Proceedings of the Fourth International Workshop

on

Laser ranging instrumentation

held at the
University of Texas in Austin, Texas, U.S.A.
October 12 – 16, 1981

Volume I

compiled and edited
by
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Earth-satellite laser ranging

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PREFACE

The Fourth International Workshop on Laser Ranging Instrumentation was held at the Thomson Center on the campus of the University of Texas in Austin during the week of 12-16 October, 1981. It was sponsored under the auspices of the Special Study Group 2.33 (Earth-satellite laser ranging) of the International Association of Geodesy and the University of Texas.

The Workshop, which for three of the five days comprised parallel sessions on hardware and software aspects of laser ranging, was attended by participants from 15 nations and information was exchanged on the status of 44 of the 51 ranging systems for which hardware is known to exist. The meeting was opened by Prof. Dr. Harland Smith, Chairman of the Astronomy Dept. at the University of Texas. In his remarks Prof. Smith spoke of the intimate association his department and the University of Texas have had with the course of laser ranging to both the moon and to Lageos, laying stress on the progress which has been made over the years since first the technique was applied.

Indeed, with this, the third set of published proceedings, it can be seen that considerable consolidation has gone on in the four years since the previous Workshop in Lagonissi. Laser ranging is at last moving from experimental to application oriented research. The contents of these proceedings high-light the changes which have taken place in system design over this time and represent the state of the art in 1981.

In the interests of expediting publication there has been no extensive editing of individual papers, which are generally presented in the form submitted by the authors. Several papers have been included which were submitted for publication, although the authors were unable to attend the Workshop. Only two or three of the papers presented at the sessions have not been submitted for inclusion in the proceedings.

Particular thanks are due to:

- the Programme-Committee (Prof. Dr. L. Aardoom - Netherlands, Prof. Dr. K. Hamal - Czechoslovakia, Dr. E. Silverberg - U.S.A. and Dr. P. Wilson - Fed. Rep. of Germany) and the session chairman, for preparing the programme;
- the hosts and hostesses of the University of Texas, for making the Workshop a valuable scientific and social experience;
- the authors, for their valuable contributions;
- the publisher, for making it possible to produce extensive Proceedings within the limitations of the available budget.

P. Wilson
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AUSTIN, TEXAS USA OCTOBER 12-16, 1981

FOURTH INTERNATIONAL WORKSHOP ON LASER RANGING INSTRUMENTATION

OCT. 12 MONDAY	OCT. 13 TUESDAY	OCT. 14 WEDNESDAY	OCT. 15 THURSDAY	OCT. 16 FRIDAY
8:00 Registration 9:00 Opening Remarks 9:30 Purpose of the Measurements *P. Bender* 11:00 Laser Ranging Progress Since 1978 *S. Tatevjan* 15:00 Current Priorities in Software *E. Silverberg and J. Latimer* Reception	8:30 General Status of the Networks *P. Wilson* 10:00 Latest Trends in Optics and Mount Development *Y. Kozai and J. Wohn* 14:00 Lasers *K. Hamal and D. Hall* Meeting of SSG 2:32	8:30 Critical Look at Current Data Quality *B. Tapley* 10:00 Problems Specific to Lunar Ranging *B. Greene and P. Shelus* 14:00 Timing, Time Keeping and Calibration *J. Gaignebet and M. Pearlman*	8:30 Current Results *D. Smith* 10:00 Electro-optics and Detection Hardware *F. Zeeman and R. Neubert* 14:00 MERIT Meetings (Communications & Standards) 19:30 Banquet - San Miguel Restaurant	9:00 Developmental Priorities *M. Pearlman* 10:30 The Status of Advanced Ranging Developments *C. Alley and P. Morgan* 14:00 Remaining Problems (panel discussion) Concluding Summary *G. Veis and Y. Kokurin*
		HARDWARE WORKSHOP		
		SOFTWARE WORKSHOP - ROOM 2-110		
	10:00 Organizational Session 11:00 Realtime Operating Systems	10:00 Predictions and Pointing	10:00 Data Handling Communications and Other	

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FOURTH INTERNATIONAL WORKSHOP AND LASER RANGING INSTRUMENTATION

SESSION 1

PROGRESS SINCE 1978; A REPRESENTATIVE OVERVIEW

CHAIRMAN

ERIC C. SILVERBERG

Within the limits of a short proceedings it is impossible to go into great detail on all of the changes which have occurred in the last few years. There are now well over forty active laser ranging efforts in the world, many of which were not in existence in 1978 at the time of the last workshop. Some of these systems have undergone major overhauls, involving from first and second generation laser ranging to systems of third generation capability, while others have had only minimal improvements. The intent of this first session is to give a representative, but by no means complete, sample of the various programs and to outline these changes which have resulted in improvements to this area of technology since 1978. The following papers, some of which were not read at the meeting, serve that purpose admirably and place in context the more specific discussions which follow in the later sessions.

UPGRADE AND INTEGRATION OF THE NASA LASER TRACKING NETWORK

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1.0 Overview of the NASA Laser Tracking Network

The Goddard Laser Tracking Network (GLTN) consists of both fixed and mobile laser tracking systems used for precision satellite tracking to provide precise geodetic measurements. The mobile systems are deployed and operated at various locations around the world in response to program requirements. The composition of the GLTN will vary throughout the decade. Initially, the network will consist of seven mobile laser systems (Moblas-2, 3, 4, 5, 6, 7, and 8); three transportable laser ranging systems (TLRS-2, 3 and 4); and two fixed laser ranging stations (SAO-2 and 4) located at Arequipa, Peru and Orroral Valley, Australia, respectively.

The SAO-4 at Orroral will be deactivated at the end of FY84, and will be replaced by the Australian National Mapping Laser (NATMAP). This laser will be operated and maintained by the Government of Australia.

In 1983 a single mission contractor will manage the GLTN to provide specified tracking data in a timely and cost-effective manner. He will be responsible for generation of the necessary orbit predictions, scheduling of GLTN activities, data management and preprocessing, and data quality assessment. He will also be responsible for planning, analysis, and design of new systems; evaluation and analysis of operational systems; and co-equal responsibility with the government for technology development and maintenance, preparation of operations and technical documentation, property management, hardware and software configuration management, implementation of GSFC directed improvements, training, telephone communications, site design and construction at GSFC direction, and maintenance and operation of the laser systems. Additionally, the contractor will have property accountability for these systems and will be responsible for associated facilities and utilities.

Figure 1 depicts the entire network of existing and planned observatories locations including the foreign cooperating observatories we hope will support the program.

From an observatory standpoint, figure 2 clearly shows the extent of measurements possible across most of the important global tectonic plates.

2.0 Upgrade of the Mobile Laser Stations

2.1 Subnanosecond Transmitter

The first set of Mobile Laser stations (MOBLAS 1-3) were equipped with high energy, cavity dumped ruby laser transmitters built by Korad. Upgrading of the latter stations, which currently achieve 2 to 3 cms precision, has been deferred for fiscal reasons. The second set of stations (MOBLAS 4-8) were equipped with Q-switched Nd:YAG laser transmitters built by General Photonics having a FWHM pulsewidth of about 7 nanoseconds. Current MOBLAS receivers are designed to detect and process laser pulses of about 5 nsec duration. In the field, these stations typically achieve ranging accuracy on the order of 8 to 12 centimeters and a serious effort is currently underway to upgrade the performance of these stations, using the best available commercial components, in order to meet the scientific requirements of the next decade.

In order to minimize the interruption of data from the stations during the upgrade period, all engineering modifications (hardware and software) will be implemented and verified on MOBLAS 4 prior to its adoption by the entire MOBLAS network. Modification and upgrade of MOBLAS 4 is being carried out in stages at the Goddard Space Flight Center and began with the installation of a passively-modelocked Nd:YAG laser transmitter in late July 1981. As of September 1981 the system has successfully tracked three satellites - LAGEOS, BEC and Starlette. The transmitter, built by Quantel International, currently provides a single 150 picosecond pulse at a repetition rate of 5 pps. The single pulse output energy is between 60 and 80 mJ and, after two stages of collimation, is confined within a 25 to 30 arcsecond transmitter field of view. In a recent LAGEOS night time pass, a total of 4700 range observations resulted in a single shot RMS scatter about the orbit of only 2.5 cms and a

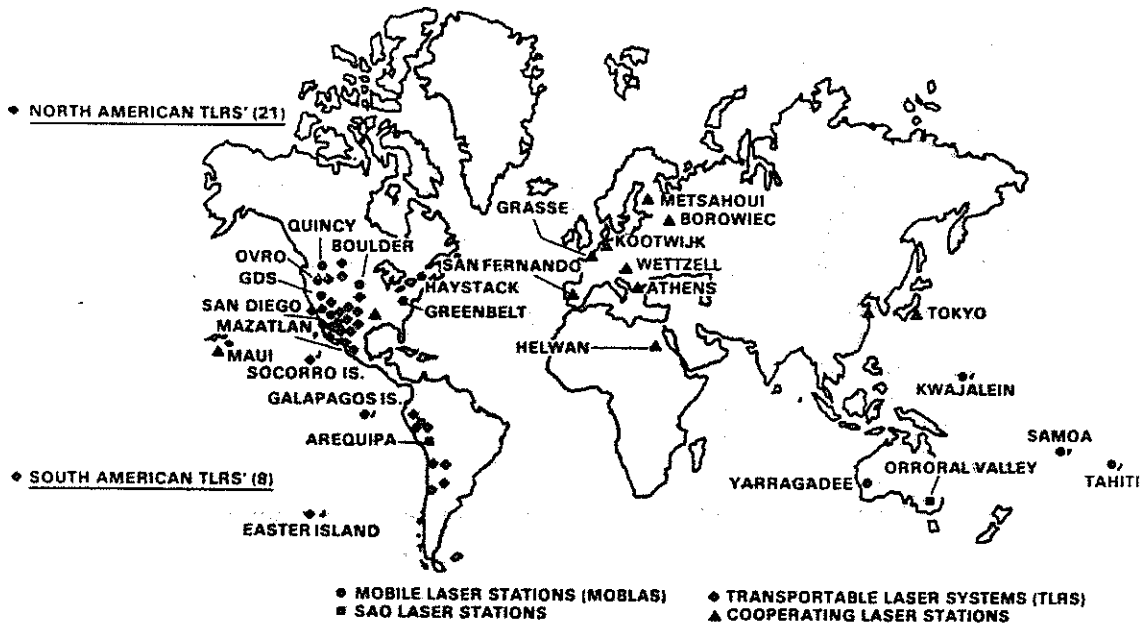

FIGURE 1: LASER TRACKING NETWORK

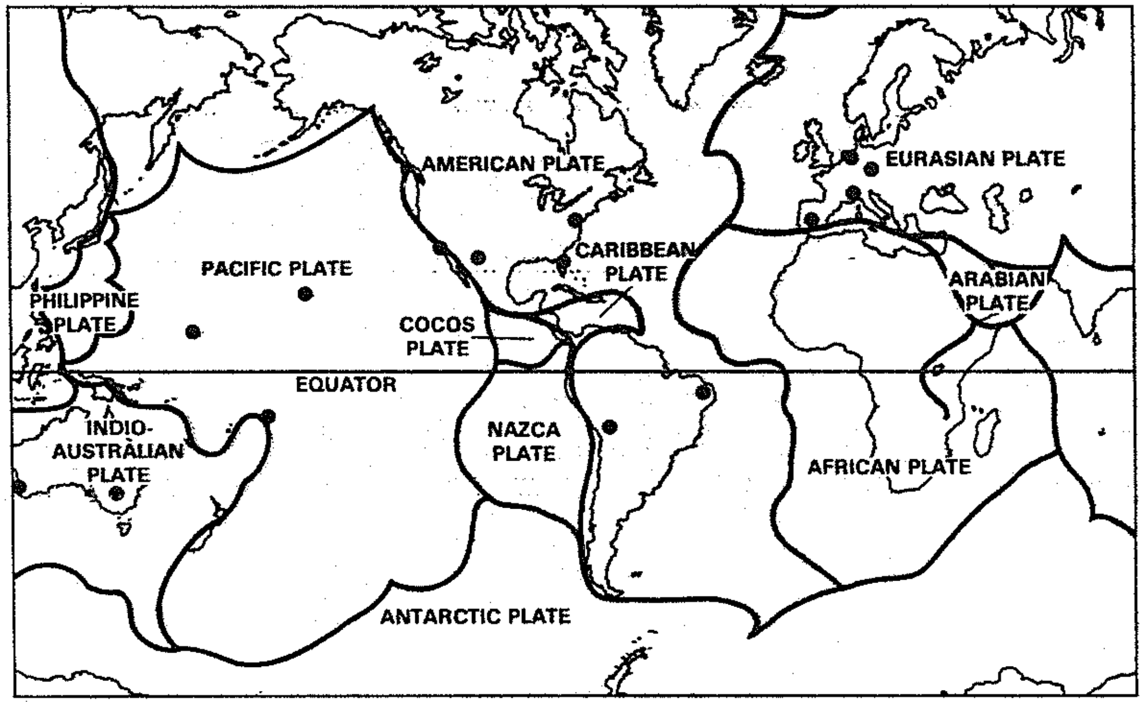

FIGURE 2: GLOBAL LASER RANGING STATIONS

normal point scatter of 1 to 2 cms as determined by the LASPREP processor. MOBLAS 4 has routinely tracked LAGEOS down to the 20^o minimum elevation angle and has had a few successful daylight passes as well with no modifications to the receiver. The passive transmitter, which is considerably less expensive than a comparable actively modelocked laser due to its relative simplicity, has proved reliable in the field, and it is anticipated that similar lasers will be installed in Moblas 5 through 8 by Spring 1983.

2.2 MOBLAS Receiver

One difficulty that remains is an occasional but, sizeable discrepancy between the pre and post-calibration measurements of the mean range to the target board. In an effort to eliminate, or at least reduce, systematic biases and to further improve the overall ranging performance, several modifications to the MOBLAS 4 receiver will be implemented and tested during October 1981. These include the replacement of the 2233B photomultiplier, which has a 2 nanosecond risetime and a transit time jitter on the order of 200 picoseconds, with a new low jitter, 300 picosecond risetime, high gain photomultiplier. Laboratory tests are currently underway to evaluate new internal microchannel plate photomultipliers available from ITT and Hamamatsu. The performance of these devices will be compared to that of signficantly more expensive electrostatic and static cross field dynode chain photomultipliers built by Varian. The latter devices are no longer available as an off-the-shelf component but quantity buys may still be possible.

