm. A current problem exists in interpreting the quick-look data messages from Metsahovi (7805) and from Grasse (7835). A 4 m bias was removed from the Metsahovi data, and a 13 m bias was removed from the Grasse data. Analysis of the Grasse data suggests that a 13 m preprocessing error was made in preparing the quick-look data from this site. It should be further noted that the stations consisting of Kootwijk, Grasse, Wettzell, Metsahovi and Helwan could be significant contributors to the strength of the global tracking solutions if these stations operate on a regular basis.

Note that the quick-look polynomial RMS for MOBLAS-4 (7102) is 3.2 cm. This can be contrasted with the 16.9 cm RMS for station 7102 during the 100-day full-rate data solution. The difference between these two data sources is due to substantial system improvements including a new Quantel laser and represents the level at which the improved NASA systems should be operating in the future. This performance level was achieved also for MOBLAS-7 which produced 47 passes with a polynomial RMS of 4.8 cm. Analysis of the range biases indicates that, with the exception of three sites, the range biases are all on the order of 10 cm or less.

In examining the data shown in Tables 5 and 6, it is apparent that the quality of the global laser data has improved substantially since the Lageos launch. However, it is also apparent that to achieve the goals of the Crustal Dynamics Project, further reduction in the systematic error components and some improvement in the measurement precision will be required. In this regard, the instances of anomalous performance of individual tracking stations is still present.

As an example, Figure 21 shows a history of the time bias determinations obtained using the quick-look data from the Platteville tracking station during the month of August 1981. Note that during the first portion of the month the time bias determinations are below .4 ms. However, on August 13, the time bias jumped to the order of 5 ms. After this time bias value was confirmed through several successive days of data, the anomaly was brought to the attention of the appropriate personnel at the NASA Goddard Space Flight Center. In early September, a portable atomic clock was taken to the Platteville site for checking the time bias, and a 4.79 ms jump in the station's cesium clock was confirmed. Note that the actual value of the discontinuity suggested by the results shown in Figure 21 is 4.98 - .24 = 4.74 ms.

The results shown in this figure illustrate another valuable use for the quick-look data, i.e., monitoring the performance of the global laser network. Such quality checks are valuable to assure the quality of the real-time polar motion products and to allow preliminary quality checks on TLRS site determinations and baselines.

Conclusions

Based on the results presented in the previous sections, it can be concluded that the laser tracking network has undergone dramatic improvement during the lifetime of the Lageos mission. There is, however, a very strong need for continuous tracking by a subset of stations satisfying the global distribution conditions. In this regard, it is extremely important that the stations on the European continent track continuously to provide strength to the polar motion solutions and to allow complete geographic and temporal monitoring of the satellite orbit for the purpose of dynamic model development. The global distribution of tracking data for continuous periods of time will also be important in obtaining the requisite accuracies for the baseline and tracking station coordinates needed for the measurement of crustal motion. To achieve the extremely ambitious goals of the Crustal Dynamics Project, further refinements in the accuracy with which the laser measurements can be made will be required. Finally, in addition to the improvements in instrument accuracy, a careful effort should be made to obtain precise surveys of the distance to the target boards and/or the development of techniques for performing internal calibrations to reduce the uncertainties in the pre- and post-calibration measurements.

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TABLE 1

GEOPHYSICAL MEASUREMENT ACCURACY FOR THE CRUSTAL DYNAMICS PROJECT

	σ_v, cm/yr	ΔT, yr	σ_d, cm	σ_n, cm
Current	2	5	11	8
Near future	1	5	6	4
Goal	.4, .7	5, 3	2	1

σ_v, velocity (baseline change) determination accuracy

ΔT, measurement span.

σ_d, precision determination accuracy

σ_n, laser range normal point accuracy

TABLE 2

SUMMARY OF LAGEOS LASER DATA CATALOG
UNIVERSITY OF TEXAS LAGEOS LONG ARC 8112.2
DATA SAMPLED TO 1 MINUTE SPACING, 7 MAY 76 - 14 NOV 81

STA ID	NO. OF PASSES	GOOD OBS	LASER SYSTEM; LOCATION
9921	675	16168	SAO 4 ; MT. HOPKINS, AZ.
9907	1566	35298	SAO 2 ; AREQUIPA, PERU
7063	429	9964	STALAS ; GREENBELT, MD.
9929	363	5485	SAO 1 ; NATAL, BRAZIL
7065	4	50	MOBLAS 3 ; GREENBELT, MD
7067	28	341	MOBLAS 1 ; BERMUDA ISLAND
7051A	26	333	MOBLAS 2 ; QUINCY, CA.
7062A	209	3903	MOBLAS 3 ; OTAY MT., CA.
7833	215	3245	KOOTWIJK, NETHERLANDS
9943	1341	35755	SAO 3 ; ORRORAL, AUSTRALIA
7082A	77	1389	MOBLAS 1; BEAR LAKE, UT.
7100	5	82	MOBLAS 3 AND 4 ; GREENBELT, MD.
7084	21	331	MOBLAS 2; OWENS VALLEY, CA.
7091A	32	395	MOBLAS 3; HAYSTACK, MA.
7085	20	318	MOBLAS 1 ; GOLDSTONE, CA. (DSS-14)
7834	118	1419	WETTZELL, GERMANY
7068	4	34	MOBLAS 2 ; GRAND TURK ISLAND
7101	8	131	MOBLAS 6 ; GREENBELT, MD.
7104	13	281	MOBLAS 7 ; GREENBELT, MD.
7103	18	348	MOBLAS 6 ; GREENBELT, MD.
7102	128	2654	MOBLAS 5 AND 4 ; GREENBELT, MD.
7069	17	141	RAMLAS ; PATRICK AFB, FL.
7210	68	1250	HOLLAS ; MT. HALEAKALA, MAUI, HI.
7091B	285	6841	MOBLAS 7 ; HAYSTACK, MA.
7096	124	2211	MOBLAS 6 ; AMERICAN SAMOA
7114A	288	6816	MOBLAS 2 ; OWENS VALLEY, CA.
7115	377	8333	MOBLAS 3 ; GOLDSTONE, CA. (DSS-13)
7086A	169	3828	MOBLAS 1 ; MCDONALD OBS., TX.
7090	1008	25292	MOBLAS 5 ; YARAGADEE, AUSTRALIA
7092	57	1121	MOBLAS 8 ; KWAJALEIN ATOLL
7120	353	7372	MOBLAS 1 ; MT. HALEAKALA, MAUI, HI.
7899	47	582	TLRS 1 ; GREENBELT, MD.
7805	24	386	METSAHOVI, FINLAND
7835	31	685	GRASSE, FRANCE
7896	66	1214	TLRS 1 ; PASADENA, CA.
7105	86	1893	MOBLAS 7 ; GREENBELT MD.
7086B	17	225	TLRS 1 ; MCDONALD OBS., TX.
7892	36	761	TLRS 1 ; VERNAL, UT.
7891	38	700	TLRS 1 ; FLAGSTAFF, AZ.
7831	22	253	HELWAN, EGYPT
7112	136	2360	MOBLAS 2 ; PLATTEVILLE, CO.
7110	85	1309	MOBLAS 3 ; MONUMENT PEAK, CA.
7051B	103	2895	MOBLAS 8 ; QUINCY, CA.
7082B	29	621	TLRS 1 ; BEAR LAKE, UT.
7114B	29	436	TLRS 1 ; OWENS VALLEY, CA.
7109	15	314	MOBLAS 8 ; QUINCY, CA.
7062B	31	363	TLRS 1 ; OTAY MT., CA.
TOTALS	8841	196126	

TABLE 3

QUICK-LOOK MINUS FULL-RATE DATA FOR THE MERIT SHORT CAMPAIGN

	Time Tag (μsec)	Range (cm)
Owens Valley (MOBLAS 2)	0.82 ± 0.44	2.4 ± 6.2
Goldstone (MOBLAS 3)	0.87 ± 0.39	-4.9 ± 5.2
Yarragadee (MOBLAS 5)	0.54 ± 0.21	8.2 ± 2.7
Stalas	0.78 ± 0.43	3.2 ± 5.4
Orroral	-0.93 ± 2.99	-0.6 ± 2.9
Arequipa	1.30 ± 3.41	-0.6 ± 3.2
Natal	4.80 ± 5.23	-0.7 ± 3.1

TABLE 4

LASER STATION IDENTIFICATION

Station Name	Station No.	System No.
Arequipa, Peru	9907	SAO-3
Natal, Brazil	9929	SAO-2
Orroral, Australia	9943	
GORF, GSFC	7063	STALAS
Maui, Hawaii	7120	MOBLAS-1
Owens Valley, CA	7114	MOBLAS-2
Goldstone, CA	7115	MOBLAS-3
GORF, GSFC	7102	MOBLAS-4
Yarragadee, Aus.	7090	MOBLAS-5
American Samoa	7096	MOBLAS-6
Haystack, MA	7091	MOBLAS-7
Kwajelein Atoll	7092	MOBLAS-8
GORF, GSFC	7899	TLRS-1
Pasadena, CA	7896	TLRS-1
Kootwijk, Netherlands	7833	
Grasse, France	7835	
Metsahovi, Finland	7805	
Haleakala, Hawaii	7210	HOLLAS
Wettzell, Germany	7834	
Platteville, CO	7112	MOBLAS-2
Monument Peak, CA	7110	MOBLAS-3
Helwan, Eqypt	7831	
GORF, GSFC	7105	MOBLAS-7
Quincy, CA	7109	MOBLAS-8

TABLE 5

SUMMARY OF RESIDUAL ANALYSIS FOR 100 DAY INTERVAL FROM
80 SEP 23 - 80 DEC 31 FROM LAGEOS LONG ARC 8109.3

STA ID	NO. OF PASSES	TOTAL OBS	EDITED OBS	PCT EDITED	GOOD OBS	RAW RMS	RB TB RMS	POLY RMS
9907	68	1130	0	0.0	1128	48.2	36.4	34.3
7063	23	414	0	0.0	414	32.1	11.4	10.1
9929	24	214	0	0.0	214	76.8	37.1	33.4
7833	5	115	0	0.0	115	58.4	46.5	42.6
9943	94	2227	0	0.0	2227	44.5	38.2	36.7
7102	23	355	0	0.0	355	37.7	18.7	16.9
7091	59	1534	0	0.0	1533	37.3	19.2	17.6
7096	22	376	0	0.0	376	25.4	12.2	11.5
7114	68	1421	0	0.0	1421	34.2	15.4	13.3
7115	72	1329	0	0.0	1329	28.7	11.3	9.4
7090	144	3965	0	0.0	3964	34.8	14.7	14.0
7092	13	292	0	0.0	292	45.7	23.5	22.0
7120	69	1362	0	0.0	1359	34.3	12.5	11.4
7899	10	125	0	0.0	125	31.9	15.1	12.4
7805	18	275	0	0.0	275	102.6	68.4	57.3
7835	24	569	0	0.0	569	48.3	24.2	23.0
7896	66	1219	0	0.0	1219	33.7	11.0	8.8
TOTALS	802	16922	0	0.0	16915	40.3	23.8	22.1

MULTIPLE PASS RANGE BIAS AND TIMING BIAS SOLUTIONS

STATION	PASSES	RBIAS	STD ERR	SIGMA	TBIAS	STD ERR	SIGMA
9907	66	-9.5	2.7	3.0	81.3	17.2	19.4
7063	23	3.2	5.7	4.9	35.7	18.9	31.8
9929	24	-49.5	5.7	10.0	47.6	52.0	64.1
7833	5	10.2	10.8	9.4	-134.8	65.8	57.0
9943	94	-6.1	1.5	2.2	-34.8	10.9	13.3
7102	23	9.4	6.7	5.6	-57.0	17.2	35.7
7091	58	18.0	2.2	2.6	-31.7	17.4	16.5
7096	22	-4.8	4.2	5.2	29.4	17.5	32.7
7114	68	15.5	1.6	2.7	-102.5	11.4	16.9
7115	72	6.4	1.8	2.7	-19.1	16.1	19.7
7090	143	21.1	1.2	1.6	33.1	9.0	9.8
7092	13	-10.0	9.6	5.9	76.1	19.7	35.9
7120	67	5.5	3.0	2.8	57.4	11.0	17.2
7899	10	13.5	4.4	9.0	-46.8	34.8	54.2
7805	18	-30.1	9.2	6.0	53.3	108.6	41.9
7835	24	7.8	5.7	4.5	-147.7	31.8	28.7
7896	66	-.2	1.9	2.9	-94.3	17.4	18.0

TABLE 6

SUMMARY OF RESIDUAL ANALYSIS FOR 85 DAY FIT TO QUICKLOOK DATA
81 JUL 17.5 - 81 OCT 9.5

STA ID	NO. OF PASSES	TOTAL OBS	EDITED OBS	PCT EDITED	GOOD OBS	RAW RMS	RB TB RMS	POLY RMS
7063	21	956	103	10.8	853	30.0	16.0	12.6
7102	7	348	298	85.6	50	23.6	10.2	3.2
7090	118	5397	163	3.0	5234	26.3	13.3	12.7
7210	84	3658	2934	80.2	724	39.2	22.0	19.7
9907	115	6101	1016	16.7	5085	43.0	37.9	37.3
9943	54	2310	442	19.1	1868	56.1	51.3	50.3
9929	42	2067	806	39.0	1261	46.8	43.9	42.9
7805	8	197	140	71.1	57	100.1	83.7	73.7
7833	7	104	17	16.3	87	42.6	34.7	32.3
7120	78	3752	233	6.2	3519	27.1	10.9	9.9
7835	7	183	115	62.8	68	22.2	18.9	18.7
7834	16	507	334	65.9	173	37.2	23.7	23.6
7105	47	2134	105	4.9	2029	18.8	6.8	4.8
7112	77	2750	963	35.0	1787	26.9	16.8	15.8
7110	50	2025	398	19.7	1627	28.1	21.1	19.4
7831	32	1930	983	50.9	947	88.2	72.8	69.6
7109	4	196	3	1.5	193	26.0	19.2	16.9
TOTALS	767	34615	9053	26.2	25562	38.5	30.4	29.3