In a second modification, the current dual channel range receiver will be replaced by a single channel receiver which will accept both the start and the stop pulse. Single channel receivers have the advantage that timing delays caused by temperature, voltage, or radiative background changes are automatically compensated for.

Third, an additional pre-calibration procedure will be added in order to determine the time walk of the receiver as a function of the signal amplitude. This information will then be used to correct, via software in the preprocessor, for timing errors introduced by fluctuations in the signal amplitude from either the satellite or calibration retroreflector.

Finally, the HP5360 Time Interval Unit, which has a 100 picosecond bin resolution, will be replaced by the newer HP5370 having a 35 picosecond timing resolution. A similar wideband receiver operated from our Advanced Laser Ranging Laboratory to a fixed retroflector located 0.5 Km away, has provided range data with a single shot RMS scatter of only 4 to 6 mm. Typical pre-and-post calibration runs (100 point averages) typically agree to better than 50 picoseconds which is very near the limiting timing resolution of the receiver. It is hoped that comparable results can be obtained in the field.

Consistent and reliable daylight operation is also an important goal. Recent improvements in our transmitter-receiver boresight techniques have allowed us to narrow the receiver field of view for successful daylight operation - even with the 10 Angstrom bandpass filter. Star calibrations and boresighting have been greatly simplified by the recent addition of a TV monitor which displays the receiver field-of-view on a CRT screen for the computer console operator. Daylight ranging experiments will continue in which two narrowband spectral filters (1A^o and 3A^o) will be evaluated.

In November 1981, the MOBLAS 4 configuration will be frozen. The system will then undergo collocation testing with MOBLAS 7. A spare actively-modelocked Sylvania laser has been installed in the latter station, and MOBLAS 7 is replacing STALAS as the operational GSFC system. Due to the advanced age and poor reliability of several key subsystems, the STALAS operation was terminated following collocation tests with MOBLAS 7.

Following completion of collocation tests with MOBLAS 7 in mid-December, the MOBLAS 4 ranging subsystem will be installed in MOBLAS 8 and will participate in the 1982 measurement campaign in Southern California. Since the MOBLAS 4 ranging system detects multiple photoelectrons, it will provide a valuable comparison to other subnanosecond pulse systems, such as TLRS-1 and TLRS-2, which use single photoelectron detection schemes.

2.3 Safety Radar

New safety radars will only be required for MOBLAS 2, 3, 5, and 7. One spare will be procured to be used in Mexico or any other location. Installation will be completed by June 1983.

3.0 Smithsonian Astrophysical Observatory Laser (SAO)

The four SAO stations are currently operating day and night on low satellites and nighttime only for LAGEOS, with a normal point accuracy of about 10 cm. During the 1981 period, modifications will be made to improve data yield and quality on LAGEOS. These will include (1) increasing the pulse repetition rate on LAGEOS to 30 ppm, (2) upgrading the photoreceiver with a narrower band interference filter and a faster risetime photodetection system, and (3) replacing the waveform digitizer with a less complex and more accurate analog waveform detector. It is anticipated that these modifications will lead to 5 cm normal point accuracy for nighttime ranging to LAGEOS. Engineering analysis indicates that the changes needed to improve the point-to-point accuracy to 4 cm would be feasible but extensive.

4.0 Transportable Laser Ranging Station (TLRS)

Significant increases in station mobility are now possible because of technology improvements and the years of experience accumulated in satellite and lunar laser ranging.

The Transportable Laser Ranging Stations-1 and -2 developed by the University of Texas and GSFC, respectively, are expected to achieve the 1 cm normal point goal of the Project.

TLRS-1 is presently operational and has become an integral part of the crustal dynamics measurement program.

The TLRS-2 is based on a modular concept, which differs from TLRS-1 in that the station is transported by truck and aircraft and assembled at the site. It has been designed for high mobility and low cost and represents the limit on size reduction achievable with current technology. TLRS-2 is currently in the integration and testing phase scheduled for September-December 1981. Tests are scheduled for completion by December 1981, with deployment and field use starting in January-December 1982.

Two additional TLRS systems are planned for procurement beginning in FY82. These stations are required to meet Crustal Dynamics Project needs for regional deformation studies in South America, New Zealand, and the Caribbean.

The combination of operational data accumulated by TLRS-1 and engineering/packaging data and test data accumulated by TLRS-2 will be used to determine the design of the follow on TLRS. At that time, a decision will be made as to whether TLRS-3 and -4 should be fabricated by GSFC or procured through a competitively selected contractor. Primary considerations in arriving at this decision will be the Crustal Dynamics Project schedules as dictated by project objectives and international agreements, costs, and availability of in-house manpower.

5.0 Haleakala Laser Facility

It is expected that the Haleakala Laser Facility will have two separable ranging functions in the Crustal Dynamics Project. The first function is ranging to LAGEOS and the second is ranging to the lunar retroreflector arrays.

According to data submitted to the University of Texas, there were about 100 returns from the lunar arrays in 1977 using the combination of the multi-element Lurescope receiver telescope and the Lunastat transmit optics. There have been no attempts to range to the moon since 1978 due to problems with staffing, the multi-element telescope and and priorities for satellite ranging.

At the present time the station has ranged recently only to satellites. However, there are some serious limitations to the amount and quality of the data being collected. For example, the station does not have daylight LAGEOS capability, due primarily to the unique arrangement of the transmit/receive optics.

In July 1980, operation of the facility was interrupted to incorporate satellite laser ranging upgrade and improvements. The following changes are completed. These changes are expected to improve the accuracy (4 cms or less) by reducing systemmatic errors and to increase the quantity of satellite ranging data.

1. Establish system delay calibration
2. Optimize receiver
3. Install new time interval unit

4. Optimize electronics/optics
5. Install new computer and develop additional software

Following the satellite ranging upgrades, it is planned to devote effort to achieving lunar laser ranging on a regular basis. At present, it is not evident whether this will require minor or major system modification. Tests of the Lurescope will be conducted in early 1982 and will provide the basis for a definitive plan.

6.0 McDonald Laser Ranging Station (MLRS)

In December 1979 a contract was issued to the University of Texas for design and fabrication of the MLRS. This system, which is a result of earlier work leading to TLRS-1, will be capable of ranging to the moon and to LAGEOS.

The MLRS will be permanently located at the site of the McDonald Observatory. After completion of the MLRS testing program in late 1981, the MLRS will assume the lunar ranging function performed by the Observatory since 1969.

7.0 Australian National Mapping (NATMAP) Laser Facility

The Australian National Mapping Laser Facility at Orroral Valley was provided by the U.S. to Australia on a loan basis in 1974. This system currently has only a lunar ranging capability. Initial ranging with this system has achieved lunar ranging at the 30 cm level. Improvements being carried out by NATMAP should result in ranging at the 15-18 cm level. However, this accuracy is not adequate to support the global program of lunar ranging. In addition, it would be desirable (from the U.S. viewpoint particularly) for this facility to also range to LAGEOS.

Through a series of discussions during the past year, it has become evident that both Australia and the U.S. would benefit from a cooperative program to modify and upgrade the NATMAP facility for both lunar and satellite ranging.

This modification would include:

1. Replacement of the current telescope mount with a new X-Y system.

2. Installation of a Coude system.
3. Replacement of the laser and laser electronics.

It is planned to accomplish the modification through agreement with NATMAP. The U.S. would provide funds for system hardware and NATMAP would provide personnel to manage the development, assist in the installation and checkout, and to operate the facility.

PERFORMANCE AND RESULTS OF SATELLITE RANGING LASER STATION AT KAVALUR, INDIA IN 1980 - 81

by

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ABSTRACT

In this paper, the environmental data during 1980-81, Laser ranging system, system calibration and its accuracy under various conditions, system stability, quality of the data obtained during 1980-81, methods of range reduction, system limitations and the proposed method for upgrading the system accuracy and its capability with reference to Interkosmos laser ranging station at Kavalur (India) are discussed.

1 INTRODUCTION

A Satellite Tracking and Ranging Station (STARS) is established in the campus of Indian Institute of Astrophysics, Kavalur ($12^o34'N$, $78^o51'E$ and 700 m above MSL), India for a joint scientific and technical collaboration between the Indian Space Research Organisation (ISRO) and the Academy of the Sciences of the USSR (AS-USSR) for the investigations in the field of Geodesy, Geodynamics and upper atmospheric research. The Station is equipped with Interkosmos satellite ranging laser radar, AFU-75 satellite tracking camera, timing equipments and data processing systems. The basic characteristics of the Interkosmos laser ranging radar has been described in the references cited (A.G.Massevitch et al. 1973, K. Hamal, 1978).

In Fig.1 is shown the monthly statistics of cloud-free nights for satellite observations at Kavalur during 1980-81. In Fig.2 is shown the monthly statistics of the trend in refraction constant during 1980-81 at Kavalur, showing the quality of environment for the satellite and astronomical observations.

II DESCRIPTION OF LASER EQUIPMENTS

The detailed description of the first and second generation Interkosmos laser radars are described in the references cited (A. Asaad et. al, 1978, K.Hamal et. al, 1978). At Kavalur laser ranging station, the first generation Interkosmos laser radar is equipped with HP 5061A Cesium beam frequency standard, HP 105B crystal controlled oscillator with time code generator, Datum 9880A VLF receiver and Volana-K all-wave HF receiver to maintain epoch for laser and camera in UTC and UT_1 (BIH time scales) respectively.

Epoch at the station is maintained primarily by means of portable clock trips from National Physical Laboratory (NPL), New Delhi, custodian of time and frequency in India. VLF tracking receiver provides an accurate method of monitoring record of time position relative to the setting obtain ed from the portable clock comparision. The HF time signals offeres the station a convenient epoch of the order of ± 0.5 ms as well as regular DUT_1 correction to UTC time scale. The current accuracy of the Station's clock in UTC is of the order of ± 5 micro seconds.

III SYSTEM CALIBRATION

Fig.3 shows the target calibration in micro seconds for the return signal strength measured in photo-electrons for a fixed target located at a distance of 519.18 ±0.01 meter from the laser radar and using a median detector (W.Kielek, 1977). The performance of three photomultipliers i.e. RCA 8852, FEU 84 (0560) and FEU 84 (9143) of USSR origin are shown in the Fig.3. Except for detector internal delay for a given pulse detection system (adaptive threshold) all the three photomultipliers, show similar performances. The detailed target calibration shows the overall laser ranging system accuracy of the order of 30 cm. In Fig.4 is shown the performance of the above said three detectors using a constant fraction (0.125) detection system with an integrating amplifier. For the Kavalur laser radar both the adaptive threshold as well as constant fraction detection technique gives almost the same accuracy in the range measurements. This may be due to the fact that the resolution of the time interval counter which is of the order of 2 nano seconds and the detectable errors between adaptive threshold and constant fraction detection technique are less than 2 nano seconds.

Data taken from day to day pre and post pass calibration difference over 60 days are plotted in Fig.5 and gives a standard deviation of the order of 0.65 ns. The long term stability of the laser radar therefore could be assessed from the long term pre and post pass target calibrations. The short term stability of the system is shown in Fig.4 and Fig.5 by plotting the rms error of each observation at a pre-selected input signal strength.

IV QUALITY OF DATA EVALUATION AND RANGE REDUCTION

The laser range data obtained are processed on IBM 370/155 computer using least square polynomials, Tsechebycheff's polynomials (short arc fitting technique) and long arc orbit fitting technique (P.S.DIXIT et. al, 1978). For laser ranging radar at Kavalur the above;three methods give equivalent results if number of observations are suffciently greater than the degree of the polynomial used. In Fig.6 is shown the predicted epoch against range (ms) for Geos C (7502701) satellite The true laser returns obtained after computer processing are also shown in this figure. Least squares filtering programme is used to eliminate the spurious laser returns (P.Lala, 1976). In Fig.7 is shown the distribution of range residuals for Geos C (7502701) satellite computed from several passes for 1980-81.

In Table 1 are shown the number of laser shots fired, estimated probable returns and actual laser returns obtained from computer processing of Geos A (6508901) and Geos C (7502701) satellites between September - October 1980 and January - May 1981. The overall laser ranging accuracy of the laser radar is of the order of 60 cm (RMS). In Table 2 is shown the comparision between the orbital elements of Geos C as derived from the observations (Kavalur) and that obtained from SAO for the same mean epoch in order to access the quality of tracking data. Since 1st September 1980, Kavalur laser station is involved in the tracking of Geos A (6508901) and Geos C (7502701) satellites for MERIT programme i.e. determination of polar motion and variations in the rotation of the earth in cooperation with other Interkosmos, CNES and SAO Laser network stations.

Table 1 : Statistics of laser return signals for Kavalur station during September - October 1980 and January - May 1981

Satellites	Number of laser shots fired	Number of probable returns	Number of good returns within RMS accuracy of one meter
6508901	125	95	80
7502701	1530	1170	920

Table 2 : Orbital elements of 7502701 satellite derived from laser observations at Kavalur using indigenous differential orbit improvement programme (IDOIP)

MJD : 44610.0

PARAMETER	STARS	STANDARD DEVIATION	SAO
a (km)	7219.5942	0.157705D-02	7219.593107
e (--)	0.0006005316	0.7868577D-05	0.001212951
i (deg)	114.9932	0.2634692D-02	114.9887
w (deg)	29.26217	0.1162906D+01	64.87311
Ω (deg)	197.8669	0.1379284D-02	198.2673
m (deg)	373.3692	0.1160242D+01	337.7824
n (deg/day)	5095.665	0.1669645D-05	5095.668
$\dot{n}/2$(deg/day^2)	0.001750845	0.1394849D-02	0.001350
MJD : 44694.0			
a (km)	7219.374746	0.00054676	7219.3905456
e (--)	0.001282280	0.2455407D-03	0.001250845
i (deg)	114.9930	0.14654230-02	114.9891
w (deg)	305.8063	0.1264736D+02	35.82264
Ω (deg)	67.02369	0.1836457D-02	67.41879
m (deg)	70.58636	0.1269409D+02	340.4544
n(deg/day)	5095.897	0.5789041D-03	5095.881
$\dot{n}/2$(deg/day^2)	0.002681672	0.5540522D-04	0.00167652

V CONCLUSIONS

The capability of laser range radar at Kavalur to range fainter than 9^m satellites and to improve the visibility of Geos A and similar satellites is under consideration. A three-stage image intensifier coupled with a low light level camera and a television system (Sofreterc, CF 123 NV camera with Nocticon TH 9659) will be incorporated in the laser radar guiding mechanism by June 1982. The TV guidance control is expected to improve the pointing accuracy of the laser to the satellite and thereby eliminating personal errors due to eye-sight fatigue during the observation and inturn increase the number of laser returns (P.S.Dixit et.al, 1979). The possibility of Kavalur laser station for the participation in LASSO-SIRIO time synchronisation experiment is under consideration (B.Serene et.al, 1980).

VI ACKNOWLEDGEMENT

Authors would like to express their thanks to Prof.A.G. Massevitch, Vice President of the Astronomical Council of the USSR, Dr. S.Tatevian of AC-AS USSR, Dr. K.Hamal Karel, Co-ordinator of the Interkosmos Laser Radar Working Group, Technical University of Prague, Czechoslovakia and Col.N.Pant, Director, SHAR Centre (ISRO), India for the continued suggestions and keen interest taken in our work.

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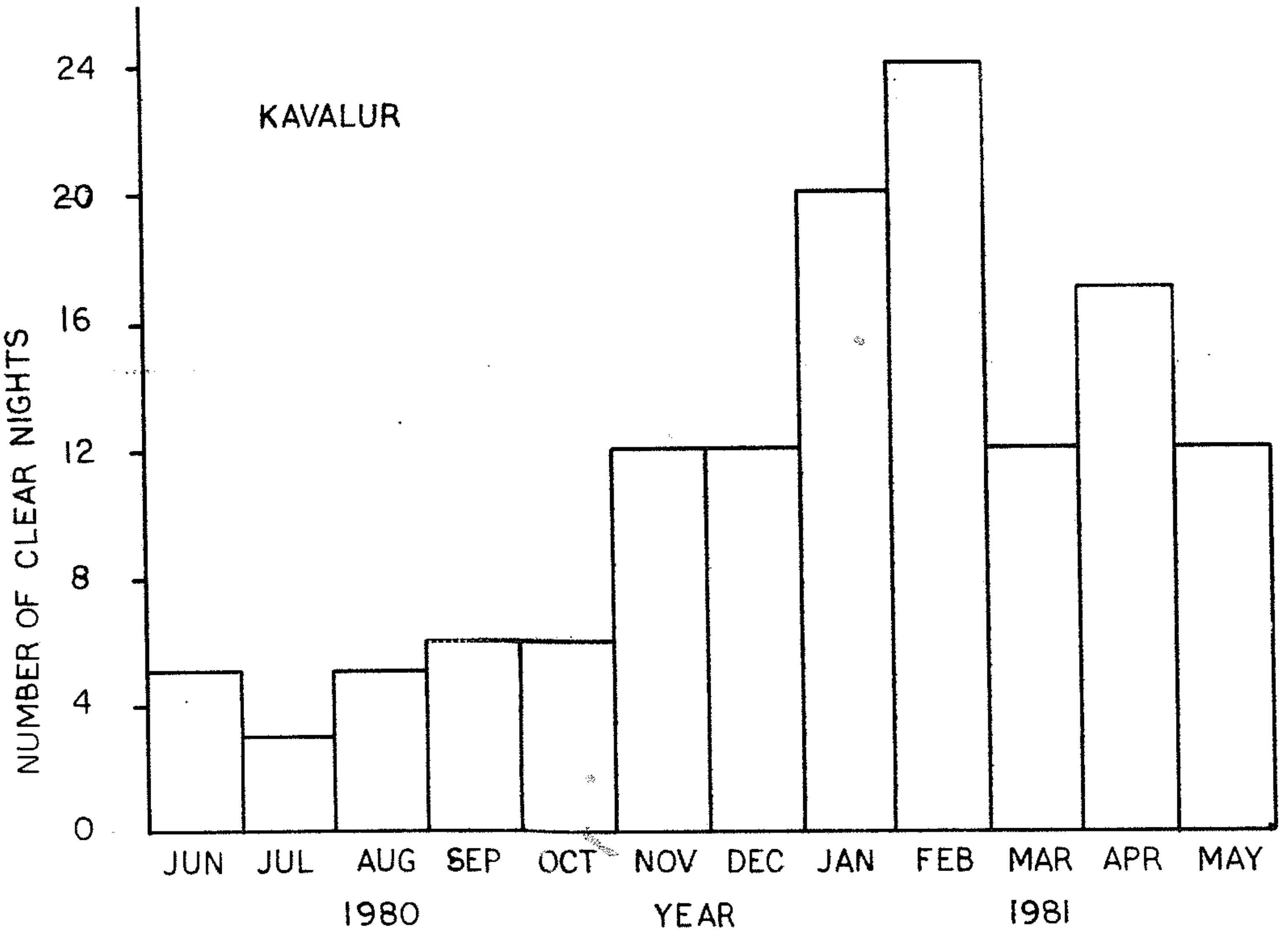

FIG.1:MONTHLY STATISTICS OF CLOUD FREE NIGHTS AT KAVALUR DURING 1980-81

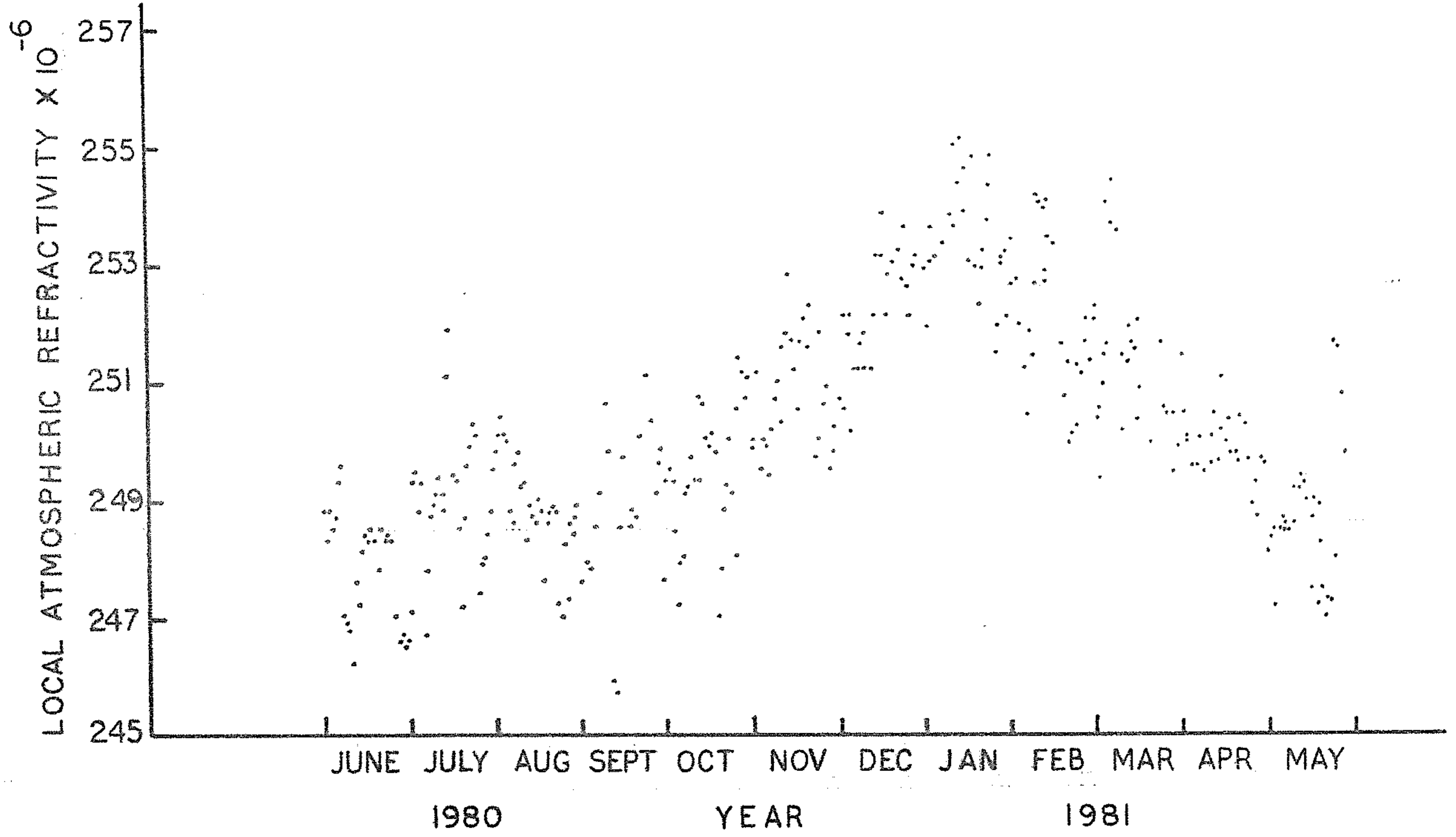

FIG.2: DAY Vs REFRACTIVITY PLOT FOR KAVALUR (1980-1981)

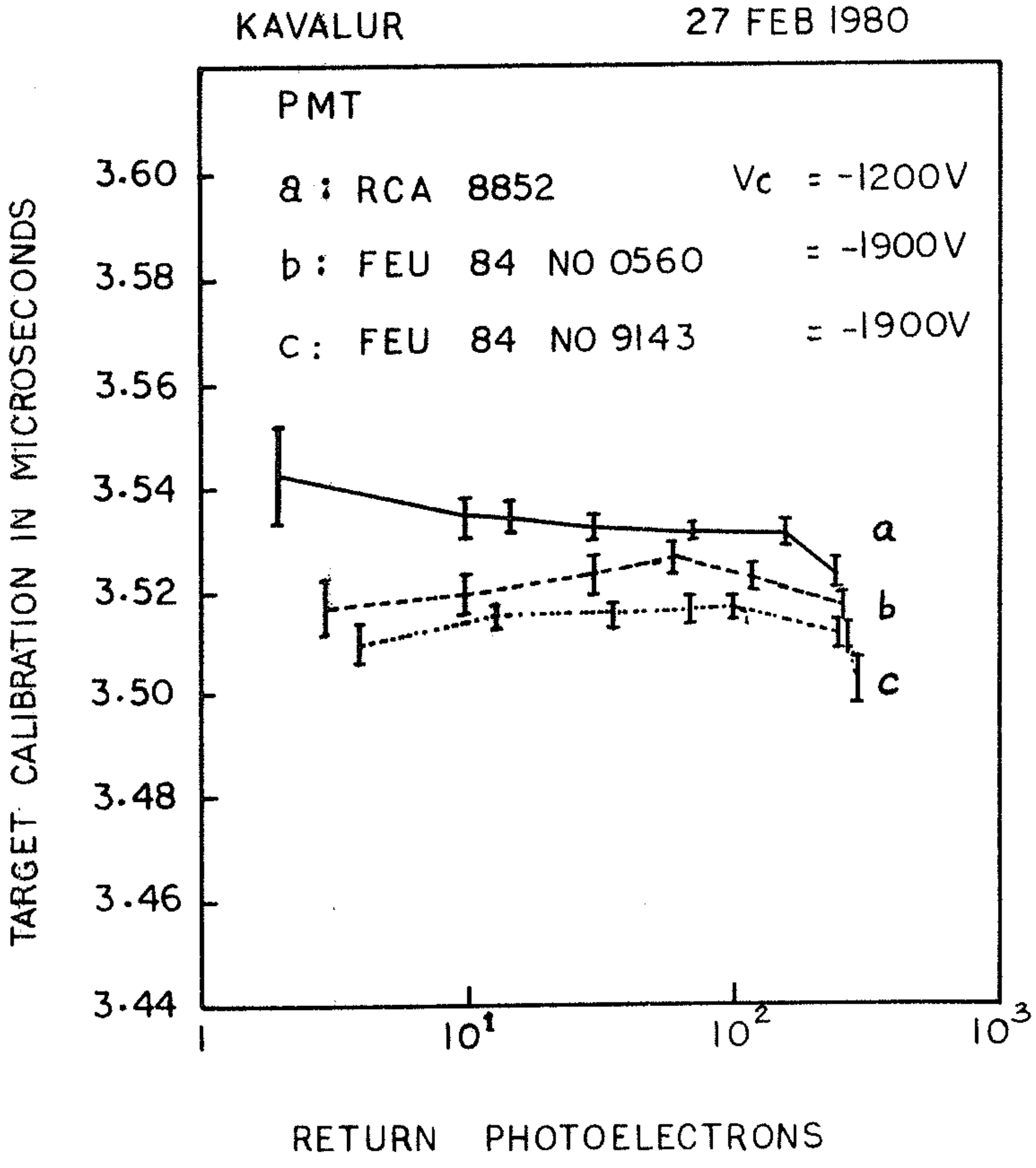

FIG.3: RETURN SIGNAL STRENGTH Vs CALIBRATION DISTANCE FOR A FIXED TARGET FOR KAVALUR STATION

(MEDIAN DETECTION TECHNIQUE)