MULTIPLE PASS RANGE BIAS AND TIMING BIAS SOLUTIONS

STATION	PASSES	RBIAS	STD ERR	SIGMA	TBIAS	STD ERR	SIGMA
7063	21	21.4	2.4	3.5	15.7	10.1	26.2
7102	7	15.6	2.9	14.3	-41.1	36.5	107.1
7090	116	3.2	1.9	1.4	2.6	7.0	9.5
7210	17	-2.2	6.3	3.7	40.4	40.4	28.7
9907	111	1.6	1.3	1.6	-80.9	8.3	10.3
9943	45	-7.7	2.4	2.4	61.0	15.9	17.2
9929	40	-3.0	2.1	2.8	3.7	14.9	23.5
7805	4	-37.3	13.6	13.3	69.3	144.0	90.7
7833	5	-2.5	9.7	11.5	81.9	39.5	85.5
7120	73	-8.4	1.2	1.7	82.7	12.8	11.5
7835	2	2.0	13.6	13.3	-22.8	83.3	88.4
7834	5	.2	14.0	19.8	13.9	157.3	141.7
7105	45	5.2	2.1	2.2	12.0	10.0	17.2
7112	52	-1.1	2.6	2.4	41.6	12.3	15.7
7110	41	-5.2	2.1	2.5	13.8	14.7	17.4
7831	22	-2.1	10.0	3.3	22.7	41.7	29.1
7109	4	-6.7	5.9	7.2	64.1	63.9	55.4

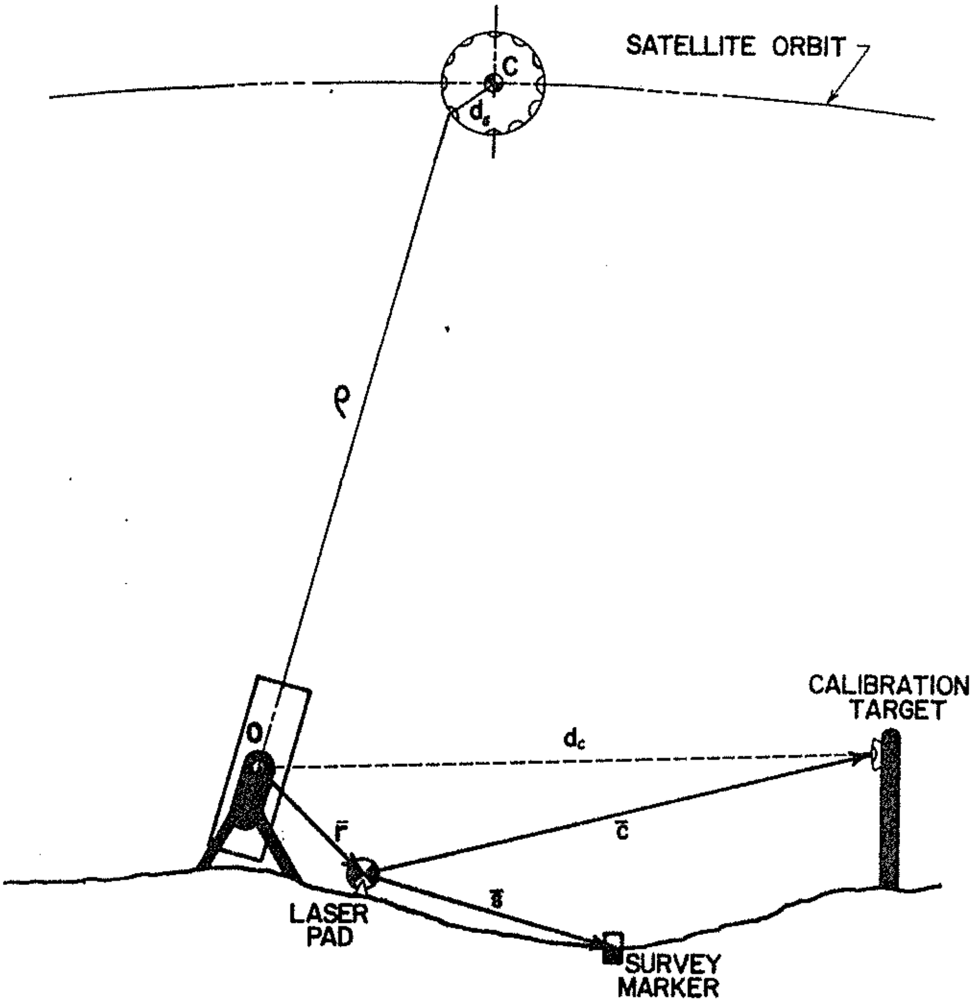


Figure I. Satellite Laser Range Measurement

FIGURE 2
LAGEOS TRACKING STATION NETWORK

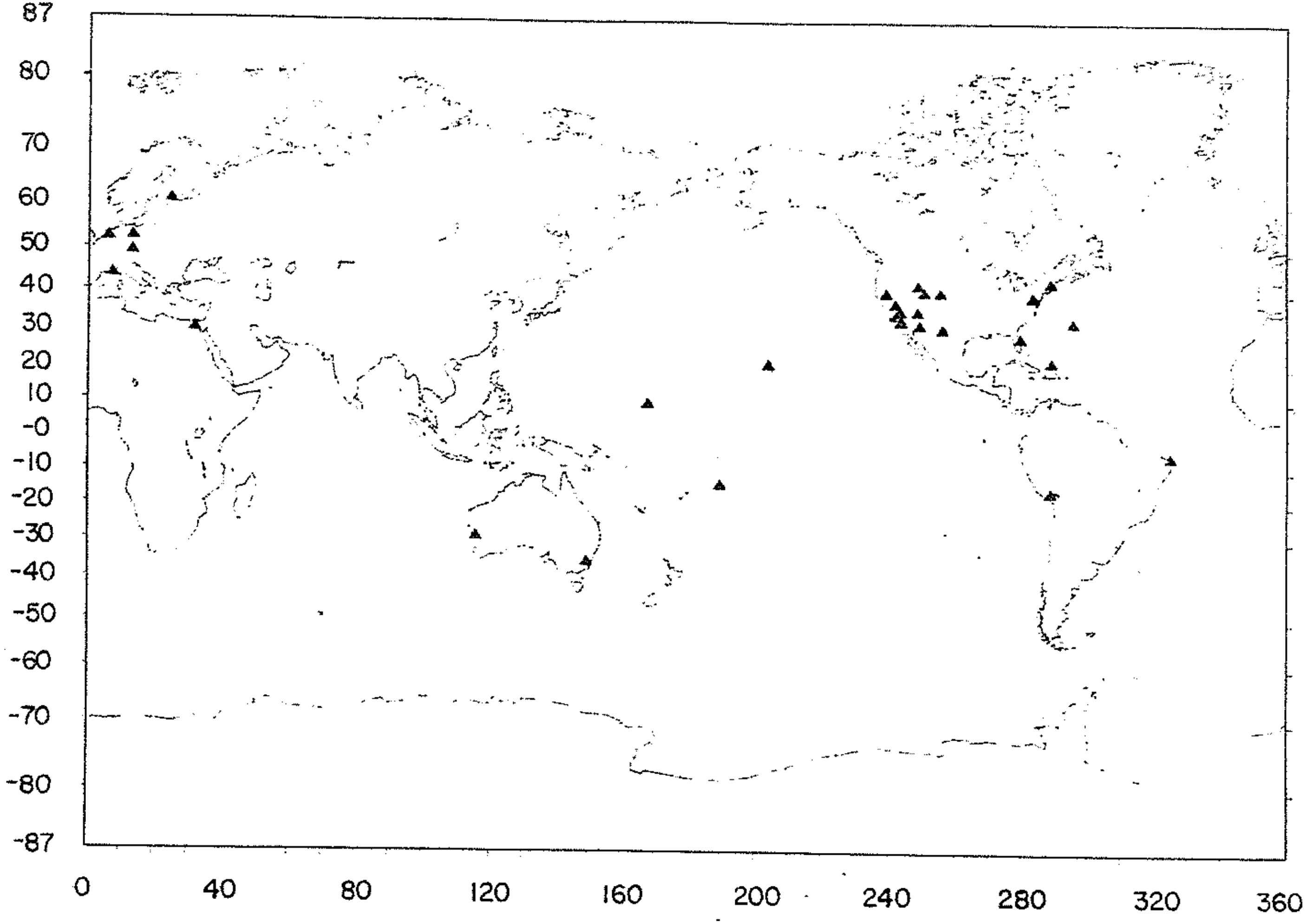
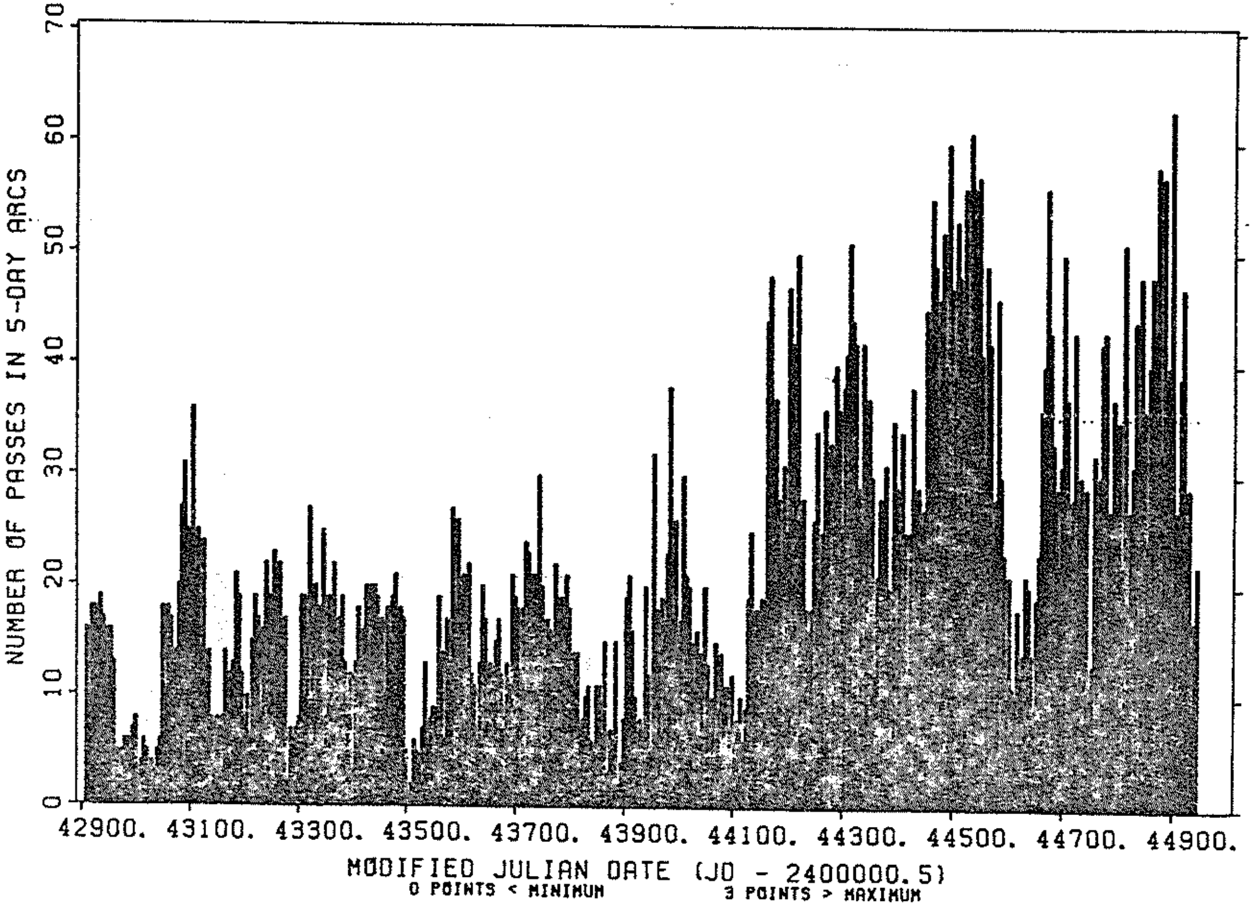


FIGURE 3

NUMBER OF LAGEOS PASSES OBSERVED IN EACH 5-DAY POLAR MOTION ARC
FROM 42909 (11 MAY 76) TO 44944 (06 DEC 81)