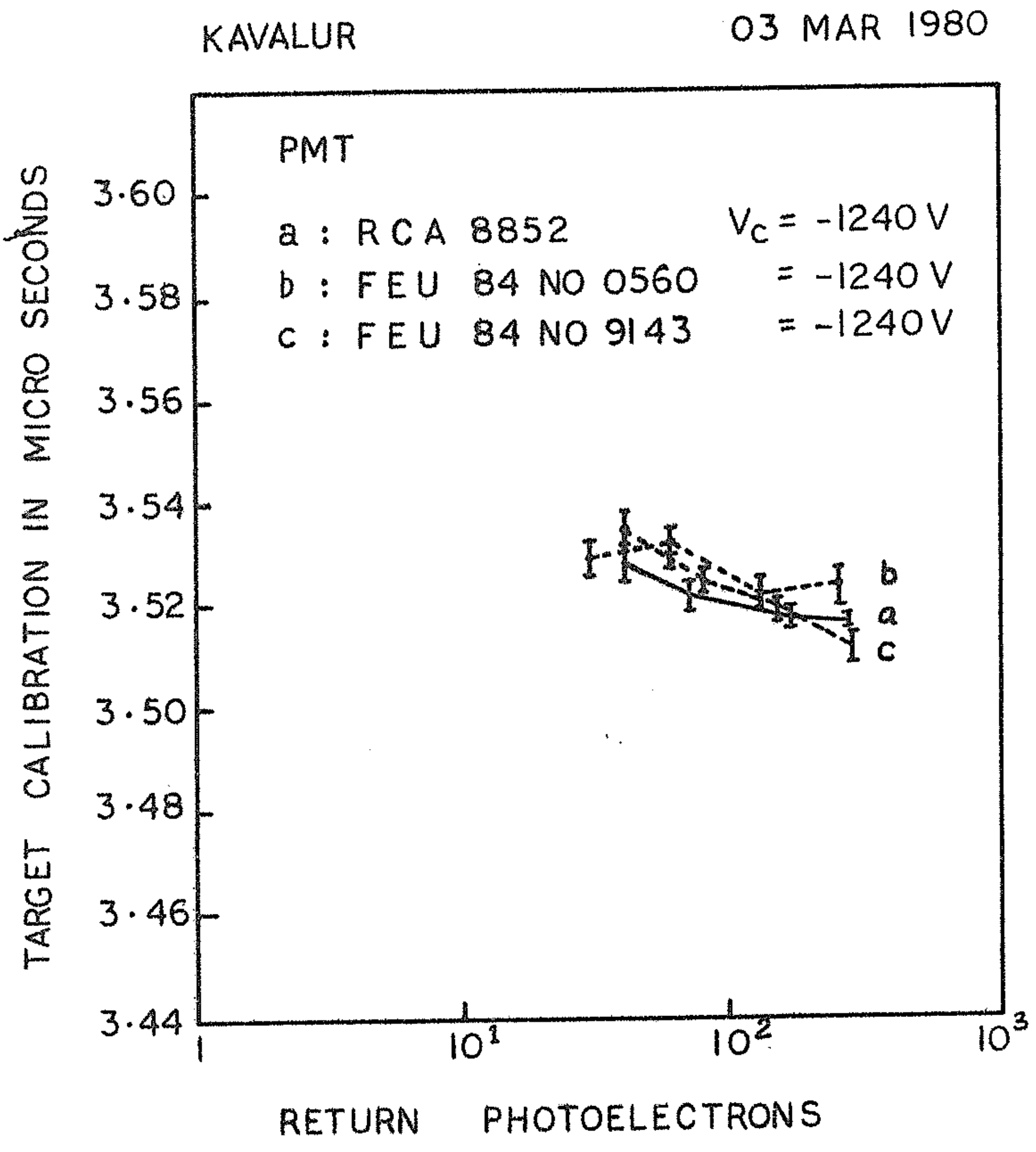

FIG. 4: RETURN SIGNAL STRENGTH Vs CALIBRATION DISTANCE FOR A FIXED TARGET FOR KAVALUR STATION

(CONSTANT FRACTION DETECTION)

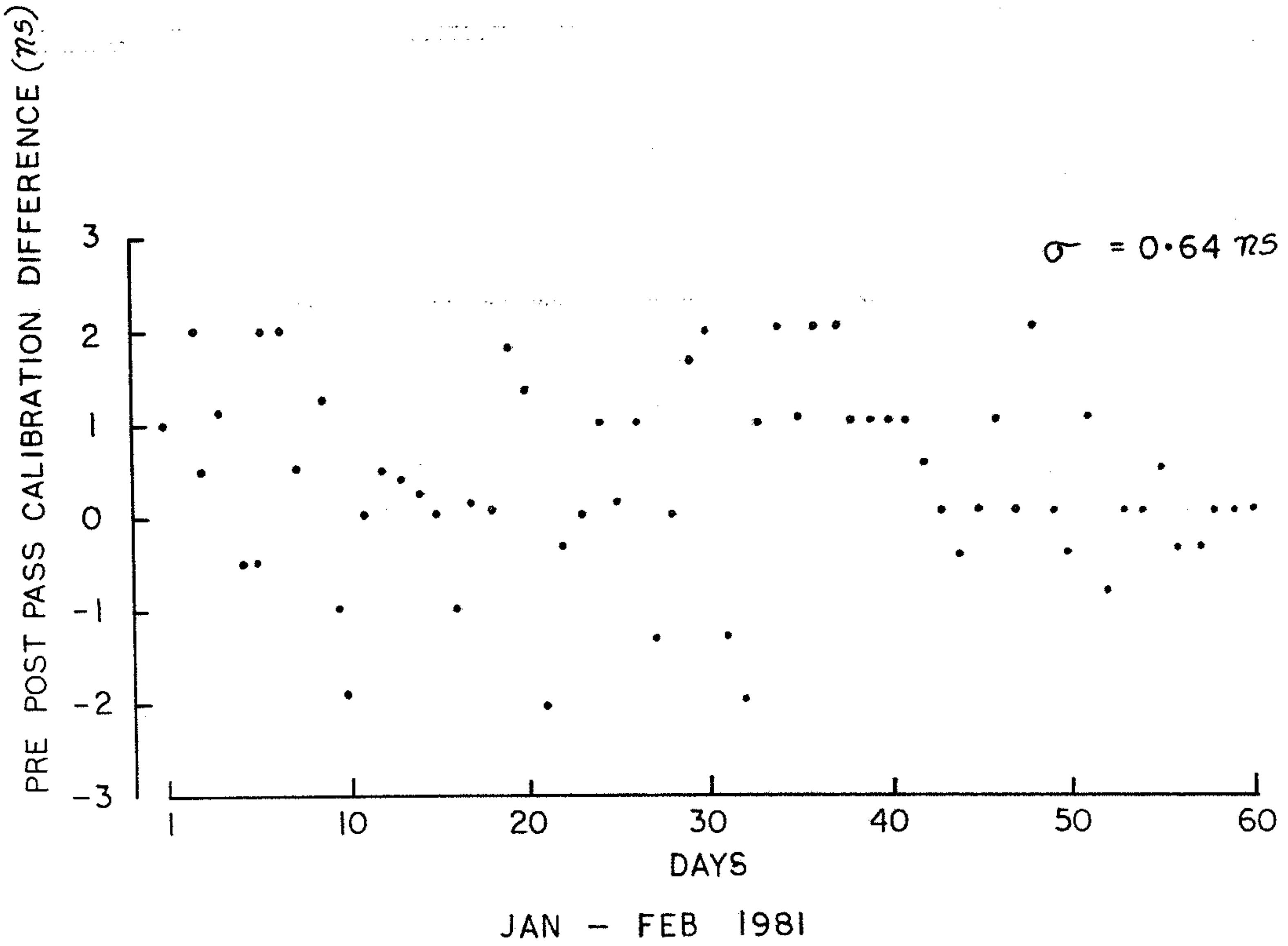

FIG. 5: PRE POST PASS CALIBRATION STABILITY FOR KAVALUR LASER 1980-81

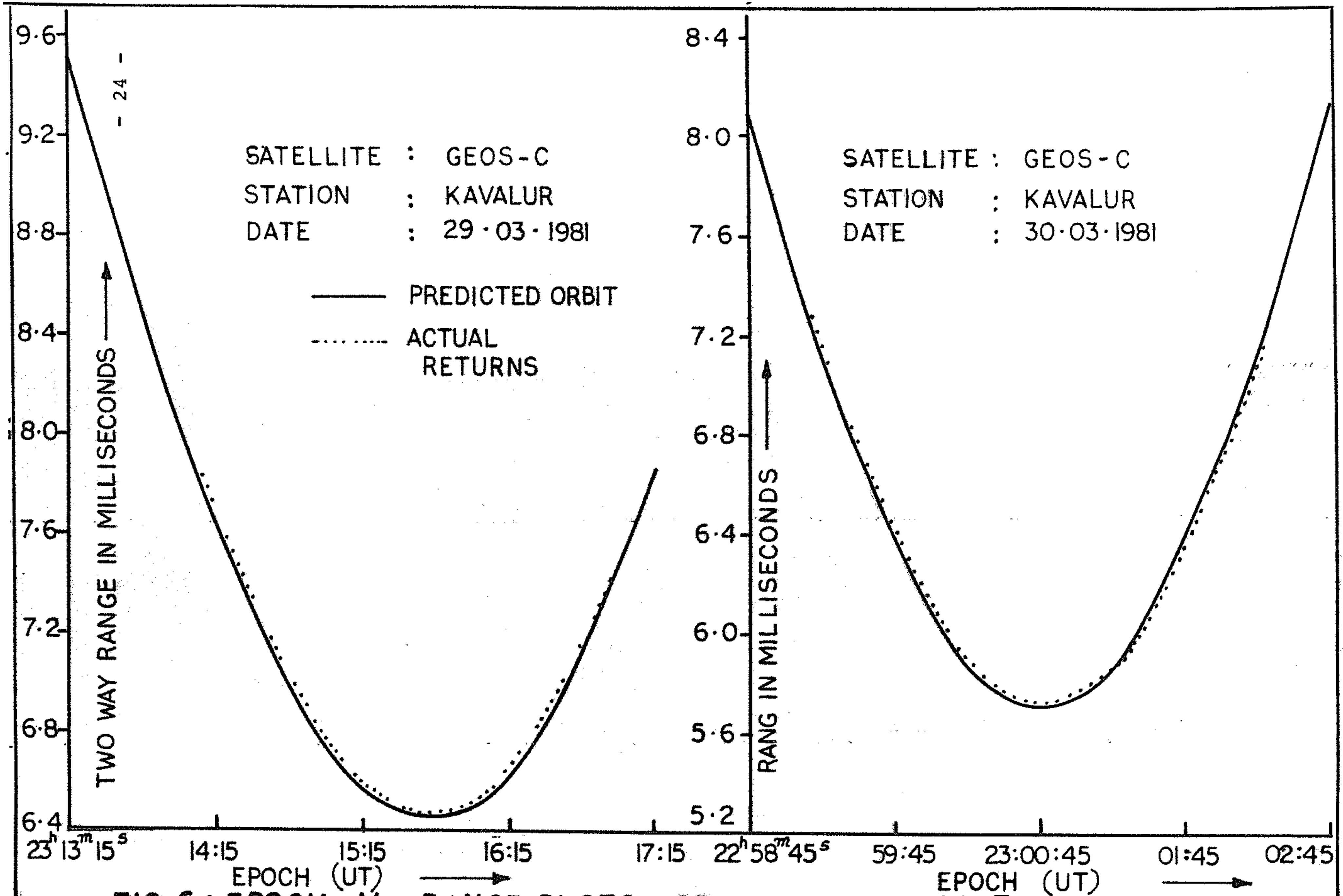

FIG.6 : EPOCH Vs RANGE PLOTS FOR GEOS-C SATELLITE

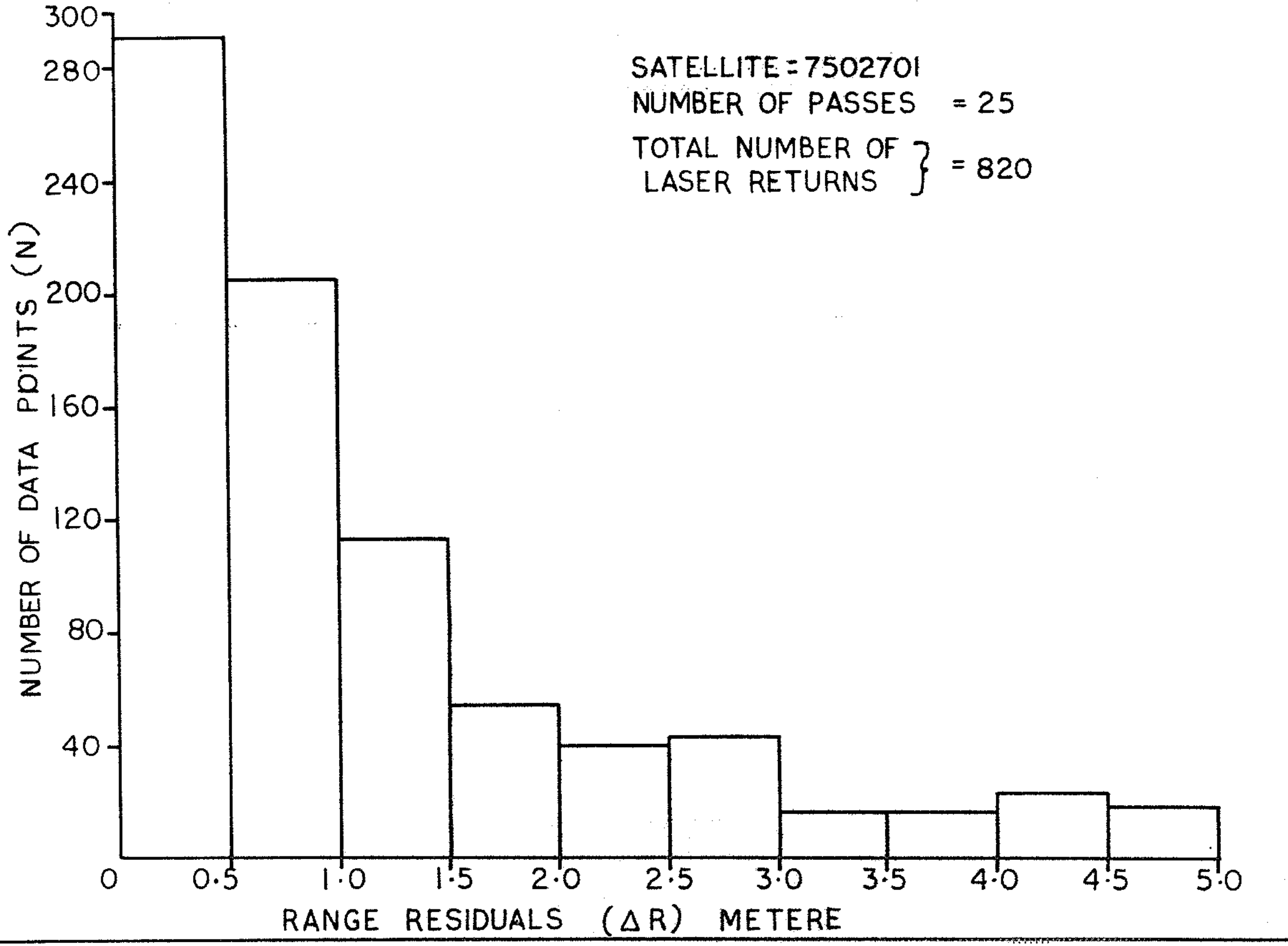

FIG.7 : DISTRIBUTION OF RANGE RESIDUALS FOR 7502701 SATELLITE

INTERKOSMOS SECOND GENERATION SATELLITE LASER RADAR

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To range the satellites, the Interkosmos Laser Radar Network of the first generation has been built since 1971 /1/ /2/.The network consists of 14 stations located in Africa, Asia,Europe,South America and Cuba/3/. The visual tracking, inherent for most of these stations, allowes a broad field of view; however, the operational efficiency is limited because of sun ilumination requirements, daylight observations are excluded. To avoid these limitations, the prototype of the second generation laser station /hardware+software package/ had been built during 1978-80 and since December 1980 it has been operating in Helwan, Egypt /4/.

Content :

System description :	Technical parameters	Table 1.
	Laser ranging system	Fig. 1.
	Computer hardware system	Fig. 2.
Calibration		Fig. 3.
System capability	Opeartional summary	Table 2.
Photograph of the mount/laser/receiver subsystem		Fig. 4.
Literature		

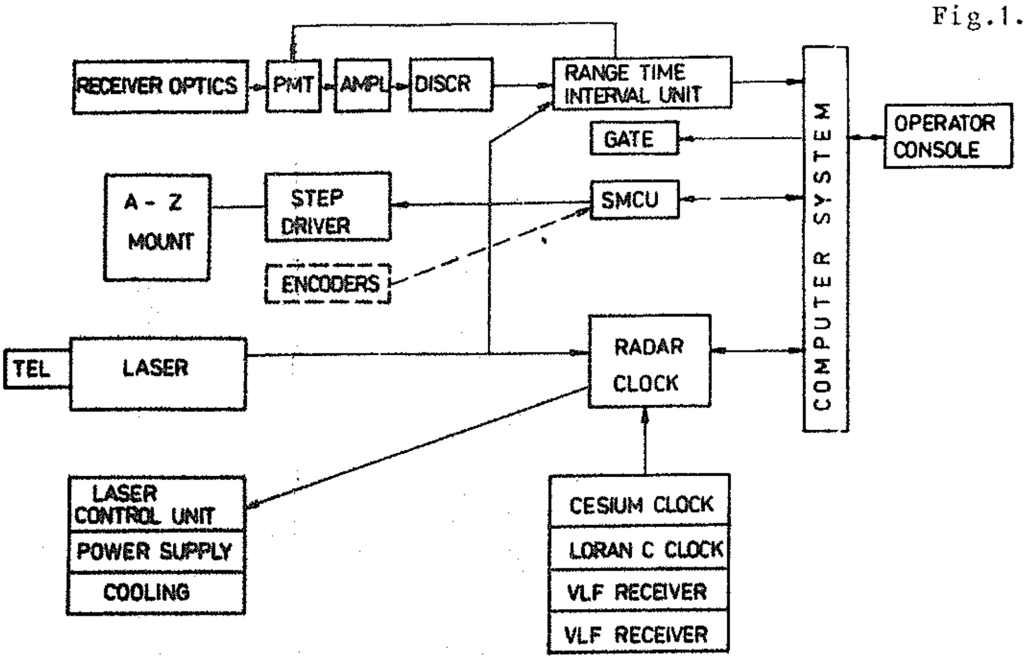
INTERKOSMOS LASER RADAR NETWORK

TABLE 1

2. GENERATION LASER RADAR (HELWAN 7831)

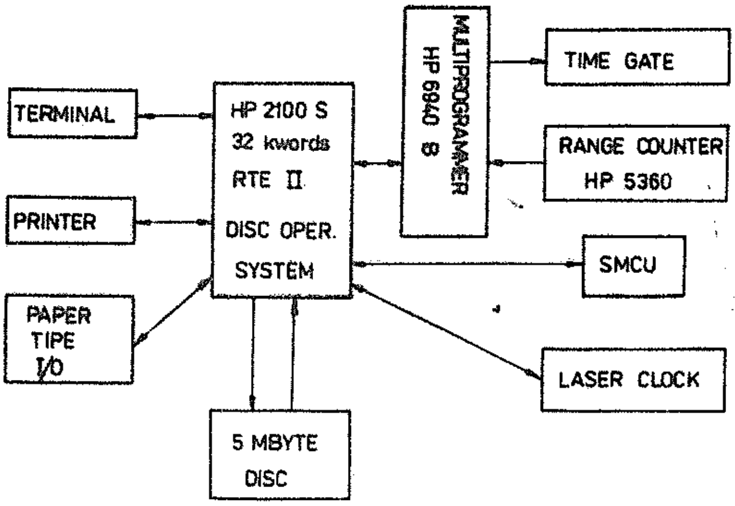
MOUNT	CONFIGURATION	AZIMUTH - ELEVATION
	TRACKING	CONTINUAL
	TRACKING RATE	UP TO 1 DEG/SEC
	RESOLUTION	4.5 ARCSEC
LASER	TYPE	OSCILLATOR - AMPLIFIER
	OPERATIONAL	Q-SWITCH/PTM/PFM
	ENERGY	0.1-0.2 JOULE/NSEC
	PULSE LENGTH	20/6/5/4/3/2 NSEC
	PULSE REPRATE	15/MIN
RECEIVER	OPTICAL ARRANGEMENT	REFRACTOR,ASPHERICAL
	DIAMETER	0.4 METER,F=0.8 METER
	RANGE GATE	COMPUTER CONTROL,100 NS MANUAL VERNIER
	THRESHOLD DETECTOR	CONSTANT FRACTION
	DETECTOR	PMT RCA 8852/RCA C31034
TIMING	TIME INTERVAL RES	100 PICOSEC
	FREQUENCY STANDARD	CESIUM CLOCK
	EPOCH REFERENCE	LORAN C,FLYING CLOCK
COMPUTER	CPU FLOATING POINT	32 KWORDS OF 16 BITS
	STORAGE MEDIUM	5 MBYTE DISC
	I/O FACILITIES	CONSOLE,PAPER TAPE,PRINT
SOFTWARE	PREDICTION	MODIFIED SAO WETTZELL
	CALIBRATION	POINTING,RANGING,ETC
	SAT TRACKING	MANUAL TIME VERNIER ON-SITE PREDICTION
	POST DATA HANDLING	NOISE REJECTION INTERNAL ACCURACY CHECK TELEX TRANSMITTION

Fig.1.



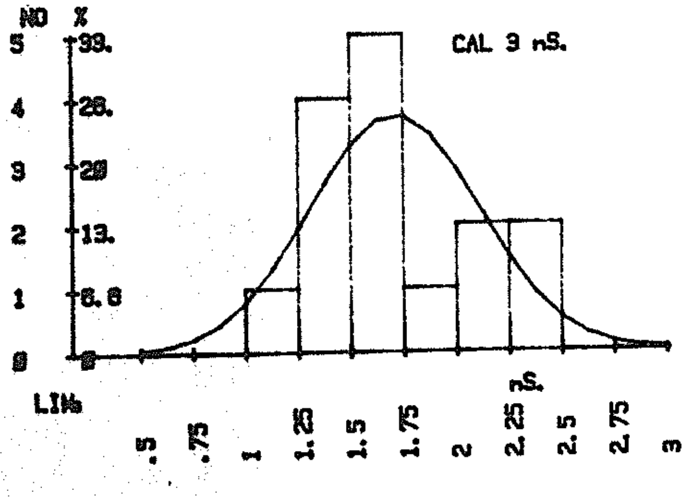
Laser ranging system.

Fig.2.



Hardware computer system.

FIG. 3.



TIME INTERVAL MEASUREMENT	+/-2.2 CM
GEODIMETER	+/-0.5 CM
ATMOSPHERIC CORRECTION	+/-1.0 CM
TOTAL	+/-2.5 CM

CALIBRATION ACCURACY

MONTHLY REPORT

TABLE II.

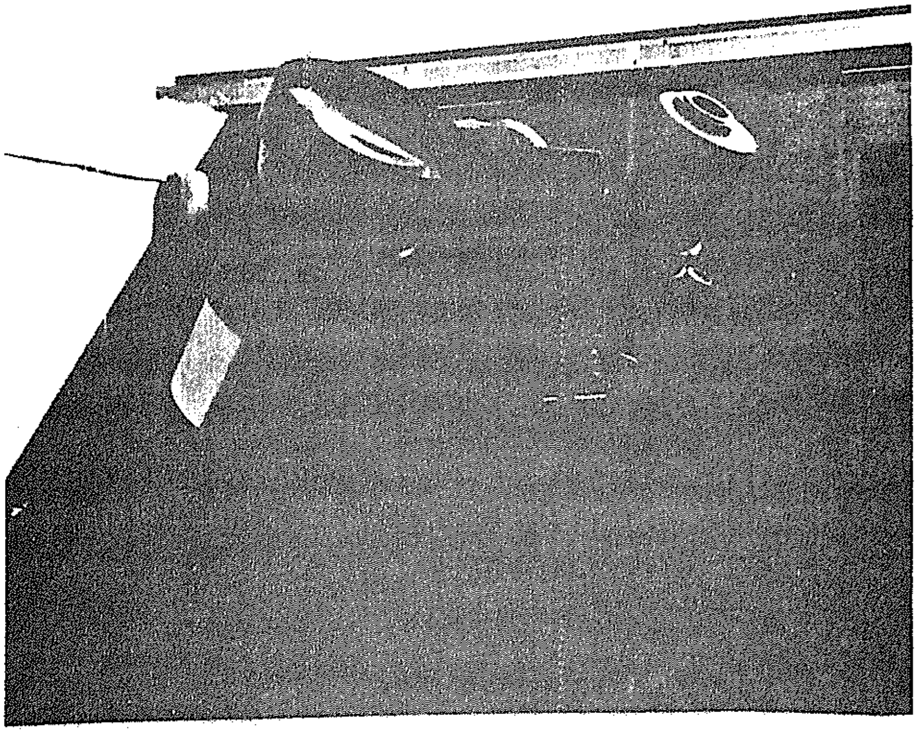
PERIOD AUGUST 1981
STATION HELWAN 2, 7831

	BE-C	GE-A	STARL	GE-C	LAG	TOTAL
TRACKED	31	33	39	25	27	155
MEASURED	26	29	33	21	24	133
NO RETURN	2	4	0	2	2	10
HARW.FAILURE	3	0	1	2	0	6
SOFT.FAILURE	0	0	1	0	1	2
CLOUDY SKY	0	0	4	0	0	4
NO.OF ECHOES	1459	2860	1412	889	1710	8321

TOTAL NO.OF OBSERVING NIGHTS : 29
TOTAL NO.OF LASER SHOTS : 36 000

SYSTEM CAPABILITY,OPERATIONAL SUMMARY

FIG. 4



Photograph of the mount/laser/receiver subsystem

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LASER RANGING SYSTEMS IN THE FAR EAST AREA (CHINA AND JAPAN)

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There are not so many satellite tracking facilities, particularly, satellite and/or lunar laser ranging instruments in the Far East Area. As far as I know there is one laser ranging system at Tokyo Astronomical Observatory in Japan and there are four systems in China, namely, at Peking(Beijing), Shanghai(Zo-se), Yunnan and Shensi observatories. Also in Japan the Hydrographic Department intends to install a modern satellite laser ranging system by this December(1981).

At the Tokyo Astronomical Observatory the project to install a satellite laser ranging instrument was started around 1967 with cooperation of technical staff of the Hitachi Ltd.(T. Takenouchi et al., Satellite Ranging with a Laser, Hitachi Review, 19, 153, 1969). It was installed at the Dodaira Station of the Tokyo Astronomical Observatory where a Baker-Nunn camera was. We could range geodetic satellites by this instrument with 60cm accuracy, however, since the instrument was driven manually any daytime observations as well as those when satellites were invisible were not possible(Y. Kozai et al., Satellite Laser Ranging Instruments Operated at Tokyo Astronomical Observatory, Tokyo Astron. Bull., No. 223, 1973).

Then by use of 188cm reflector at Okayama Astrophysical Station we made some experiments for lunar laser ranging in 1970-1971(Y.Kozai, Lunar Laser Ranging Experiments in Japan, Space Research XII, 211, 1972; A.Tachibana et al., Lunar Laser Ranging System in Japan, Space Research XII, 187, 1972).

After that we intended to install a new laser ranging instrument for both satellites and the moon at the Dodaira Station and a reflecting telescope of 50cm aperture and 380cm metal-mirror telescope were installed there. The 50cm telescope is on X-Y mount and for the tansmitting for the moon and the receiving for satellites and the 38cm telescope is on alt-azimuth mount and for the receiving for the moon. All the axes are driven by torque motors which are connected with a minicomputor. We bought also a ruby laser oscillator with three amplifiers for the moon and an electric chopper for satellites.

Unfortunately the progress after that is very slow. We could range some of geodetic satellites even in daytime and when satellites are invisible, however, the percentage of the number of the returned signals over that of the transmitting ones is not so high because alignments of the three axes, the optical axes of the transmitting and receiving telescopes and the laser beam axis are not good and changing as the telescopes move because of flexure of the transmitting telescopes. We are now trying to range Lageos satellites by introducing new techniques to keep good alignments and by using the laser oscillator for the moon.

For the moon we have been struggled with the torque motors to drive the telescopes. Our problem is that once the telescope points the predicted direction the computor, of course, does not want to move the telescope and, therefore, no torque acts on the motors. However, once wind comes the telescope moves. Such a standing torque is our serious problem, however, by introducing new device I hope that we can solve the problem in near future.

The instrument which the Hydrographic Department wants to have is one of the same type Wettzel station has. It will be Wakayama, south of Osaka, and will be in operation as soon as it will arrive there.

There are reports on the laser ranging instruments at Shanghai and Yunnan observatories. It is very glad to hear that a new system will be installed at Shanghai and it will range Lageos satellite even in daytime.

METSÄHOVI SATELLITE LASER RANGING STATION

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1. INTRODUCTION

This report gives a brief description of the status of the Metsähovi satellite laser ranging station (7805) of the Finnish Geodetic Institute. System planning was initiated in 1972 in cooperation with the Helsinki University of Technology with financial support from the Academy of Finland. The system has been in operation since September 1978 and has so far produced about 6000 range observations to various satellites.

2. EQUIPMENT

The equipment is in essence similar to that reported at the previous Laser Workshop in Lagonissi /1/. The main technical data are given in Table 1.

The laser transmitter uses an electro-optically Q-switched multimode ruby laser oscillator with an output energy of 1 J, a pulse length of 25 ns, a collimated beam divergence of 1.2 mrad and a repetition rate of 1/15 Hz.

A 630 mm diameter parabolic mirror is used in the receiver. The field of view is also 1.2 mrad. An RCA C 31034

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*Also with the Communications Laboratory, Helsinki University of Technology, SF- 02150 Espoo 15, Finland photomultiplier is used in night work and an RCA 8852 in daylight. The pass band of the interference filter is 3 nm. An electromechanical shutter is used to protect the photomultiplier from laser light backscattering from the near atmosphere. Approximated matched filtering with an impulse response of $t \cdot \exp(-t/\tau)$ /2,3/ is used in detection. The half widths of the laser pulse and the impulse response of the filter are equal. Presently the integration time of the photomultiplier preamplifier has been increased to 40 ns to test the performance of median detection /4/. The start pulse is filtered in the same way. The travel time of the laser pulse is measured with a Nanofast 536B counter and a M/2 half-max plug-in (detection fraction 0.5 of the true peak), providing about 0.15 ns instrumental resolution.