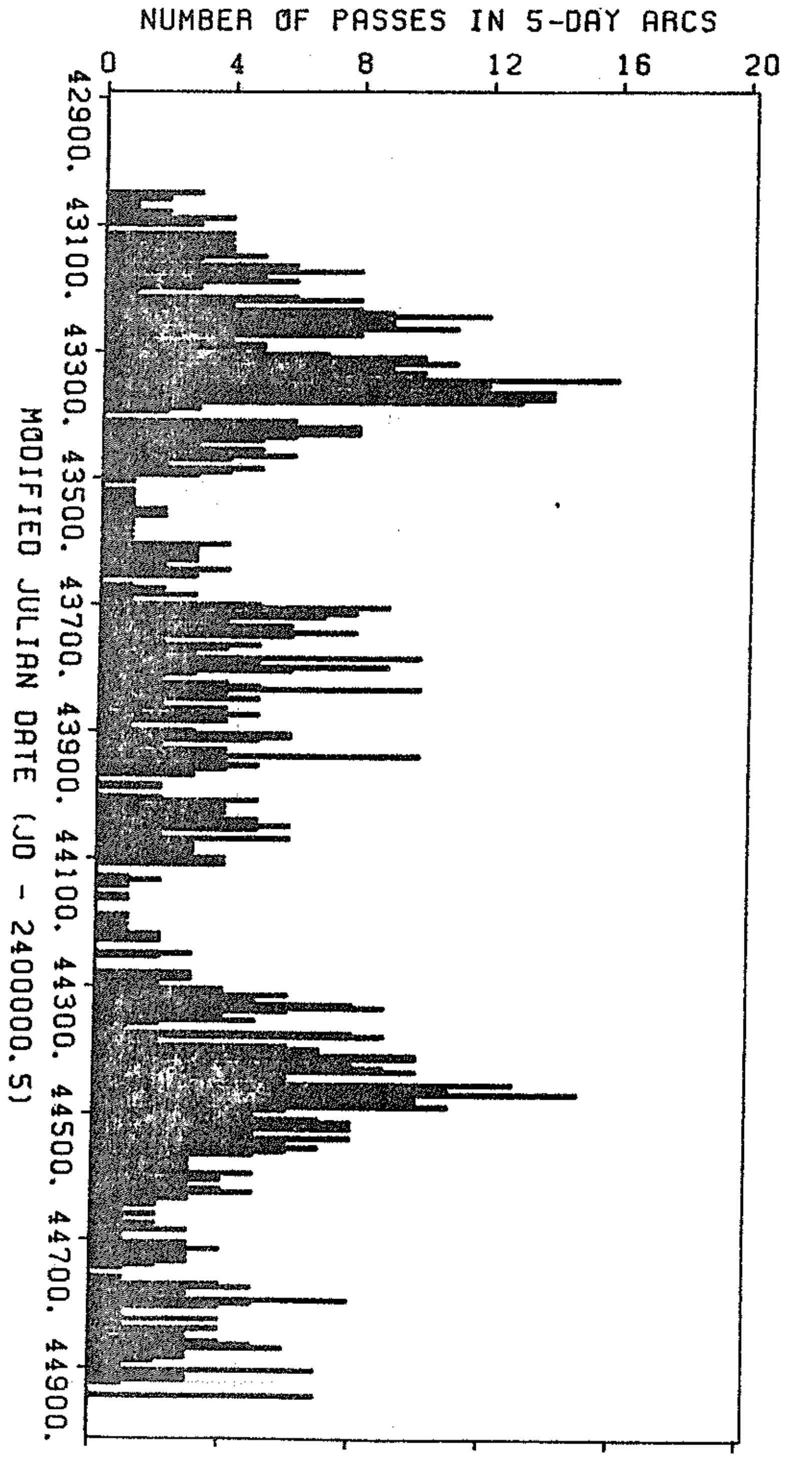


FIGURE 4

NUMBER OF LAGEOS PASSES OBSERVED BY ORRORAL IN EACH 5-DAY POLAR MOTION ARC FROM 42909 (11 MAY 76) TO 44944 (06 DEC 81)

FIGURE 5

MAXIMUM ENTROPY SPECTRAL ANALYSIS OF LAGEOS OBSERVATION DISTRIBUTION

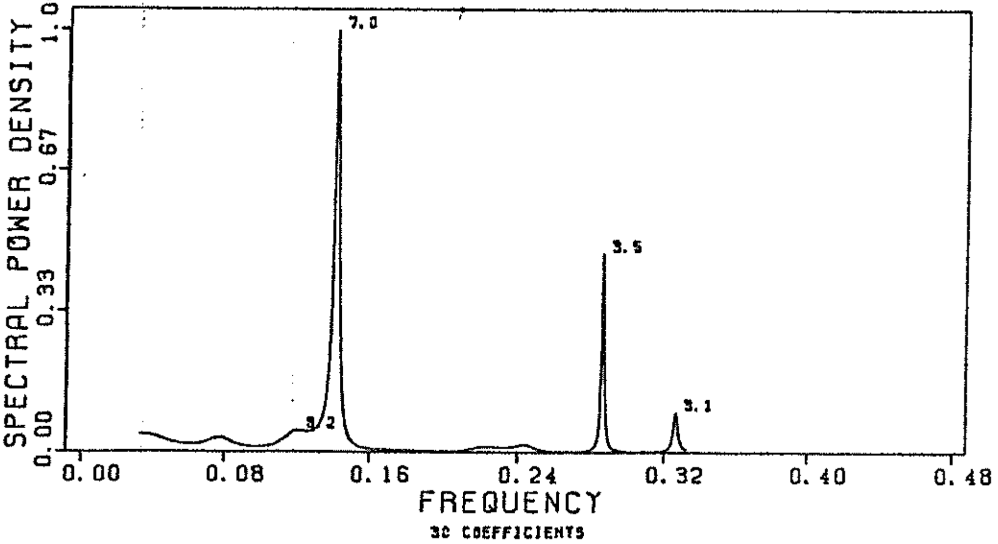


FIGURE 6

VARIATION OF THE QUANTITY OF LAGEOS DATA OBTAINED DURING THE MERIT SHORT CAMPAIGN. FIT WITH 7 AND 3.5 DAY PERIODS

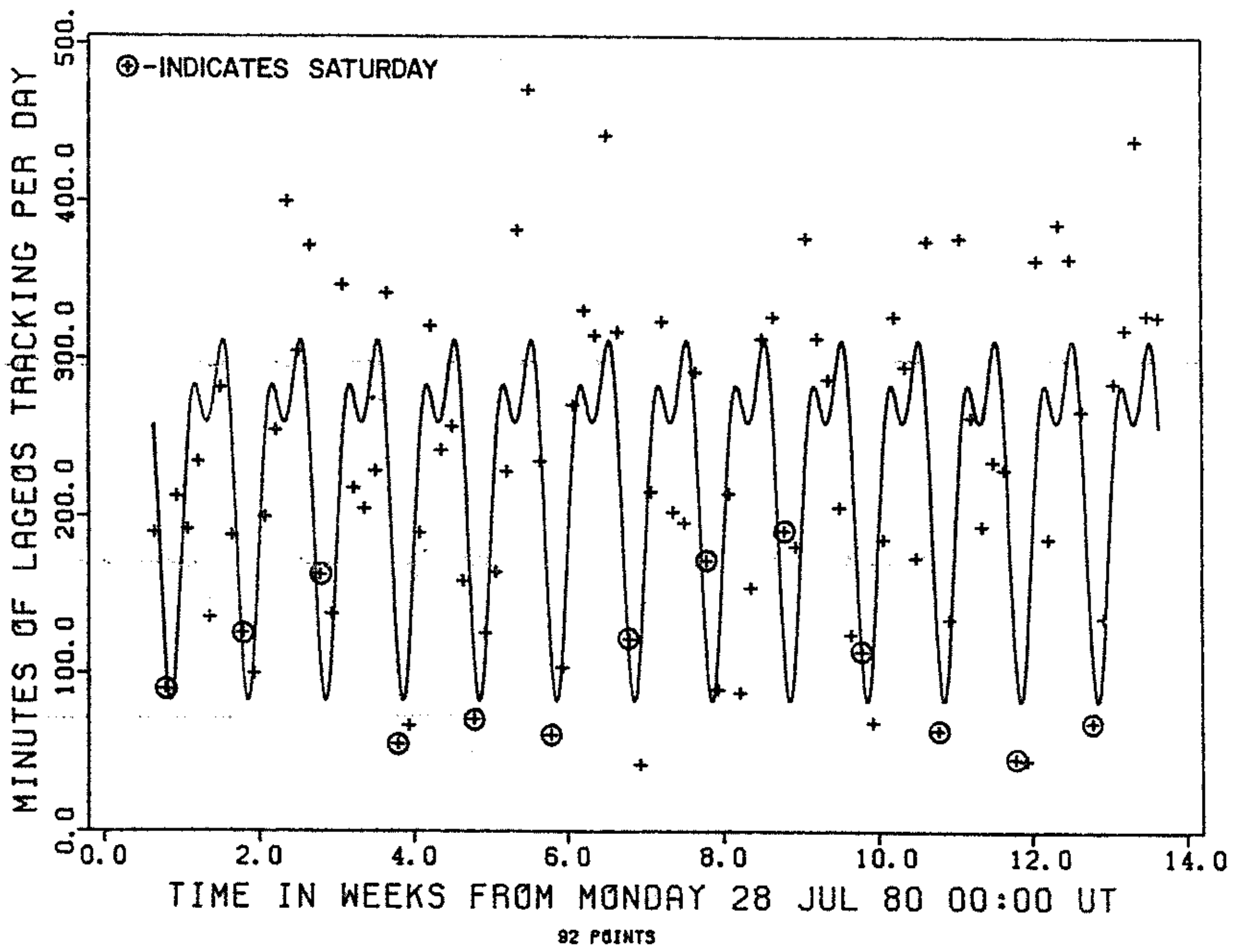
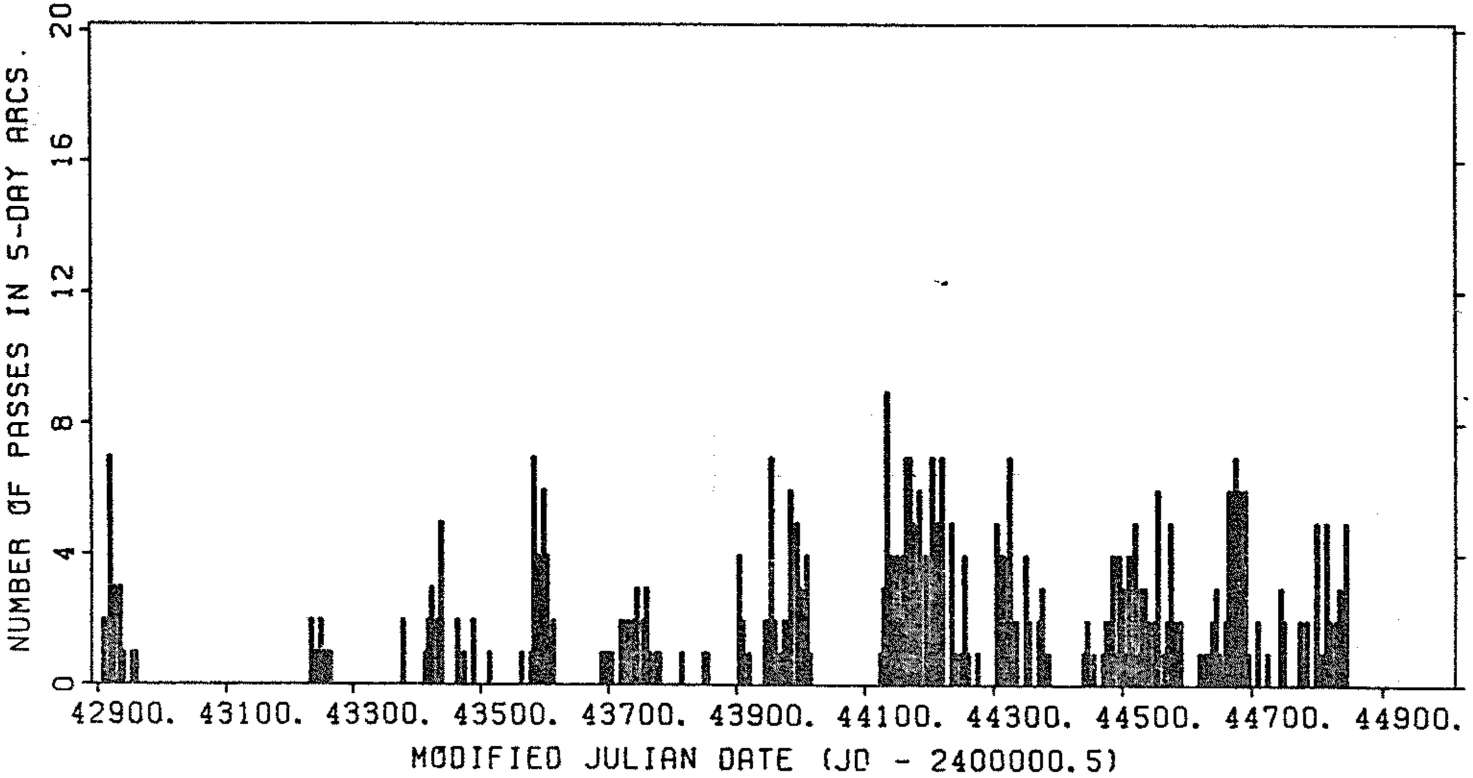


FIGURE 7
NUMBER OF LAGEOS PASSES OBSERVED BY STALAS IN EACH 5-DAY POLAR MOTION ARC FROM 42909 (11 MAY 76) TO 44944 (06 DEC 81)