A new equatorial, sidereally driven, telescope mount was installed in 1979. The telescope system uses open loop, computer operated, stepper motor actuated point-to-point tracking with a step size of 6 arcsec. The pointing accuracy is about 0.3 mrad. The laser is mounted on top of the telescope. The laser and telescope systems are operable down to at least -22°C. The ranging system can be operated by one person. Aircraft detection is done visually.

Satellite positions are calculated in advance using SAO elements and a new quick orbit program /5/ and stored on magnetic tape. The range gate, which is computer controlled, has a resolution of 1 μs. The gate widths used are in the range 10 - 40 μs. The difference between the observed and predicted (O-C) satellite distance is calculated on line and fed to a printer to allow monitoring of the return rate and gate position. The resulting data (epoch with 1 μs resolution, time interval with 0.1 ns resolution, the direction angles used, air pressure, temperature and humidity and O-C differences) are logged on magnetic tape. Corrections to the firing time of the laser can be made via the keyboard. Visual detection of the satellite, when possible, is used to check any time offsets.

Station time keeping is achieved using a quartz oscillator (HP 105 B), which is phase locked to LORAN C transmission (Sylt). The accuracy is better than 10 μs. The operating frequency of the counter (1 MHz) is derived from this source.

Several problems have been encountered in the course of operations. A major problem has been inadequate fastening of the flashlamp electrode. Also, the original Pockels cell was replaced by a liquid filled cell when it was found to be producing multiple pulses. The counter is somewhat

Table 1. Technical data of the Metsähovi laser rangefinder

Laser	ruby, helical flashlamp, water cooling, Pockels cell Q-switched
Energy	1 J, stability 10%
Pulse width	25 ns
Repetition rate	1/15 Hz
Beam divergence(laser)	3 mrad
Transmitting optics	Inverted Galilean telescope, aspherical objective Ø 115 mm, power 7 X, adjustable collimation, 1.2 mrad used
Receiver optics	Ø 630 mm parabolic mirror, f=1730 mm
Field of view	1.2 mrad
Interference filter	3 nm pass band, 0.7 transmission
Overall transmission	0.5
Photomultiplier	RCA 8852, quantum eff. 4 %, for day and night operation RCA C 31034, quantum eff. 10%, for night operation
Electronic amplifier	8 MHz bandwidth (3dB), two cascaded RC- stages,impulse response 25 ns (FWHM), also preintegration possible
Time interval counter	Nanofast 536B
Timing processor	" M/2, half-maximum plug-in, 50 % of the true peak detected 0.15 ns r.m.s. resolution
Telescope mount	Equatorial,sidereally driven, offsetted by stepper motors and worm gears, computer controlled, computer 16 bit, 32kwords
Tracking	Automatic, point-to-point, speed 1.5 degrees/s max.
Guiding telescope	Celestron 8, Ø 200 mm, field of view 1 degree.
Timing	Quartz clock HP 105B, phase-locked to LORAN C (Sylt), accuracy better than 10 μs
Calibration	Flat target, 333.48 m distance

temperature sensitive and can produce quite stable false sublevels in readings. Also, the timing discriminator creates variable positive biases, even over 10 ns, for small pulses that are just sufficiently over the treshold. Because no return pulse monitoring is in use, the effects of small and saturating pulses may be found in the observations.

3. RESULTS

The number of observed passes and ranges are shown in Table 2. Passes with less than five ranges are not included. The best ranging season is expected during the months March-May and August-December. There are 50-80 clear nights during these months in one year. June and July nights are luminous.

Table 2. Satellite passes and observations

	LAGEOS		STARLETTE		GEOS-3		GEOS-1	
Period	Passes	Obs	Passes	Obs	Passes	Obs	Passes	Obs
1978 Sept-Oct	-	-	-	-	16	140	-	-
1979 Sept-Oct	8	85	1	5	2	25	16	380
1980 March-May	14	420	1	13	8	130	13	360
1980 Aug-Dec	25	1180	13	200	16	250	15	270
1981 March-May	34	1160	11	195	-	-	11	370
1981 Aug-Sept	8	330	2	30	6	110	-	-
	89	3175	28	443	48	655	55	1380

3.1. Range capability

The measured range capability of the Metsähovi laser ranger is shown in Table 3. Ranges to LAGEOS are currently limited by the capacity of the storage system for predictions (150 points, minimum elevation 34°). Daylight operation to GEOS-3 has been found feasible (ranges to 1700 km).

3.2. Precision

Several common methods of data preprocessing have been used: polynomial fitting to the O-C differences, Kepler orbit fitting with J_2 term (called Sterne solution /6/) and direct polynomial fitting to ranges. Also a new method called Quick-orbit has been tested. A reference orbit is constructed using the first and last observation of the pass (accurate ranges, directions taken from the predictions, accurate to

Table 3. Range capability

Satellite	Measured range (km)	Min. elevation (degrees)	Data yield (%, max.)
LAGEOS	7550	34	60
STARLETTE	2490	17	80
GEOS-3	1850	20	100
GEOS-1	3600	25	95

±0.6 mrad as in /6/. The range differences of the observations are then formed. The quality of the range observations can be determined by fitting a polynomial of suitable degree to the range differences(generally under 1000 m). No iterations nor precisely computed predictions are needed. Fig. 1 shows an example of the residuals obtained with different methods. For this and the previous pass the SAO QUICK LOOK processed data was also available. It is easy to see that the QUICK LOOK and the double pass Sterne solutions show trend-like residual behaviour. The single pass Sterne, QUICK LOOK with a third degree polynomial and the Quick-orbit with a fourth degree polynomial produce very similar residuals, but with somewhat different standard deviations. It is obvious that this phenomenon is connected with the quality of the reference orbit used and the degree of the polynomial required to remove the trends.

In ranging to LAGEOS photon counting or single photoelectron detection /7,8/ has been used from the very beginning. The voltage of the photomultiplier is increased until the single photoelectron impulses are able to trigger the counter. Both photomultiplier have been used. Fig. 2 shows an example of range residuals obtained with the Quick-orbit (sixth degree polynomial). There were 74 signal counts from 116 possible, and no noise counts. The air pressure was 1014 mb, temperature 2.8°C, humidity 80% and the gate width 12 μs. The histogram of the distribution of the residuals is shown in Fig. 3. The standard deviation is 0.68 m. Generally, the precision to LAGEOS has been about 1 m. In one monitored pass (signal counts amounting to 20, RCA 8852 tube), where only a couple of two photoelectron pulses was seen, the precision was 0.84 m. This is somewhat better than could be expected theoretically by noting the duration of the transmitted pulse ($\sigma_R = 0.5c \cdot 0.425T$). The precision to GEOS-3 has generally been in the range 0.3-0.8 m, and to STARLETTE and GEOS-1 0.4-1 m.

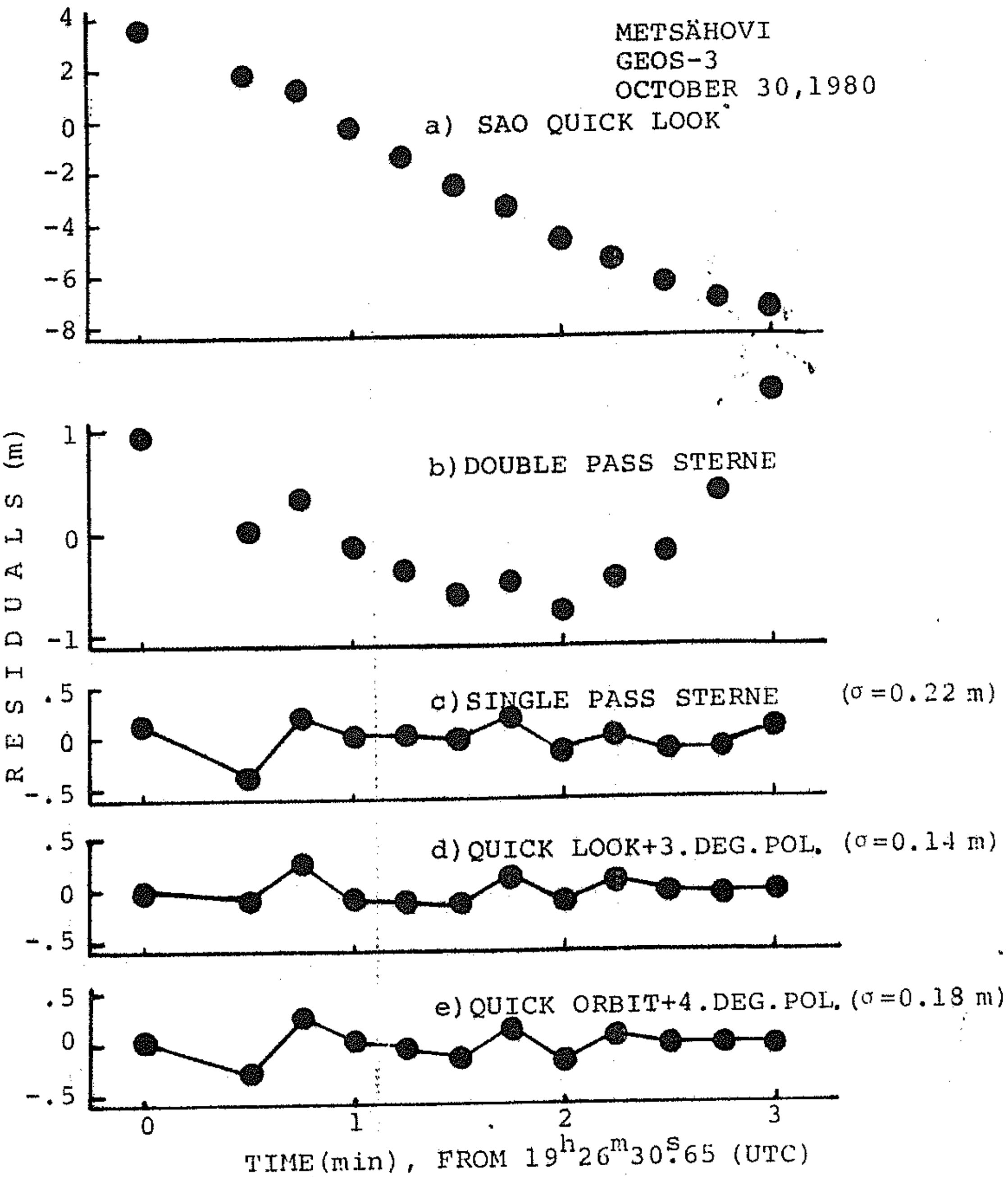

Fig. 1. Range residuals of a GEOS-3 pass from different processing methods

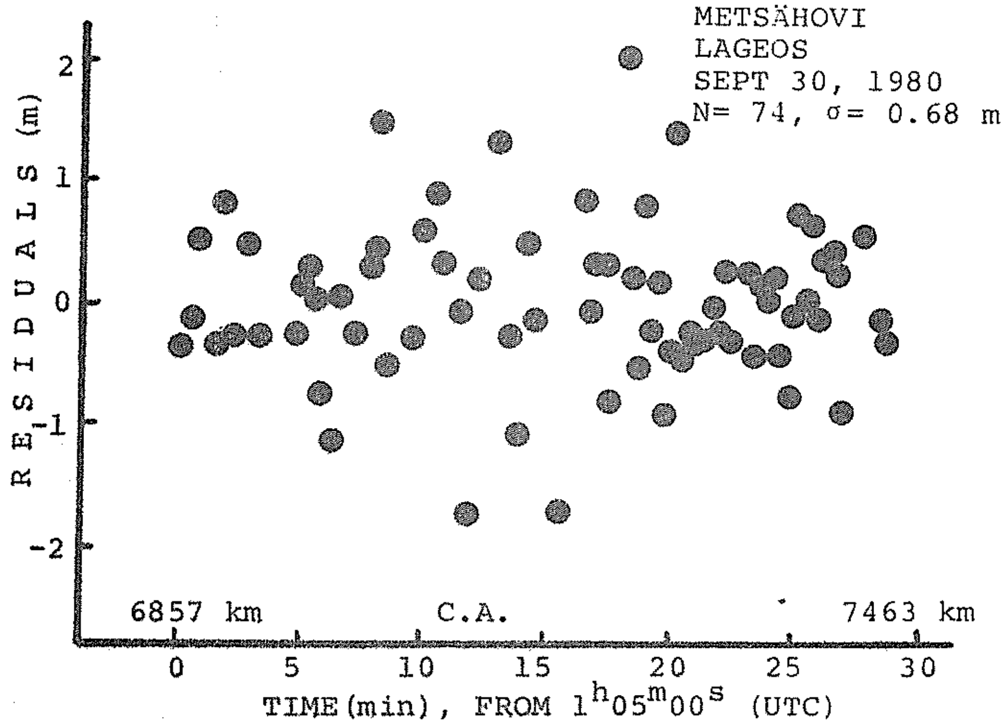

Fig. 2. Range residuals of a LAGEOS pass processed by the Quick orbit (6th degree polynomial).

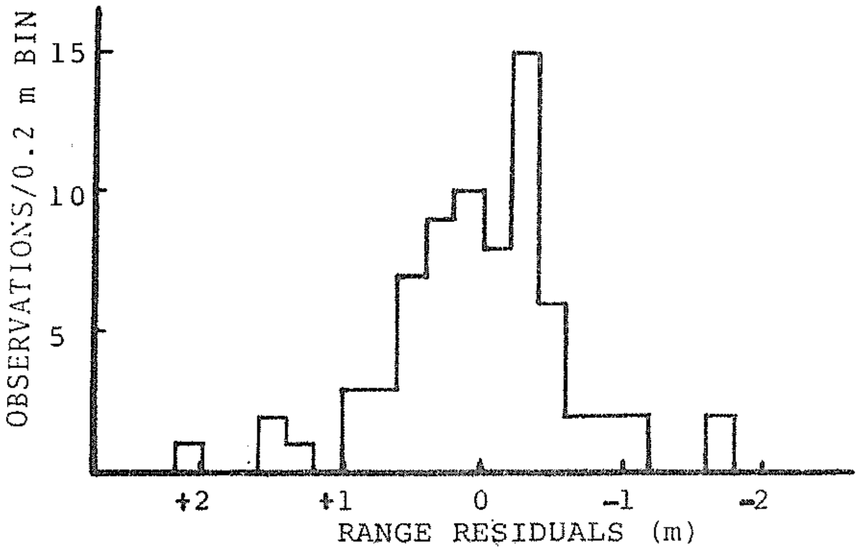

Fig. 3. Histogram of the residuals of the LAGEOS pass Sept 30, 1980, Fig. 2.

3.3. Accuracy

The coordinates of the Metsähovi laser have recently been determined from the LAGEOS data obtained during the short MERIT Campaign /9/. These coordinates and the Doppler coordinates (NSWC 9Z-2) of the laser from the EROS-DOC determination /10/ are compared in Table 4. A small correction ($\Delta x = 0.05$ m, $\Delta y = 0.00$ m, $\Delta z = -0.20$ m) to the Doppler coordinates is applied because of the new mount. Because different coordinate systems are used, a coordinate transformation is necessary before the results can be compared. Applying recently reported corrections to Laser and Doppler coordinates with respect to VLBI /11/ (to Laser: rotation angles $\varepsilon = -0''.09$, $\psi = 0''.01$, $\omega = -0''.23$, scale $-0.01 \cdot 10^{-6}$, translations $\Delta x = 0.44$ m, $\Delta y = -0.84$ m, $\Delta z = -3.64$ m and to Doppler: rotation angles $\varepsilon = 0''.07$, $\psi = -0''.01$, $\omega = -0''.84$, scale $-0.51 \cdot 10^{-6}$, translations = 0 m) gives the transformed coordinates shown in Table 4. The resulting difference in distance is 0.54 m. If a recently published combined Doppler solution is used (corrections $\Delta x = -0.66$ m, $\Delta y = 0.18$ m, $\Delta z = 0.13$ m) the difference in Laser and Doppler determinations becomes $(\Delta x, \Delta y, \Delta z)_{L'-D'} = (0.13$ m, -0.04 m, -0.09 m) or in range 0.16 m. The comparison with the Kootwijk and Wettzell stations also shows consistency of the ellipsoidal height to within 0.5 m, longitude to within $0''.22$ and latitude to within $0''.04$.

Table 4. Coordinates of the optical center of the Metsähovi laser ranger

Determination	x (m)	y (m)	z (m)
LAGEOS, MERIT data /9/	2892598.21	1311806.00	5512609.93
DOPPLER, EROS-DOC /10/	2892603.97	1311796.61	5512609.42
LASER, TRANSFORMED	2892596.89	1311805.97	5512606.95
DOPPLER, TRANSFORMED	2892597.42	1311805.83	5512606.91

4. PLANS FOR FUTURE WORK

To improve the performance of the Metsähovi laser station, construction of a short pulse Nd:YAG laser has been started. The pulse length should be around 1 ns and the repetition rate 1 Hz. So far, only the power supplies and discharge circuits have been designed. The telescope will use 50 cm diameter Cassegrain optics. The mount will be azimuthal.

There may still be some interest in uppgrading the old ruby laser. A technique for shuttering a pulse of a few nanoseconds duration has been developed using KN 22 (EG&G) krytron switch tubes.

5. CONCLUSION

The Metsähovi laser ranger still belongs to the first generation. The performance has met, and in some respects surpassed, the initial expectations. However, more work is required to stabilize operation. The precision obtained is about 0.5 m. The first results concerning station coordinate determination indicate an accuracy of about 1 m or better.

6. ACKNOWLEDGMENT

The author is indebted to the Academy of Finland for support during different phases of this project.

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CURRENT STATUS AND UPGRADING
OF THE
SAO LASER RANGING SYSTEMS

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The SAO lasers, which have been in routine operation since 1971, have been upgraded several times with resulting improved accuracy, data yield and reliability. At the last Laser Workshop in 1978 we reported on the installation of the pulse processing system centered around a waveform digitizer and some fast pulse modules to determine pulse centroid and signal strength. The work reported was based on our experience with the 25 nsec wide ruby laser pulse. See Pearlman, et al., 1978.

CURRENT STATUS

Since the last Laser Workshop, SAO has introduced pulse choppers into the laser systems to reduce laser pulse width to 6 nsec. This, coupled with the previously installed signal processing system centered around a waveform digitizer, gave us a very dramatic improvement in system ranging accuracy now estimated at about 10cm (1 sigma).

The chopper is, basically, a Krytron-activated Pockels cell with entrance and exit dielectric polarizers for necessary transmission and isolation. (See Figure 1). A Blumlein circuit provides the proper high-voltage pulse to operate the Pockels cell and a PIN diode and avalanche transistor circuit to trigger the system. The Blumlein is essentially a delay-line structure, in which delays and reflections are used to produce a high voltage rectangular pulse of desired width from a voltage step provided by the Krytron. The configuration, installed in 1978, used a ceramic Blumlein with a length of 15 cm, a width of 1.75 cm, and a dielectric constant E = 30. This reduced the laser pulse width from 25 nsec to a 6 nsec output pulse with a 2-3 nsec risetime.

The optical assembly of the chopper was designed to fit between the original laser oscillator and amplifier sections, thus minimizing installation impact in the field. The assembly consists of a thin-film dielectric polarizer sharpener and analyzer, a KD*P 50Ω Pockels cell. The Pockels cell is operated in pulse-on for transmission mode. The pulse chopper timing is controlled in a gross sense by an optical attenuation in front of the PIN diode. Fine tuning is made by bias adjustments to the pin diode.

The chopper was designed by SAO and Lasermetrics Inc. of Teaneck, New Jersey. It was built by and is available from Lasermetrics.

The return pulse shape, is recorded with the LeCroy Waveform Digitizer (WD2000) with sampling channels set 1 nsec apart. Pulse centroid is determined in real time on the station minicomputer using a cross-correlation technique based on a sample output pulse recorded at the beginning of each pass. Experience has shown that the pulse shape is well constrained by the pulse chopper and does not vary appreciably during a pass (or even day to day).

The current characteristics of the system are summarized in Figure 2. Further details on the hardware and software are given in Pearlman et. al., 1978.

ASSESSMENT OF PERFORMANCE

The ranging performance capability of the lasers with the pulse chopper has been assessed by examination of both systematic errors and range noise. These refer to performance of the ranging machine itself, leaving aside issues such as atmospheric correction, spacecraft center of mass correction, and epoch timing for discussion elsewhere.

The systematic errors of the laser system have been divided into three categories: spatial, temporal, and signal-strength variations. Spatial variations refer to differences in time of flight depending on the position of the target within the laser beam. Temporal variations relate to system drift between prepass calibration and postpass calibration. Variations in range due to changes in signal strength from pulse to pulse are a function of receiver characteristics and digitizer sampling interval.

Spatial variations, or the wavefront error, which arise from the multimode operation of the ruby lasers, have been measured at Mt. Hopkins using a distant target retroreflector to probe the beam. Figures 3A and 3B shows the results before and after installation of the pulse chopper. The wavefront measurements performed with the chopper show a maximum deviation within the beam of +/-0.3 nsec (4.5 cm) from the mean value across the wavefront. The standard deviation of the excursions is about 0.2 nsec (3 cm).

The temporal variations on system drift are estimated by the difference between prepass and postpass calibrations measurements. These differences represent an upper bound, since other statistical errors are also included. A typical example of a month's calibration data is shown in Figure 4; monthly means for all of the SAO stations average 4-6 cm.

Variations in apparent range with signal strength have been examined with extended target calibrations over the dynamic range of the laser instrument. Figure 5 shows an example of one such calibration. The mean calibration over the operating range of 1-300 photoelectrons is typically flat to better than +/-0.4 nsec (+/-6 cm).

Using systematic error values of 4.5, 6, and 6 cm for the spatial, temporal, and signal-strength variations respectively; and assuming that these errors are independent, the root-sum squares (rss) error due to systematic sources is about 10 cm. We use this value to characterize the systematic errors that can be expected for data averaged over a pass.

In the SAO laser point-to-point range noise varies from 7-15 cm on passes of low orbiting satellites with high effective cross-section (such as Geos 1 and 3) to 25-50cm on Lageos (See Figure 6). At intermediate signal strengths the noise is dominated by the quantization statistics for the 6 nsec output pulse.

In the low signal strength Lageos operating regime of 1-3 photoelectrons we anticipate a noise level of 25-35 cm due to the 6 nsec wide pulse. In reality, we have additional corruption due to the poor response of the photomultiplier and the inadequate sampling of the digitizer at the single photoelectron level. The 5 nsec wide pulse (at the single photoelectron level) is sampled only at 1 nsec intervals. At high signal strengths, inherent PMT and detection system jitter which amounts to .2-.3 nsec (3-5 cm) plus additional contributions from propagation effects, satellite characteristics and wavefront distortions begin to play a significant role in the range noise value. See Pearlman et. al., 1981.

CURRENT LASER UPGRADING PROGRAM

An upgrading program is now underway to improve laser performance in the areas of pulse repetition rate, accuracy, and signal-to-noise (daylight) response. The current operational characteristics for the SAO lasers and those anticipated after upgrading are shown in Figure 2.

The laser power supply control unit is being modified to enable the system to fire at rates up to 30 ppm. The fundamental limitation in the past has been the tracking regime of the mount which must stop at each point to fire and is thereby limited by rates of speed and acceleration. By adding the capability to vary the firing rate by satellite and geometry, the "slower moving" LAGEOS satellite can be tracked at much higher firing rates (15-30 ppm). There will also be an advantage with some of the lower satellites that can be tracked at rates above the current 8ppm.

To improve range accuracy, the pulse width is being reduced to 2-3 nsec by changing the Blumlein structure and some of electronics in the pulse chopper. The limitation here will probably be the response of the Krytrons and the tradeoff with output energy (depth of chop). Based on our experience to date, we anticipate that the wavefront distortion effect will be reduced in proportion to pulse width with the chopper. The 2-3 nsec pulse should reduce the effect to about +/-2 cm (peak to peak). The current RCA 7265 PMT is being changed for an Amperex 2233A with an EMI Gencom base which has been tuned for low signal level response. This combination gives a considerably improved waveform stability at low signals (See Figure 7). In addition, the front of the PMT is being apertured down to 1.5 cm to reduce jitter. We were able to reduce the jitter (peak to peak) from about 0.5 nsec to 0.25 nsec (peak to peak) with this method.

To avoid accuracy limitations due to waveform sampling (at 1 nanoseconds) and to accommodate the faster pulse repetition rate, the waveform digitizer is being replaced by an analog pulse detection system. This detector consists of a matched filter tuned for the laser pulse. The filter is followed by a differentiator and slope-triggered low threshold discriminator, which functions essentially as a cross-over detector. Results of an initial field test of the analog detector with a 6 nsec lase pulse using the Amperex 2233 PMT and EMI Gencom base are shown in Figure 8. The results are similar to those found using the digitizer. The importance of this system will increase when the laser pulse width in the field is narrowed. An additional advantage of the analog detector is the simplification of system hardware and software.

Several modifications are being made to improve the signal to background noise ratio. The photoreceiver is being modified to accommodate a fast shutter and a 3 Angstrom Day Star filter, which replaces the current 8 Angstrom interference filter. The range gate system is being upgraded to accept range gate windows down to +/- 0.1 microsecond (30 meters) from the currently used +/-5 microsecond window. See Latimer et al., 1981, for a discussion on the capability of the SAO prediction software. These improvements will increase signal to noise by about 16-20 db which should permit the laser to operate on Lageos further into daylight conditions.

The prototype of the upgraded hardware and software are being installed and tested now at Mt. Hopkins. The production units are in different stages of completion depending upon the questions yet to be answered in testing. We expect to field the production units in the Arequipa, Orroral Valley and Mt. Hopkins lasers in early 1982. The modifications are also to be built for the Natal laser for installation when and if the laser is relocated.

With these modifications in place we anticipate a factor of 2-3 improvement in each of the systematic error components which should give the systems a range accuracy of 3-5 cm. Similarly, range noise should be reduced by about a factor of 3, giving a sigma of 10-15 cm on Lageos and 3-5 cm on low orbiting satellites.

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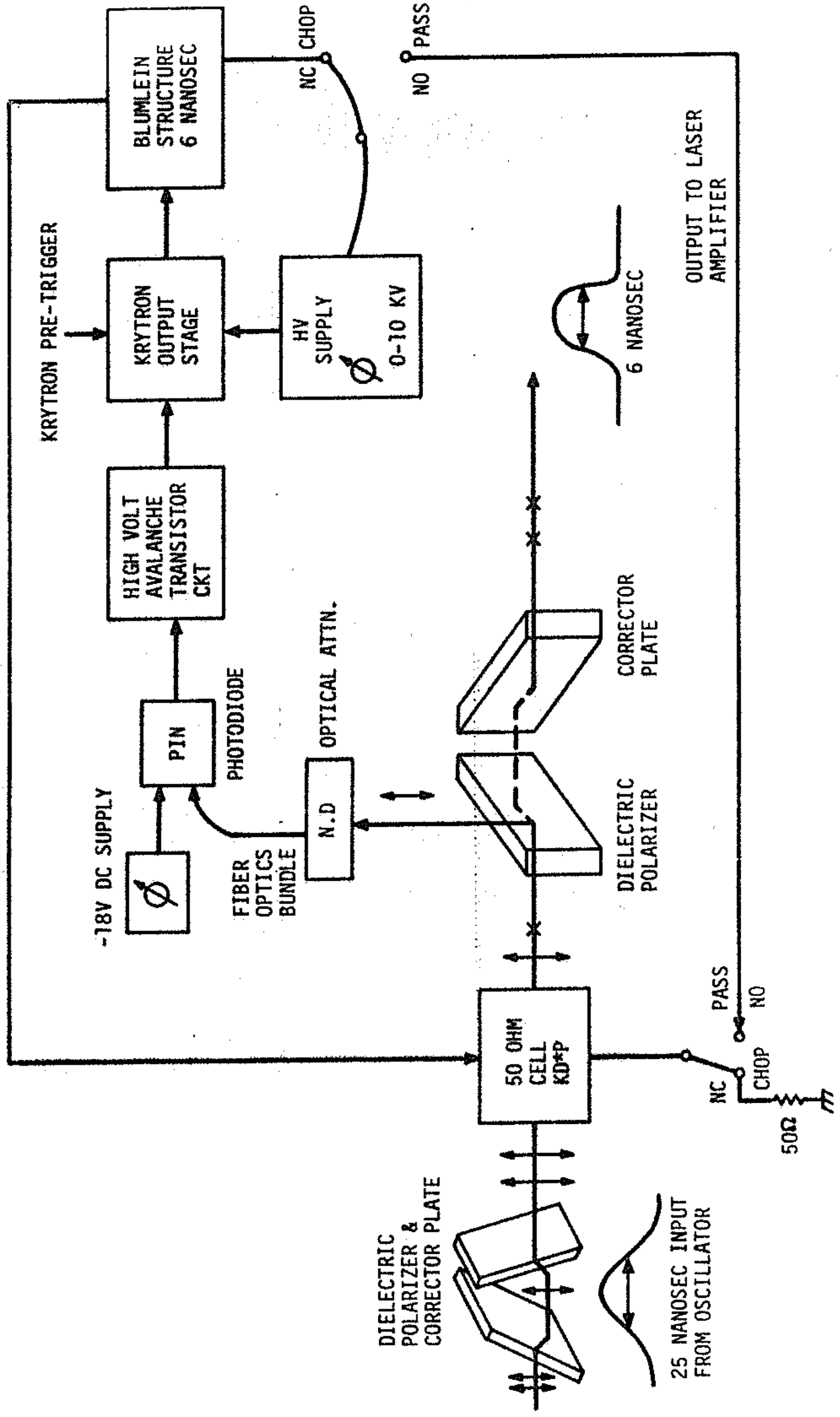

Figure 1.
Krytron activated pulse-chopping system.