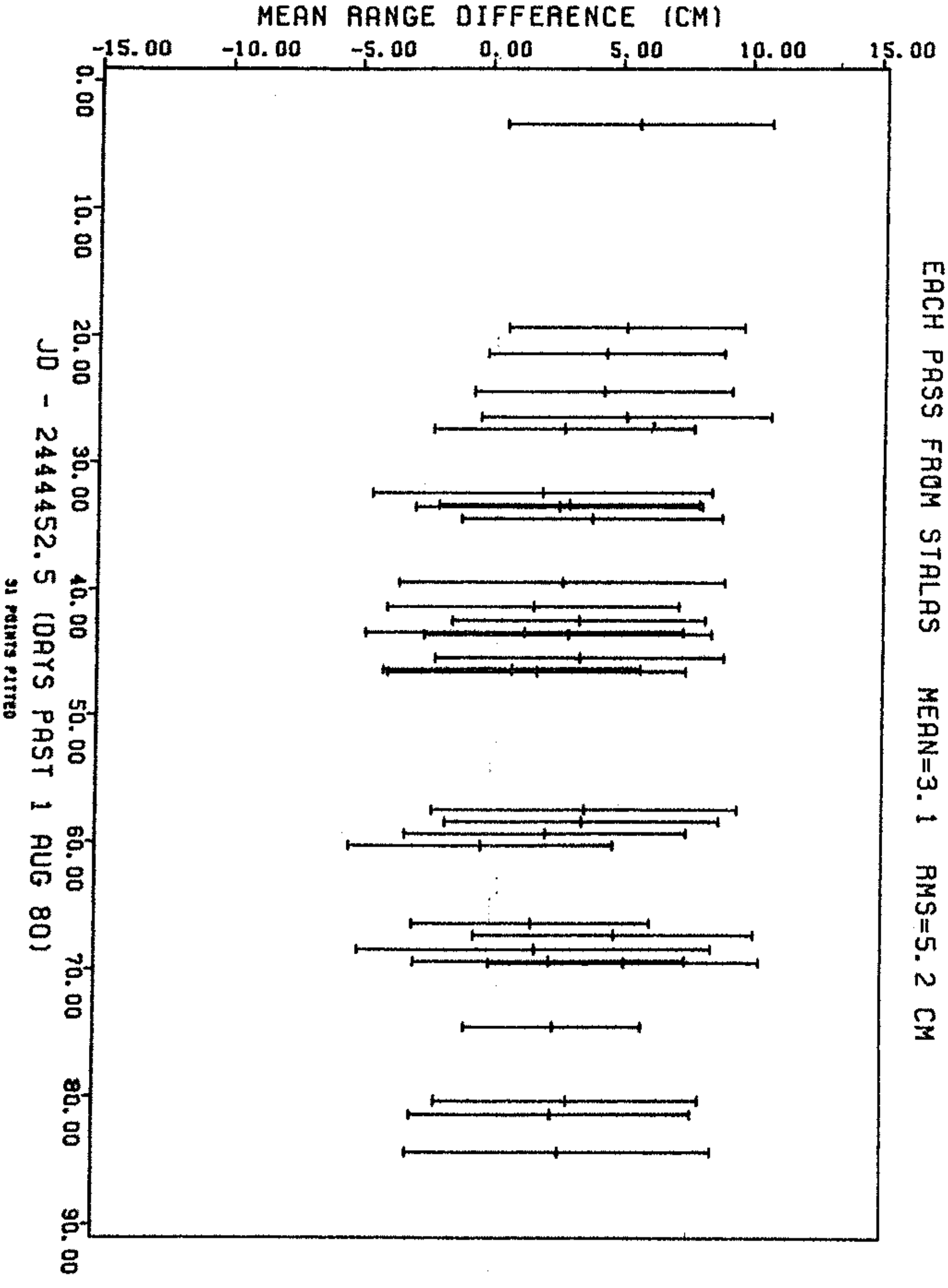


FIGURE 8

FINAL - QUICKLOOK DATA MEAN RANGE DIFFERENCE FOR EACH PASS FROM STALAS MEAN=3.1 RMS=5.2 CM

FIGURE 9

FINAL - QUICKLOOK DATA MEAN TIME DIFFERENCE FOR EACH PASS FROM STALAS MEAN=0.8 RMS=0.4 MICROSEC

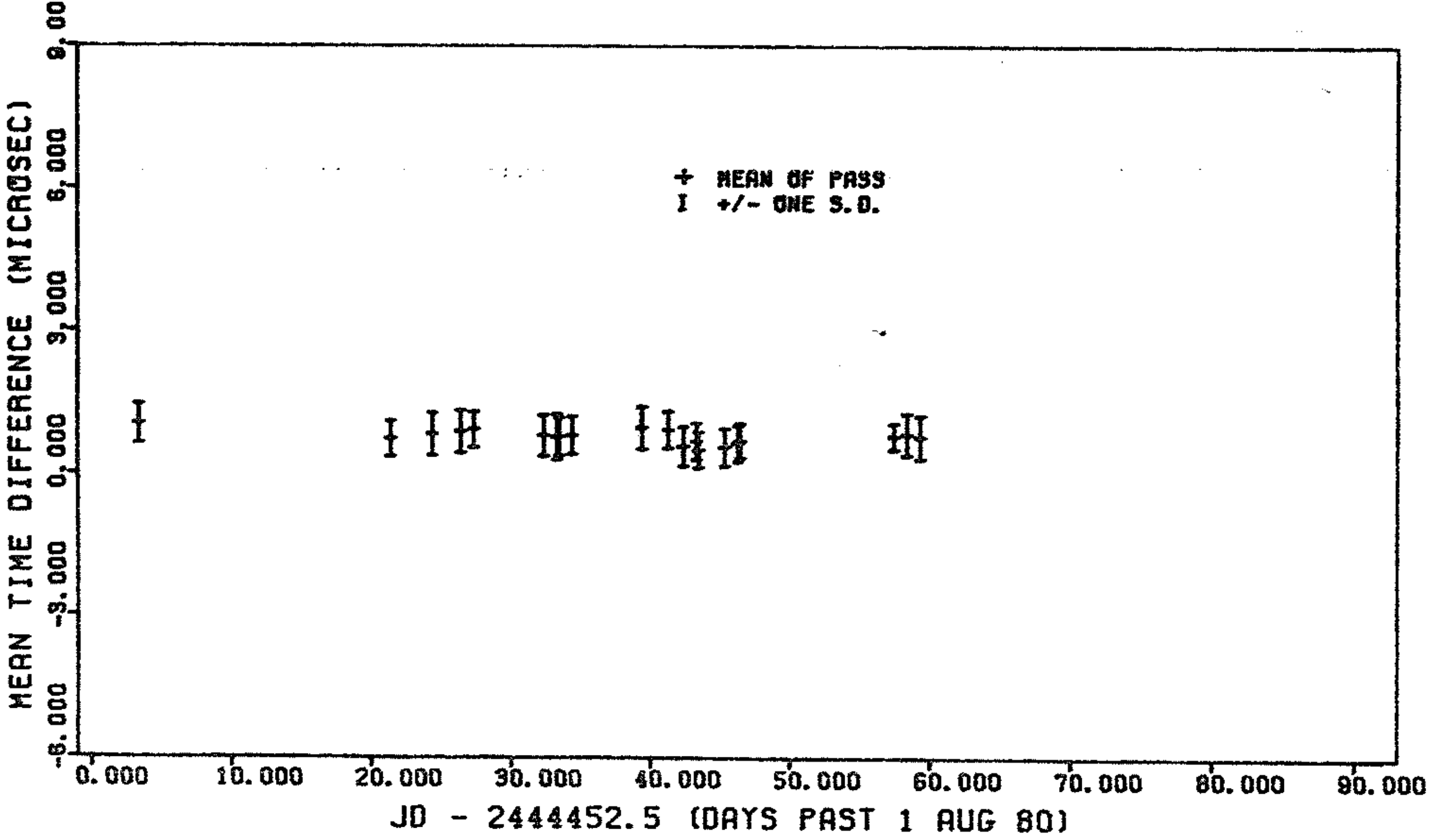


FIGURE 10
FINAL - QUICKLOOK DATA MEAN RANGE DIFFERENCE FOR
EACH PASS FROM ORRORAL MEAN=-0.6 RMS=3.0 CM

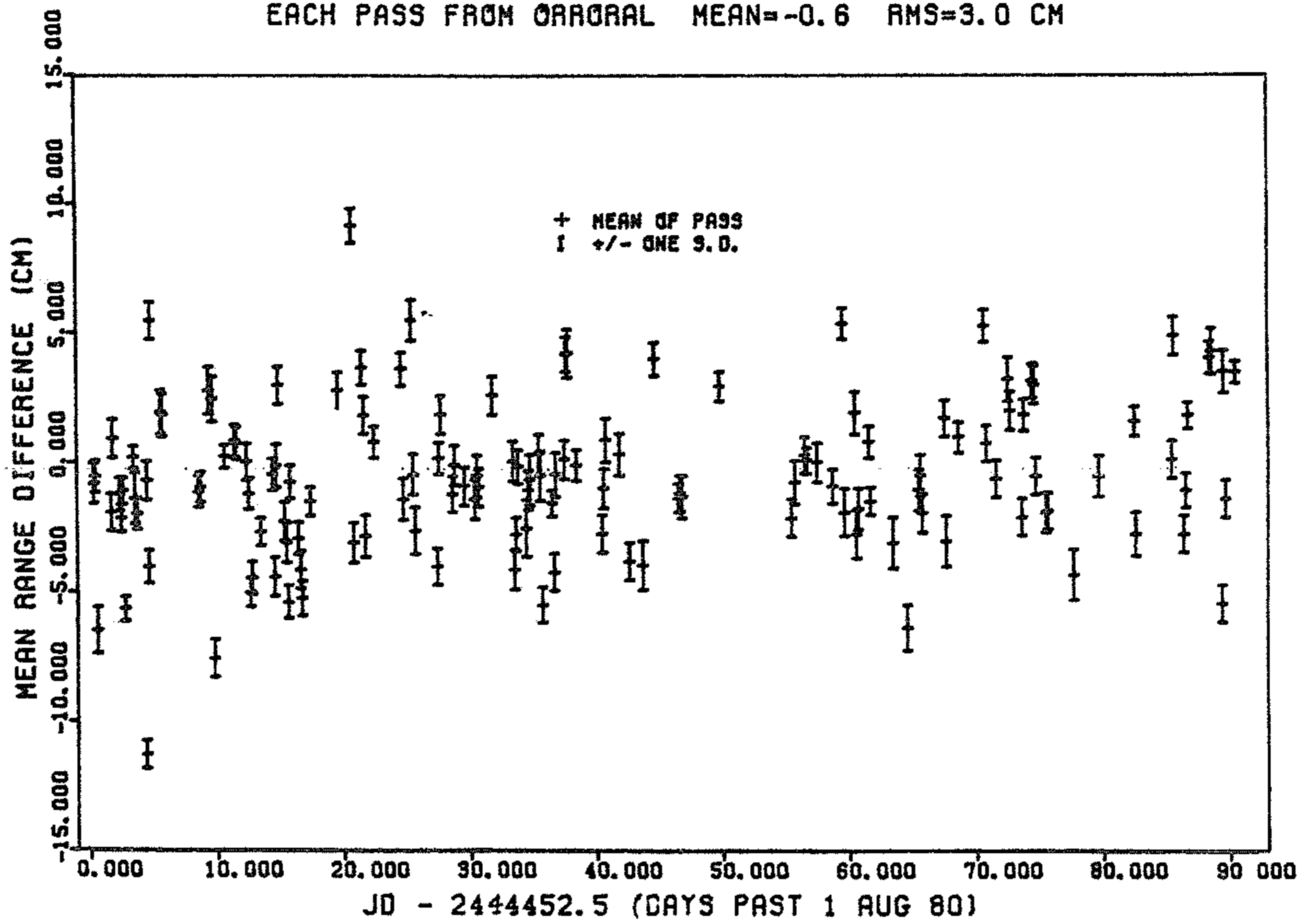
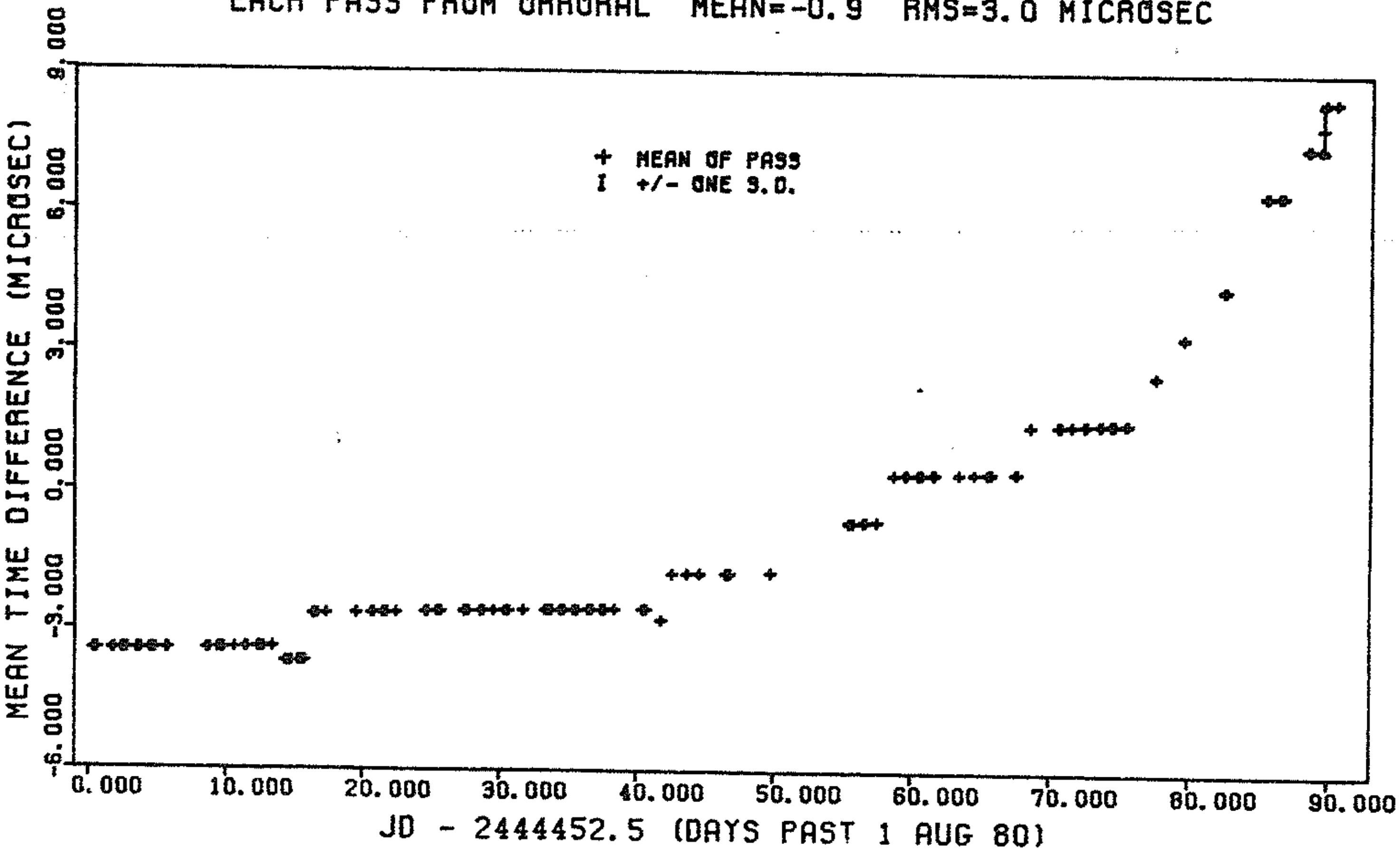


FIGURE II

FINAL - QUICKLOOK DATA MEAN TIME DIFFERENCE FOR
EACH PASS FROM ORRORAL MEAN=-0.9 RMS=3.0 MICROSEC



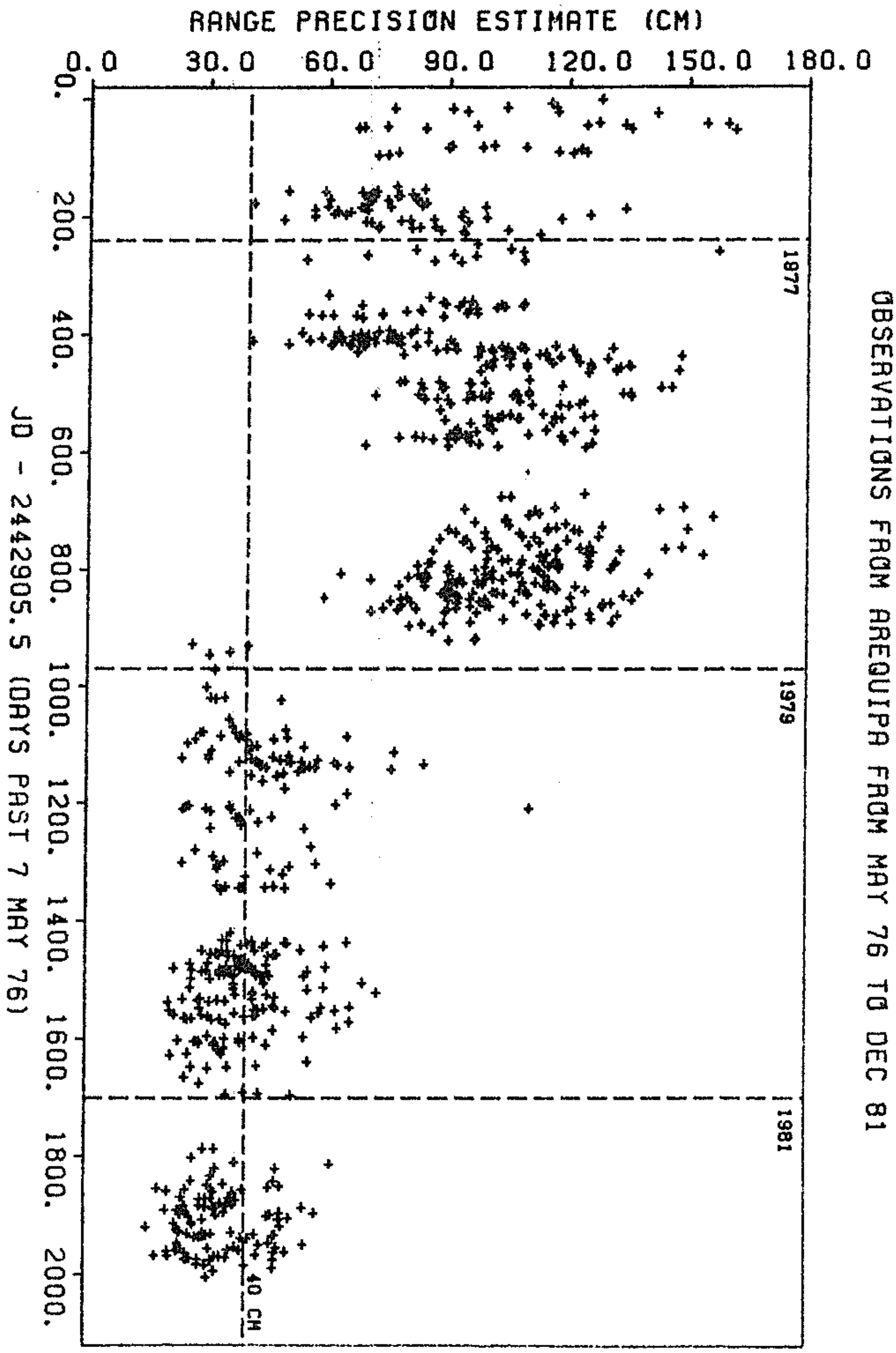


FIGURE 12

PASS BY PASS ESTIMATES OF THE INTERNAL PRECISION OF LAGEOS OBSERVATIONS FROM AREQUIPA FROM MAY 76 TO DEC 81

FIGURE 13

PASS BY PASS ESTIMATES OF THE INTERNAL PRECISION OF LAGEOS OBSERVATIONS FROM STALAS FROM MAY 76 TO DEACTIVATION IN OCT 81

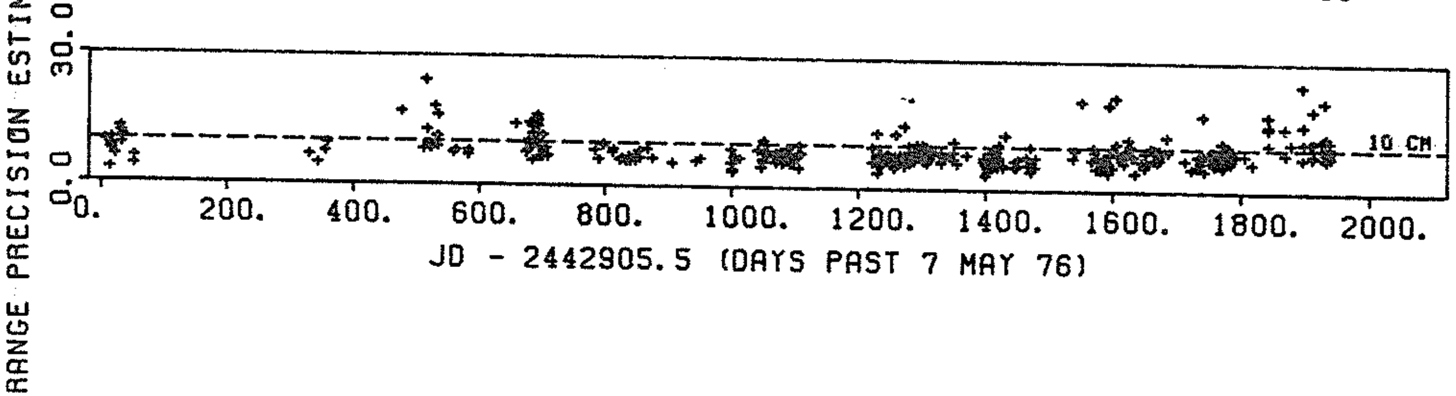


FIGURE 14

RANGE RESIDUALS FROM MOBLAS 7 PASS OF 8 JAN 82, 10 HRS UT
THE RAW RESIDUALS ARE SHOWN WITH THE RANGE BIAS-TIME BIAS FIT

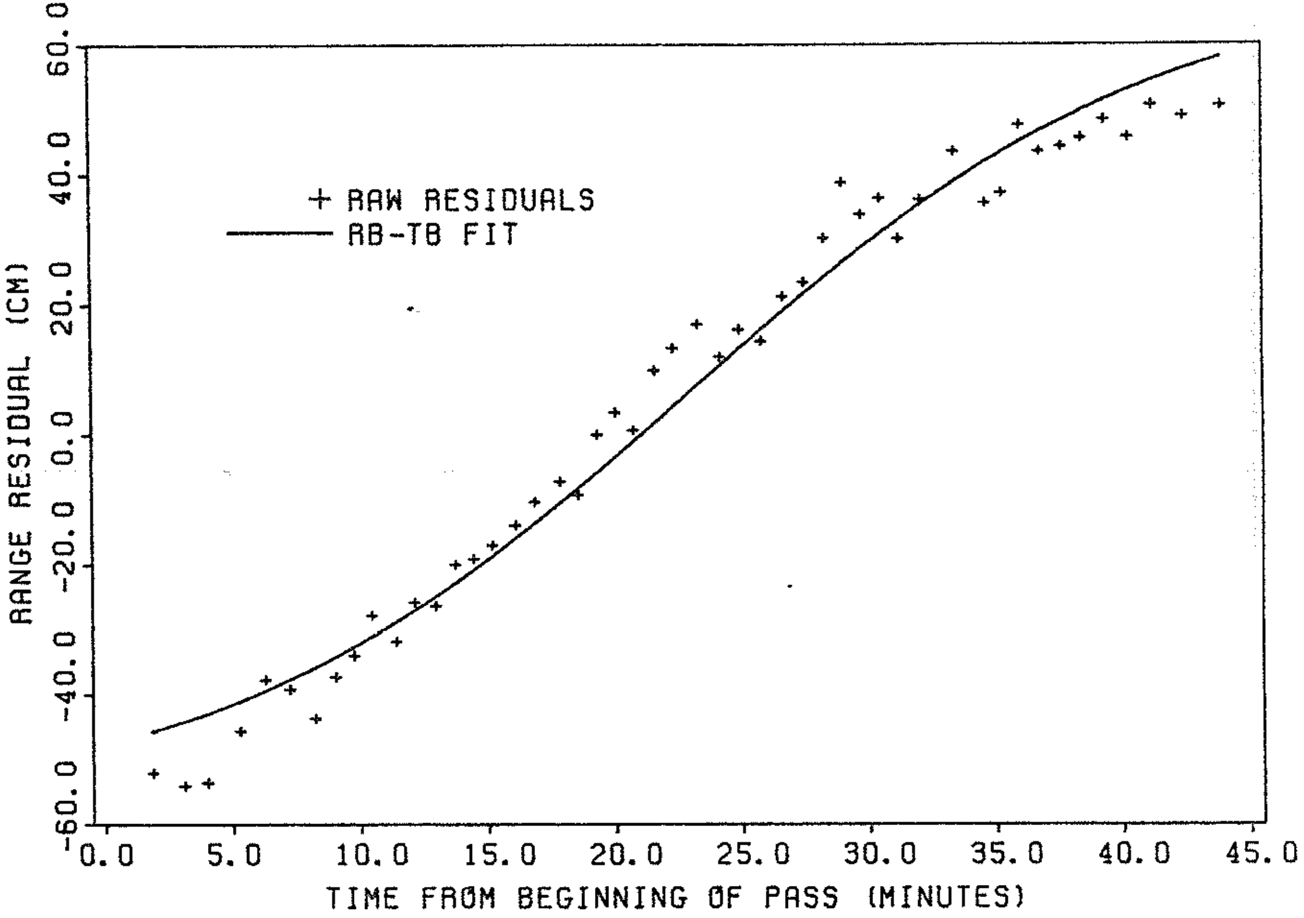


FIGURE 15

RANGE RESIDUALS FROM MOBLAS 7 PASS OF 8 JAN 82, 10 HRS UT
THE RB-TB RESIDS ARE SHOWN WITH THE POLYNOMIAL FIT

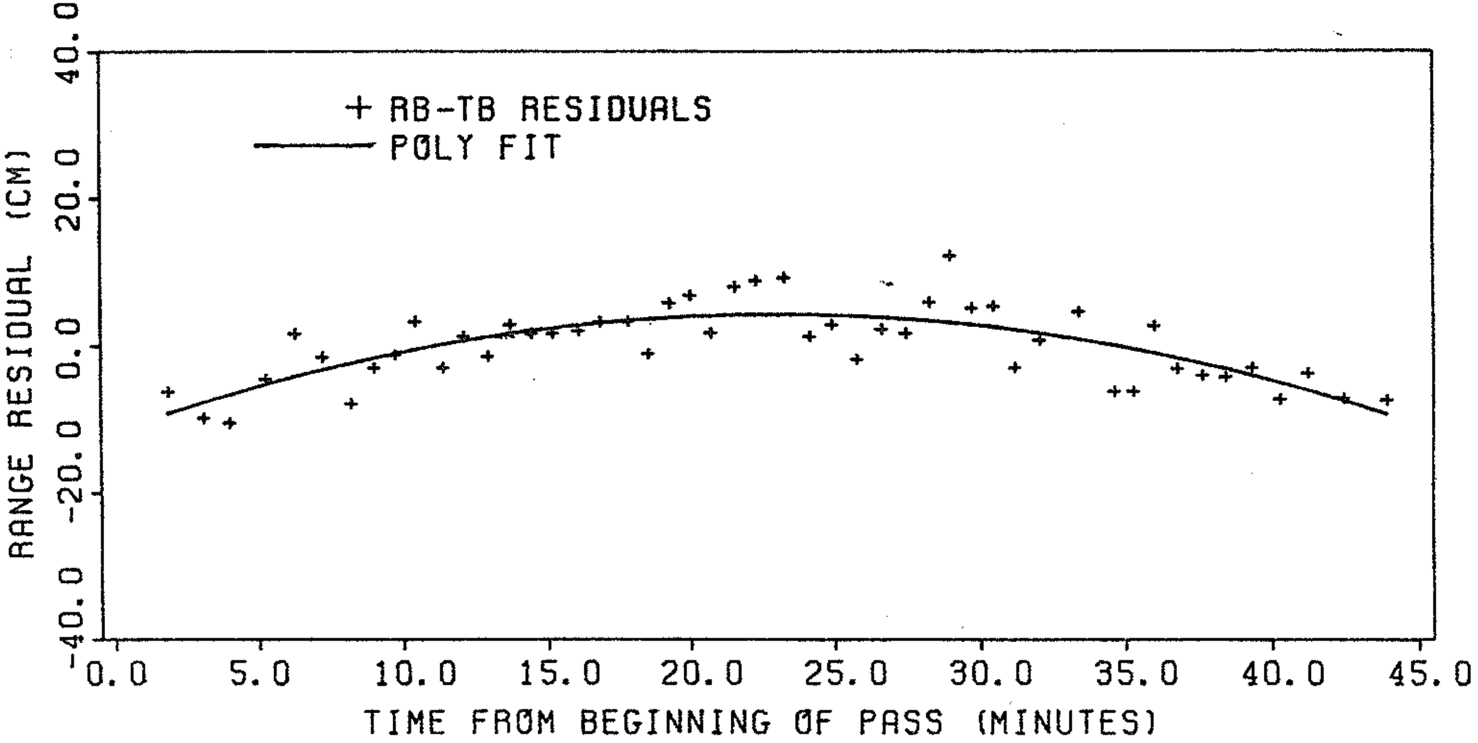


FIGURE 16
RANGE RESIDUALS FROM MOBLAS 7 PASS OF 8 JAN 82, 10 HRS UT
QUICKLOOK RESIDUALS AFTER POLYNOMIAL FIT, RMS = 3.3 CM

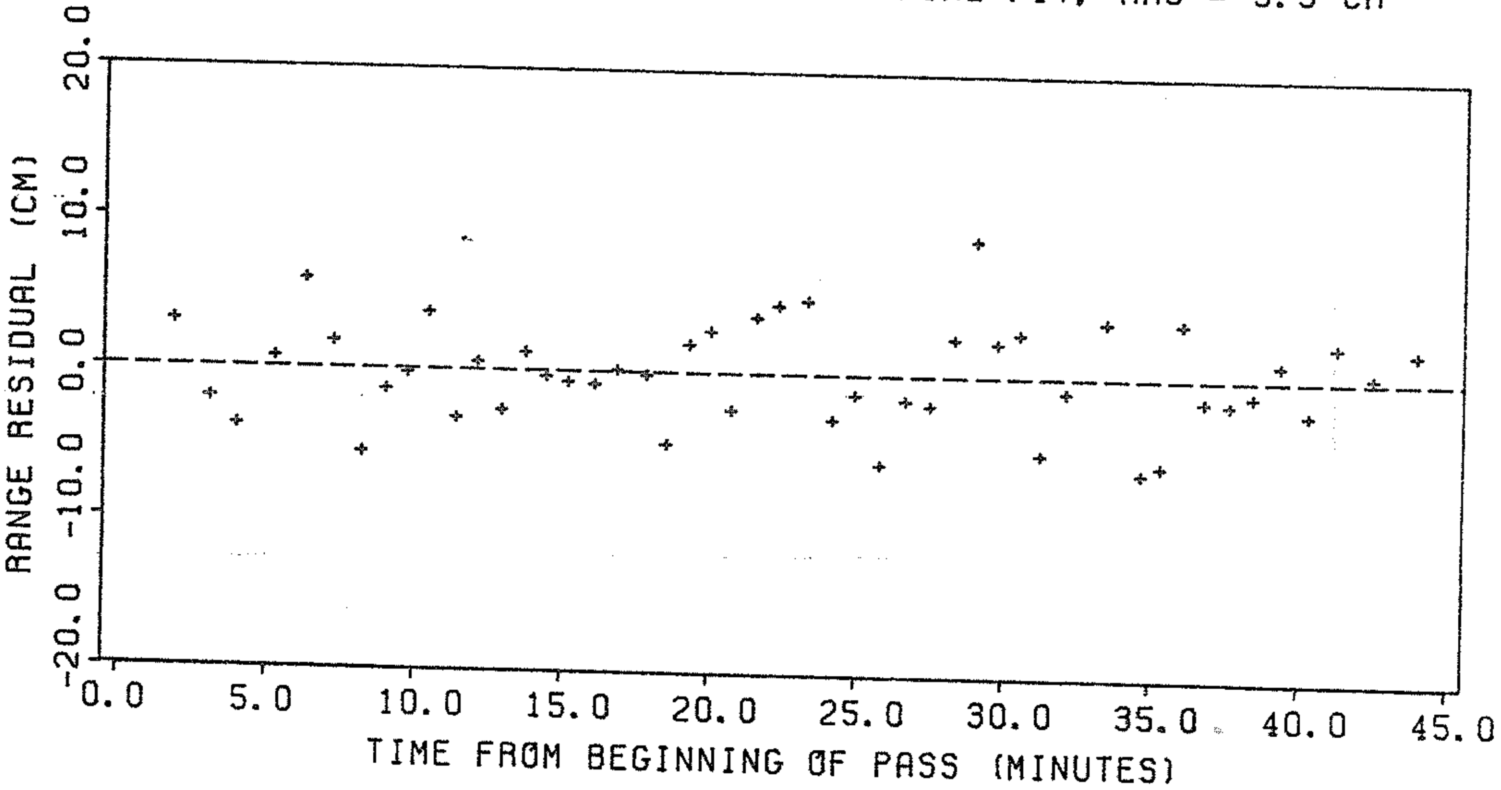


FIGURE 17
INTERNAL PRECISION OF TLRS NORMAL POINTS
DATA FROM SITE 8, PASADENA, CA.

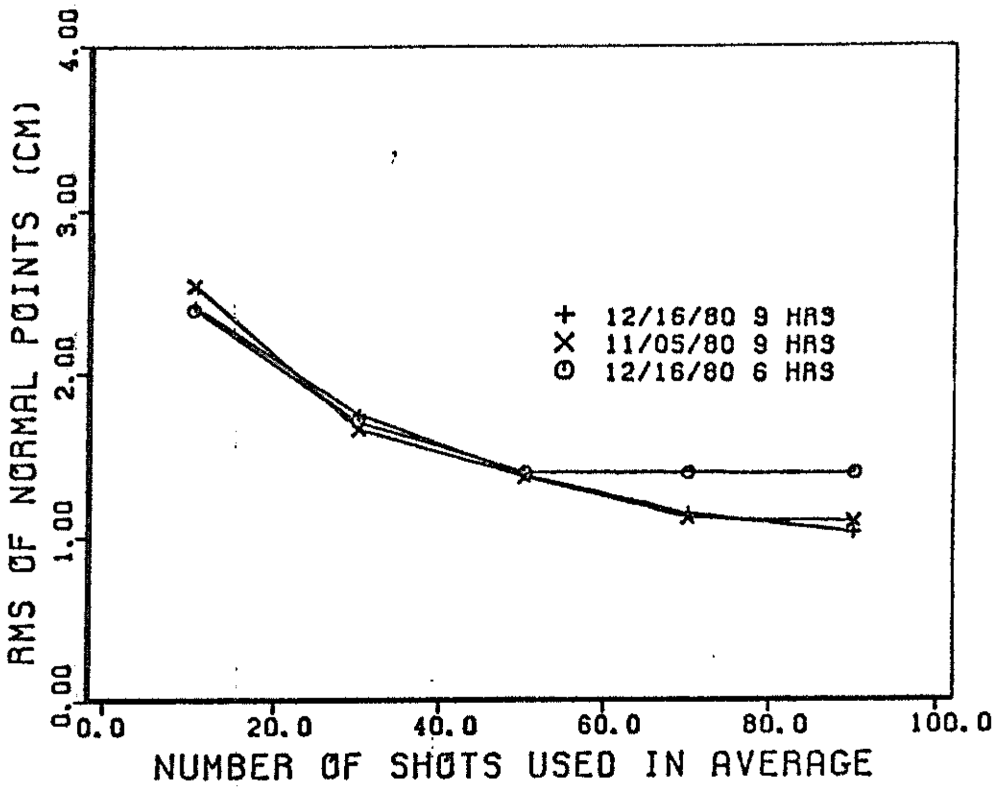


FIGURE 18

LAGEOS POLAR MOTION SOLUTION RESIDUALS FROM SMOOTHING
SHOWING IMPROVEMENT IN INTERNAL CONSISTENCY

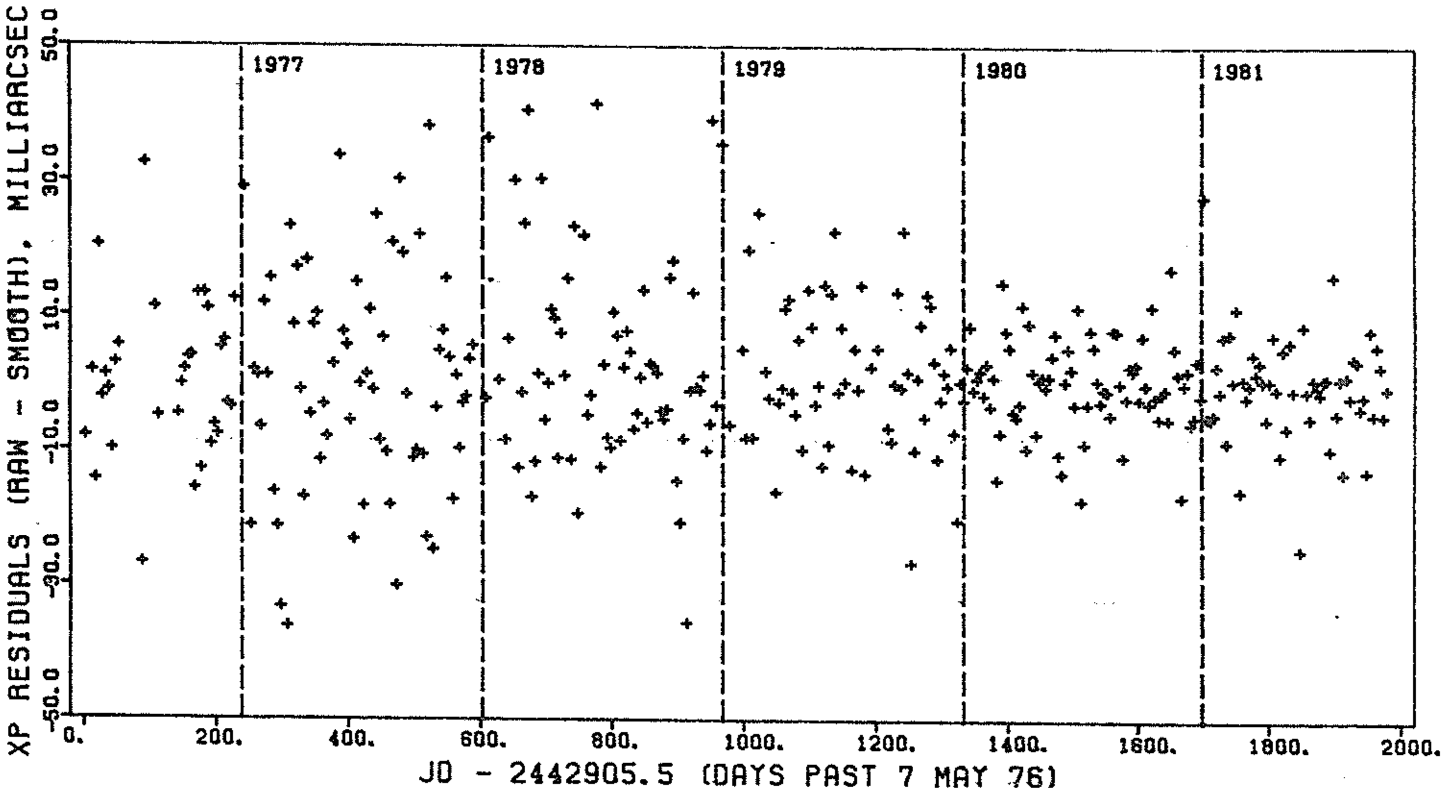


FIGURE 19

STANDARD ERROR OF THE MEAN XP SMOOTHING RESIDUAL FOR 100 DAY AVERAGES (20 FIVE-DAY ARC SOLUTIONS)

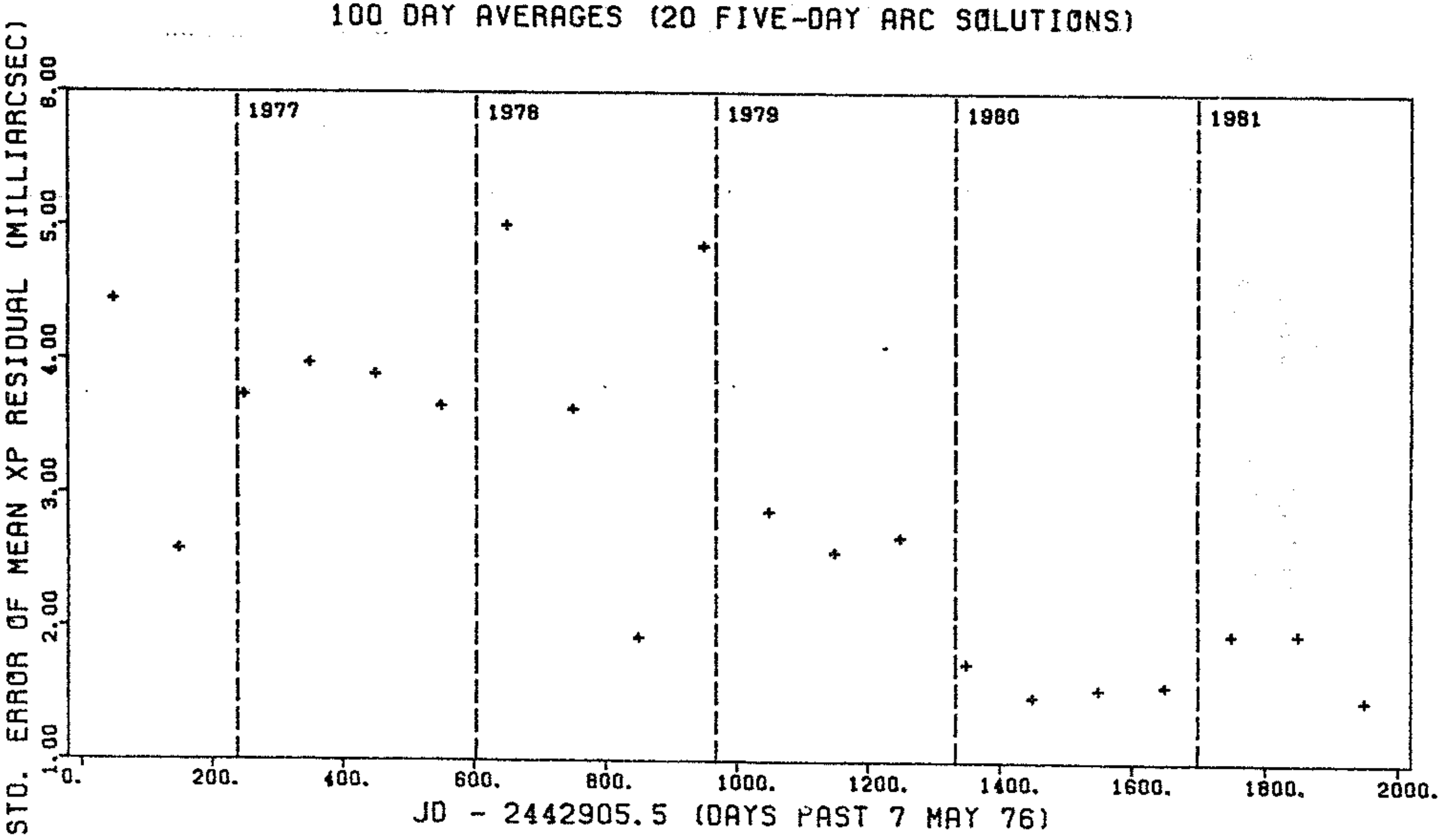


FIGURE 20

LAGEOS 10 DAY ARC INCLINATION RESIDUALS (RAW - SMOOTHED)
SHOWING IMPROVEMENT IN INTERNAL CONSISTENCY

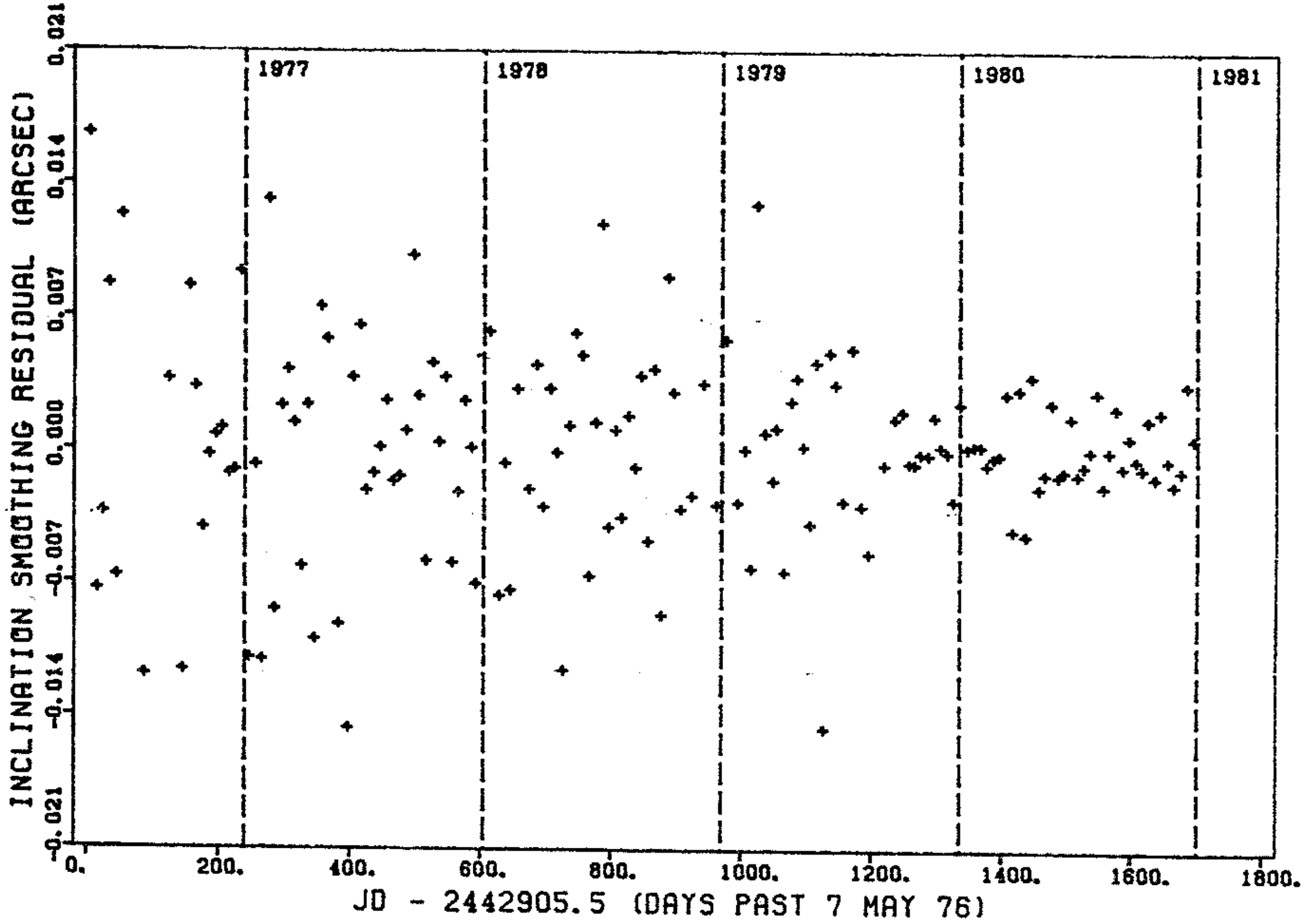
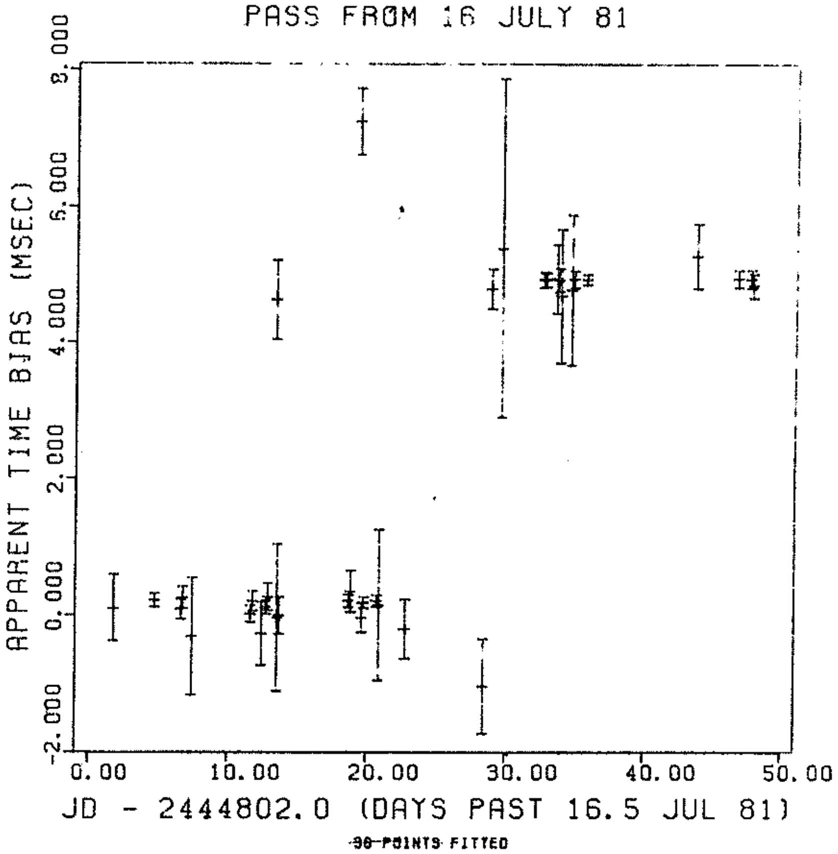


FIGURE 21

APPARENT TIME BIAS FOR EVERY PLATTEVILLE (MOBLAS 2) PASS FROM 16 JULY 81



SOME CURRENT ISSUES IN SATELLITE LASER RANGING

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60 Garden Street
Cambridge, Massachusetts 02138

The Laser Workshops have provided an important forum for us to discuss hardware and now software status and development. We have also had the opportunity to hear an elaboration of requirements and an assessment of present data quality.

In this paper we will address several very critical issues that have not been given sufficient attention to date. These include: (1) current trends in data capability, (2) accuracy, and (3) data aggregation. Recommendations are provided as a means to stimulate discussion and hopefully some organized action.

1.0 Applications and Current Trends

At the last Laser Workshop at Lagonnissi, Dr. E. M. Gaposchkin (1978) gave an overview of the applications that could be addressed in geophysics at different levels of ranging accuracy. A summary of this, with some more recent input from the NASA Crustal Dynamics Program appears in figure 1.

At the 10 cm/year level of accuracy, which is probably satisfied by many systems in the field, we should be able to make reasonable contributions to the studies of tides and polar motion. These studies are in fact underway with very promising results. Measurements accuracies of about 3 cm/year will be required to study plate tectonics and regional fault motion. Some operational lasers may be performing at this level or are on the verge of doing so. The most stringent requirement is for the measurement of intra-plate deformation that will require accuracies of 1 cm/year.

The message that was evident from the NASA Crustal Dynamics Meeting at GSFC in early September was that some investigators want ultimate measurement accuracies of 1 cm/year with at least 3 sigma assurance.

If we examine the history of ranging accuracy of operational systems from 1965 to date (see figure 2) it appears that we are improving accuracy by a factor of three every five years. Projecting forward at this rate it will be at least 1990 before we can fully satisfy the needs of the scientific community.

The technology is now available to reach the required 1 cm accuracy. It is now probably a matter of experience to refine the techniques and put them into widespread operation. Basically the current trend is toward:

1. Subnanosecond pulse width lasers for higher accuracy and lower noise
2. High repetition-low output power for reliability and eye safety
3. Single photoelectron detection to take maximum advantage of the quantum statistical properties
4. Small optics for mobility
5. High resolution timing for higher accuracy
6. Software intensive systems for lower costs and greater flexibility

It is essential that we exploit and impliment these new techniques as rapidly as possible to accelerate the evaluation in satellite laser ranging field capability. We have developed a user community, but its interest and support will wane if we are not responsive to its needs.

2.0 UNIFORM STANDARD OF RANGING ACCURACY

2.1 Requirement

As workers in the field of satellite laser ranging (SLR), we have long avoided the issue of a uniform standard (definition) of accuracy. This is in part due to the complicated nature of the error sources and the variety of system configurations that now exist. At the moment, we have the whole spectrum of concern about accuracy: Some groups have taken their whole system apart piece-by-piece to examine the characteristics of each component; at the other extreme, some groups really do nothing.

We are now at the stage where laser data is being examined for decimeter and even centimeter effects. However, current modeling capability does not permit the analyst to detect and diagnose errors at this level. In fact, historically, evolving laser data quality has always been a primary driver for model development. As a result, the analyst must rely on us, the experts in the systems, to specify data quality and error model.

In addition to our responsibility to the analysts, we ourselves suffer from a lack of uniform means of comparing one system with another and even comparing different stages of development in an individual systems.

In view of our current reticence over the definition and measurement of accuracy, and the ambitious programs that lay ahead of us, it is essential that we adopt a uniform error model to characterize our laser systems.

This standard error model should:

1. Represent a "good" estimate of the known error sources
2. Specify relevant time period or periods
3. Define a means of measuring and specifying each error component
4. Specify a means of aggregating the error components
5. Be practicable

2.2 Suggested Model

Recognizing the diversity in the nature of the error sources and the range of applications in which the data will be used, we recommend a standard error model that:

1. Is restricted to the ranging machine only, leaving the atmospheric corrections and the satellite center-of-mass for separate consideration
2. Includes two estimates of error: epoch bias and range bias
3. Uses one sigma estimates of error components
4. Characterizes system performance over a period of a satellite pass (30-45 minutes)

Epoch bias is the uncertainity in our correction of station time to a uniform standard (USNO). This is determined through the quality of: portable clock checks, frequency and epoch broadcast readings, and the timing data analysis.

Range bias estimates should consist of several components including:

1. Wavefront distortion
2. Uncorrected system drift
3. Error in target distance survey including atmospheric effects
4. Uncorrected variation in system delay with signal strength
5. Uncorrected variation in system delay with P.M.T. saturation level.

2.3 Measurements

The wavefront distortion should be measured by mapping the laser beam in the far field with a retroreflector.

System drift should be quantified by aggregating experience of pre-pass calibration minus post-pass calibration differences or through some other form of direct measurement if appropriate.

The error in target distance is the estimated accuracy of the target survey.

The uncorreced variation in system delay with signal strength should be determined from extended target calibrations over the full dynamic operating range of the system.

The uncorrected variation in system delay with PMT saturation should be estimated from extended target calibration under anticipated extreme conditions.

2.4 Aggregation of Range Bias Components

For simplicity we have suggested that the range bias error sources be assumed independent and that an rss of the 1 sigma contributions be formed to provide a single range bias characterization parameter.

2.5 Special Cases

Some of the range bias error components will not be pertinent to particular ranging systems currently in operation or under development. Those groups operating systems at the single photoelectron level will probably not be concerned with issues of dynamic range; those that have internal pulse-by-pulse calibration may compensate completely for system drift. Systems that operate only at night may not present problems with PMT saturation.

2.6 Comments from the Workshop Participants

The need for a uniform standard of Ranging Accuracy was well recognized by the membership. Comments included:

1. Estimates of bias over longer periods of time such as a month and a year should also be included.

2. The rss is not the proper way to aggregate the error component as it tends to give biased results; a more rigourous formula should be used.

A committee was formed under the leadership of Dr. Peter Wilson to formulate a recommended error model for review of the membership and the scientific community.

3.0 Uniform Method of Data Aggregation

3.1 Requirement

The current trend in satellite laser ranging is toward higher pulse repetition rates and lower return energy. Systems with repetition rates of 5-10 pulses per second are now being implemented by some groups, and many are now using or planning to use single photoelectron detection in their ranging operation.

As a result of this trend, we are already faced with occasional passes containing as many as 2000-3000 data points, and we expect this to become far more common as time goes on. This data volume is far more than the data analysts would ordinarily choose to use. However, he would very much like the averaging potential that such a data yield could provide.

Several groups already are aggregating data in a normal point formulation or are planning to do so. Unfortunately to date there is no agreed standard for data aggregation. In order to avoid the proliferation of different techniques, the satellite laser ranging community including both data acquisition and analysis people should adopt a standard method for data aggregation.

As a minimum, the model must preserve the accuracy of the full data set, including all short period orbital effects. It must also be reasonably easy to impliment which means it can not rely on long arc orbital analysis techniques which some groups may not have available.

3.2 Standard Models

In an operational sense, data aggregation is intimately coupled with data screening. We eliminate bad data through some type of fitting process, perform an aggregation on the residuals, and then construct normal points.

Although there are many different techniques for screening data, most consist of the same basic processing steps in slightly different arrangements. The largest difference is in the initial step: Some groups use a long arc orbital fit to obtain "first" residuals that are then subjected to bias and/or polynominal fits. Others avoid the long arc fit by starting with the observed minus predicted residuals and then use gross-screening measures, bias fits, and local and/or single orbit polynomial fits. At a first glance, it appears that both techniques give similar results.

We recommend that the community adopt a Standard Data Aggregation Method that:

1. Relies on current data screening techniques currently available at each group to separate data from noise.

2. Aggregates data into time periods of fixed duration: one minute for Lageos and 0.5 minutes for lower orbiting satellites.

3. Determines normal points by:

   a. Aggregating residuals to the screening process into the appropriate time bias

   b. Calculating a normal point residual at a data point epoch closest to the center of the bin using a straight line fit to the data in the bin

   c. Reconstructing the normal point range value

4. Requires that the following data be furnished:

   a. Normal points

   b. Number of points in each bin

   c. RMS of each bin

   d. RMS of the pass (full rate)

Naturally, the full data set should be made available for verification of the technique and to those who require it for specialized analysis.

3.2 Comments from the Workshop Participants

The need for a uniform standard for Data Aggregation was recognized by the participants. Comments included:

1. The full data set should still be submitted to the Data Centers
2. It would be most advantageous if normal points could be made available through the Quick-Look process
3. We must be careful that the screening processes used do not inadvertantly alias the data toward a particular result

A committee was formed under the leadership of Dr. Michael R. Pearlman to formulate a recommended Method of Data Aggregation for the membership and the scientific community.

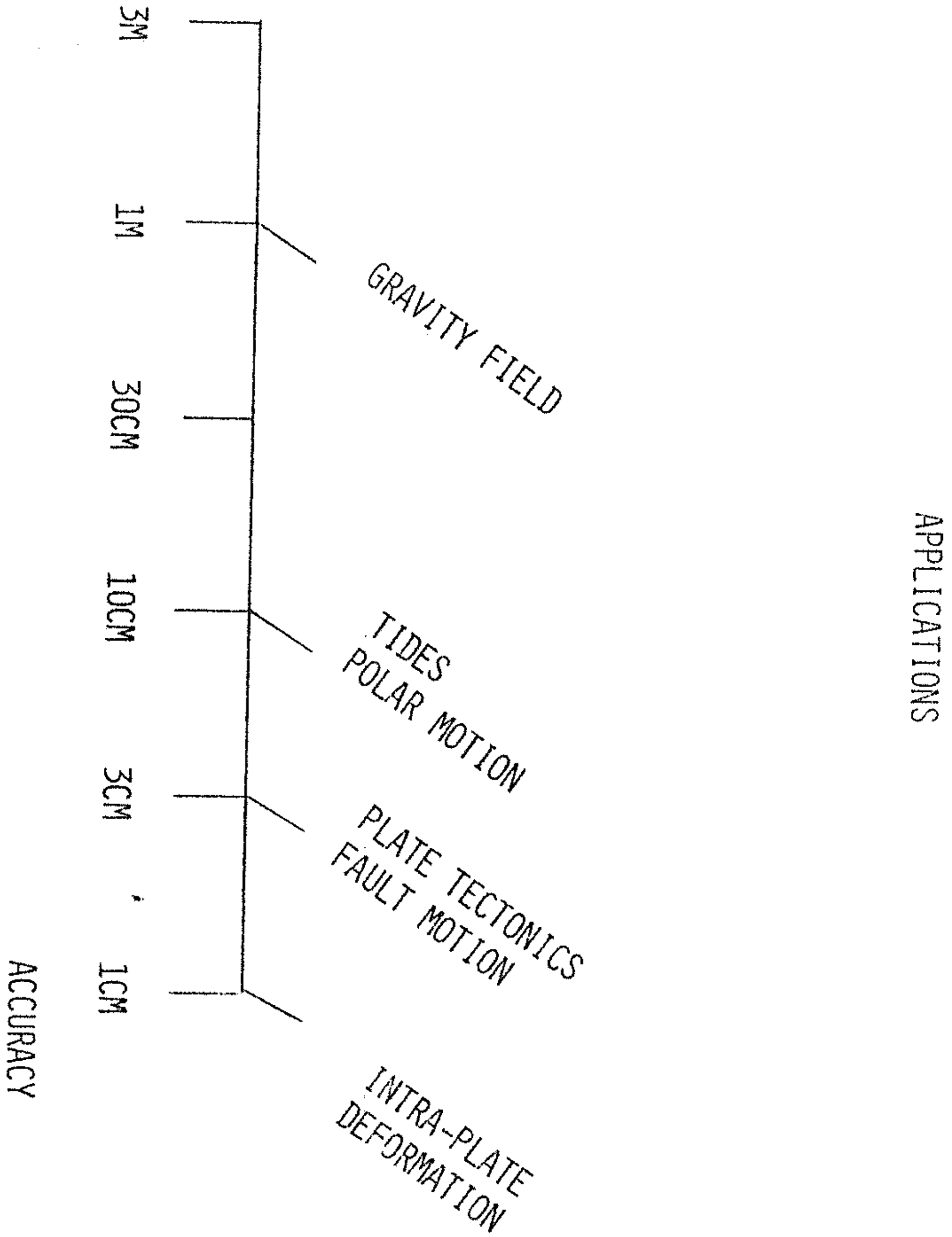
APPLICATIONS
GRAVITY FIELD
TIDES
POLAR MOTION
PLATE TECTONICS
FAULT MOTION
INTRA-PLATE
DEFORMATION
3M
1M
30CM
10CM
3CM
1CM
ACCURACY

Figure 1.

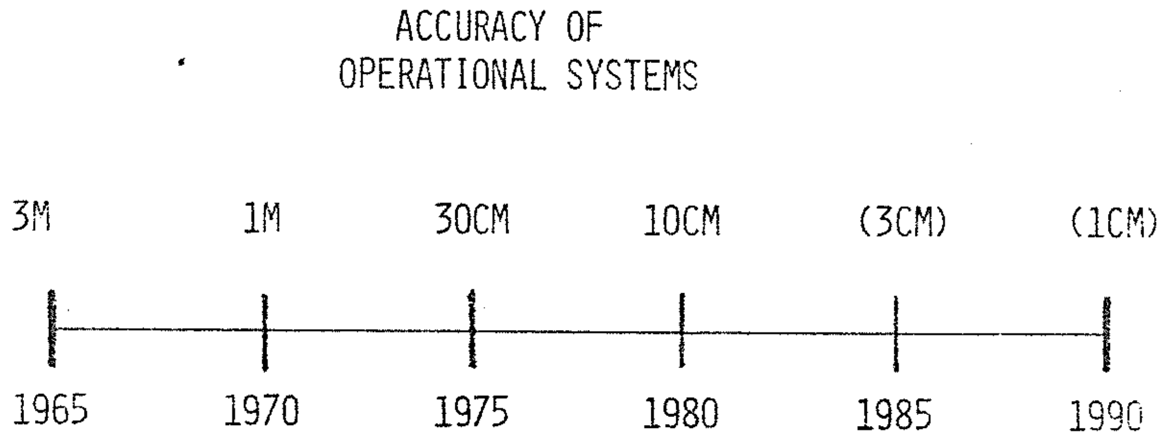
ACCURACY OF
OPERATIONAL SYSTEMS
3M
1M
30CM
10CM
(3CM)
(1CM)
1965
1970
1975
1980
1985
1990

Figure 2.

References

1978 Gaposchkin, E. M., Geophysical Uses of Laser Range Data and Related Questions. Presented at the Third International Workshop on Laser Ranging Instrumentation, Lagonissi, Greece, May.

Recommendation No. 1

Recognising: The importance of high quality laser range observations over the full 14 month period of the MERIT campaign to determine:

1. The potential contribution that satellite laser ranging may be able to make a future earth rotation service;
2. possible shorter period periodic variations in the earth rotation vector;
3. the possible existence or systematic differences between conventional inertial systems.

This workshop Recommends that operation of satellite laser rangers be configured from the present until the commencement of MERIT to ensure that systems are in the best state of readiness to commence the MERIT campaign and with the best capability to perform over the MERIT campaign with the highest possible accuracy.

Recommendation No. 2

The 4th International Workshop on Laser Ranging Instrumentation,

Considering the importance of an objective estimate of the accuracy of laser ranging instruments,

Realising that for a full and proper utilisation of ranging data such information is valuable

and Noting that commonly acceptable procedures and standards do not exist for the estimation of instrumental accuracy,

Requests the chairman of W.G. 2,33 to set up a small group of experts to prepare such procedures and standards.

Recommendation No. 3

The 4th International Workshop on Laser Ranging Instrumentation,

Considering that for several applications of satellite laser ranging there are advantages to aggregating data in the form of "normal" points and Emphasing that the original data should be preserved,

Requests the chairman of S.S.G. 2,33 to set up a group of experts to recommend standard procedures for the calculation of "normal" points which will preserve the information contained in the original data.

At the close of the meeting unanimous approval was given to the following resolution:

This Workshop, accustomed to the very high standards of performance of University of Texas personnel, acknowledges the excellent organization and running of the Workshop on our behalf. The opportunity to meet with our colleagues in congenial surroundings, in formal sessions and in formal social gatherings has enhanced the prospects of being in the desired state of readiness for the Crustal Dynamics Project and Project MERIT.

Our thanks are extended to the University of Texas at Austin, and the Director of the Mc Donald Observatory - Dr. Smith, for their support of the organizers - Drs. Eric Silverberg and Peter Shelus who we congratulate on maintaining the highest standards of excellence. Finally we extend our warmest thanks and appreciation to the Workshop organizer's staff. - Cynthia Straub and Pam Johnson, without whose hard work and dedication this workshop would have failed.