SAO LASER SYSTEM

PARAMETER	CURRENT	UPGRADED
WAVELENGTH (Å)	6943	6943
ENERGY/PULSE (J)	1.0	0.3
PULSE WIDTH (NSEC)	6	2
REP. RATE (PER MIN)	8	30
DIVERGENCY (MR)	0.6	0.6
QUANTUM EFFICIENCY (%)	4	4
SYSTEM EFFICIENCY (%)	25	25
RECEIVER DIAMETER (M)	.50	.50

Figure 2

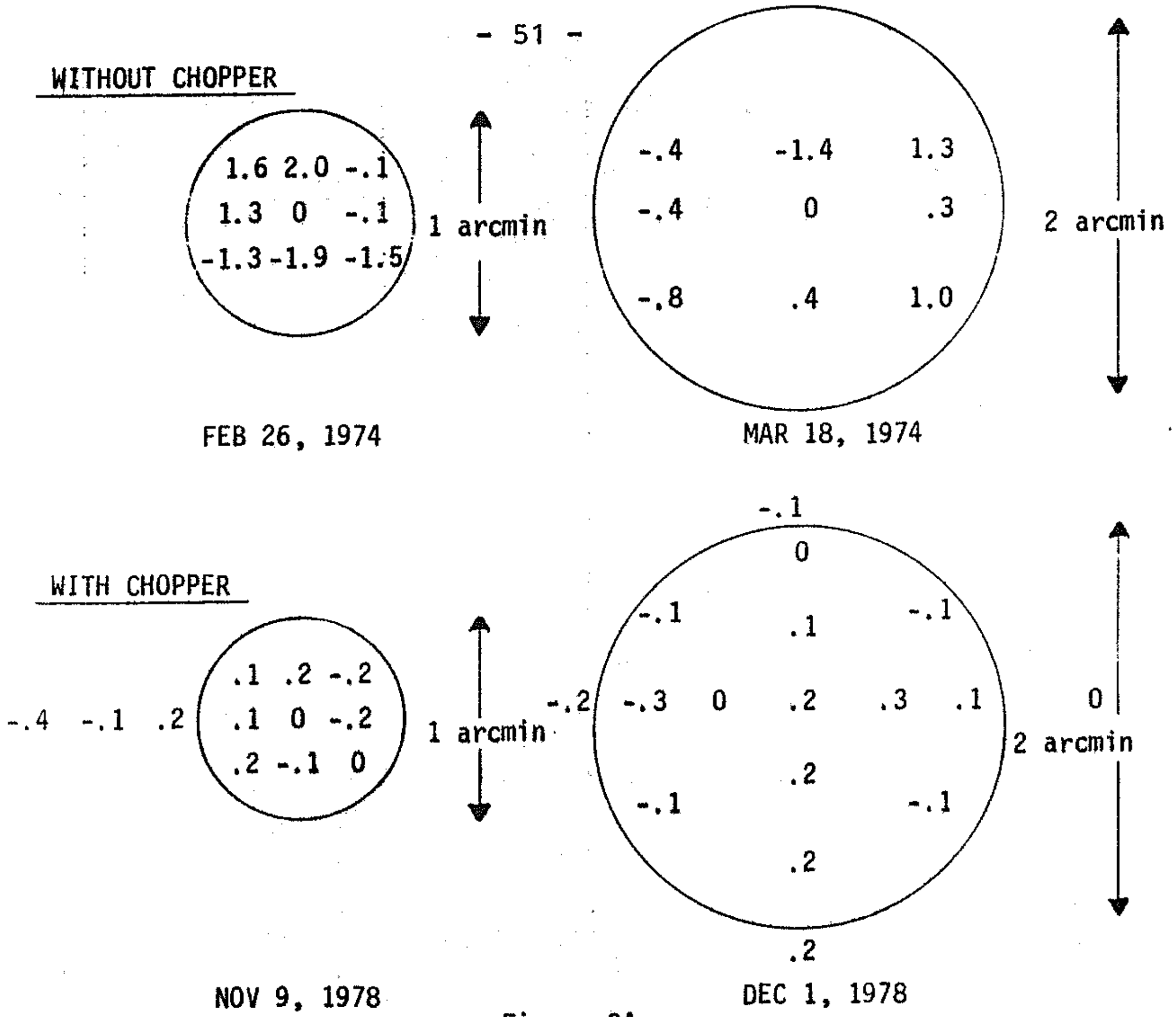

Figure 3A
Wavefront distortion in nsec. determined from
20 shot means within the laser beam (0.1 nsec = 1.5 cm)

DATE	SPACING BETWEEN POINTS (ARC MIN)	AVERAGE NUMBER OF PHOTOELECTRONS RECEIVED	RMS WAVEFRONT DISTORTION (CM)	MAXIMUM EXCURSION (CM)
FEB 26, 1974	.3	88	22.5	58.5
MAR 18, 1974	.6	56	12.0	40.5
NOV 9, 1978	.3	56	2.9	9.0
DEC 1, 1978	.42	87	2.6	9.0

Figure 3B.

Summary of Wavefront Distortion Data

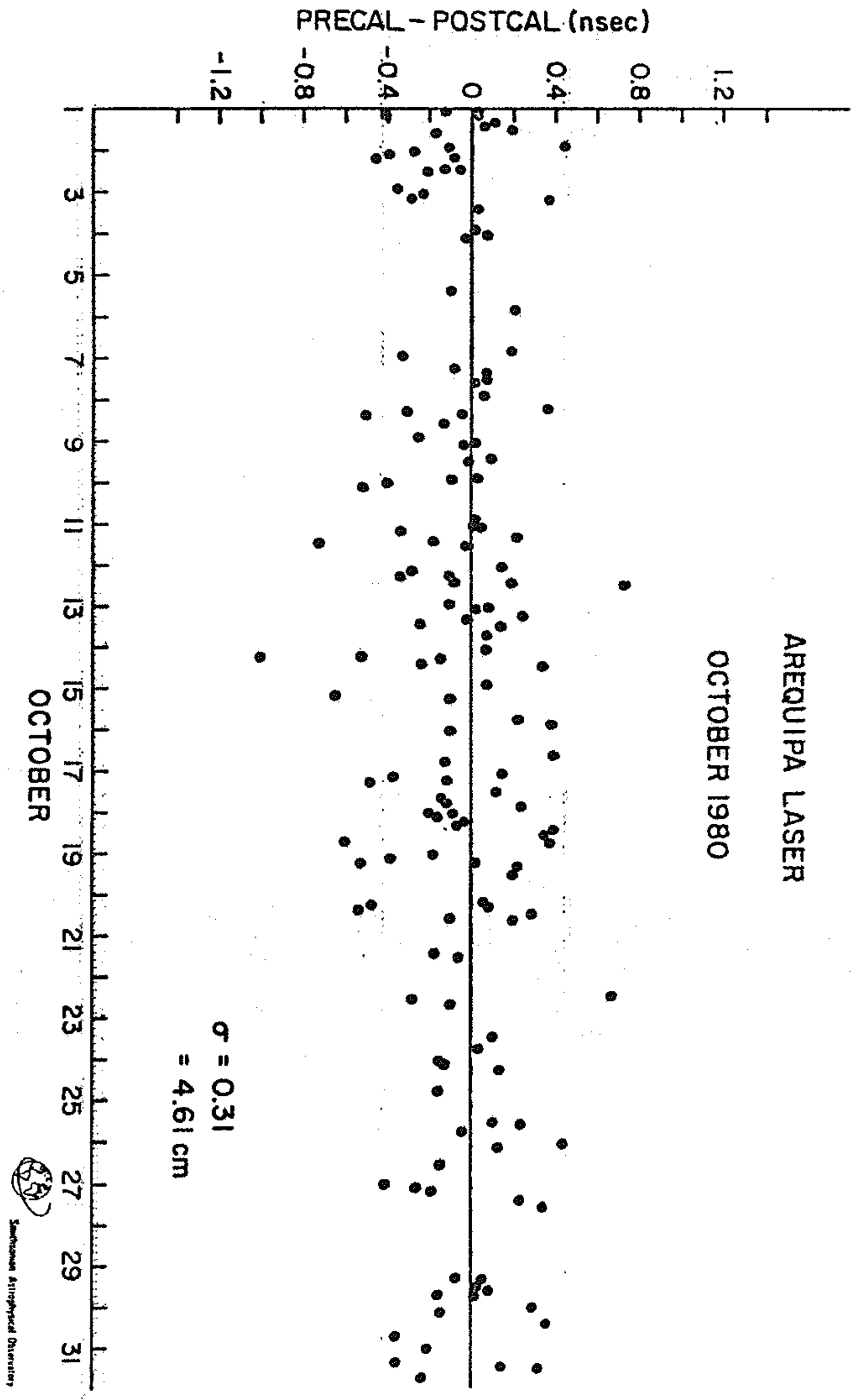

Figure 4.
Precalibration minus Postcalibration differences based on 20 shots each.

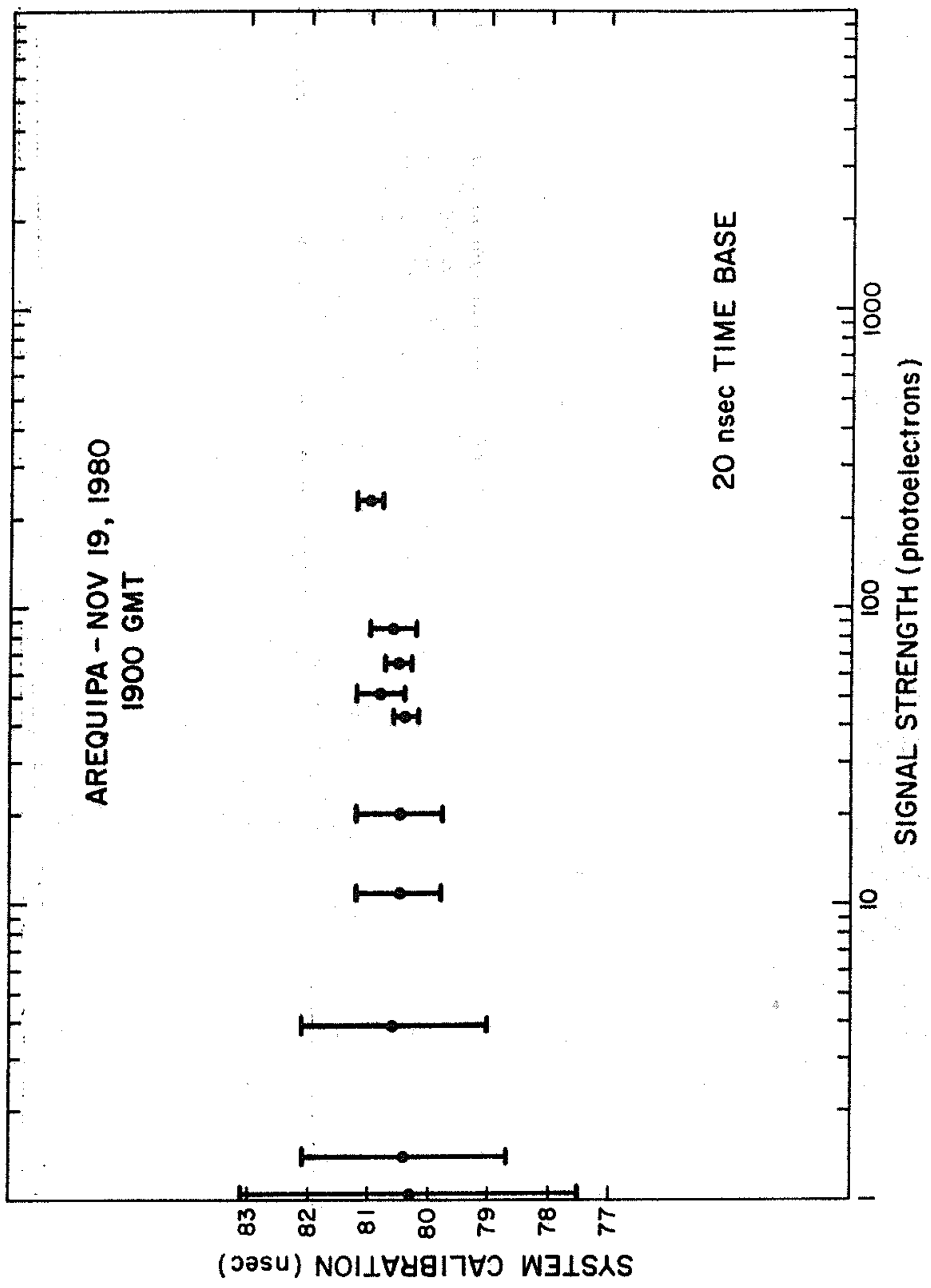

Figure 5.

Extended target calibrations based on at least 100 photoelectrons in each signal strength interval.

Figure 6
Starlette
Final Data
July 1 - 7
(1981)

Station	Date	RMS (cm)	Number of Points
Peru	7/1	33.2	65
Peru	7/1	30.3	27
Peru	7/1	17.7	32
Brazil	7/1	29.1	26
Peru	7/2	14.9	72
Peru	7/2	21.7	61
Peru	7/3	28.3	17
Peru	7/3	15.6	75
Brazil	7/4	22.3	26
Peru	7/4	9.0	78
Peru	7/4	21.0	53
Australia	7/4	14.5	39
Australia	7/4	23.2	60
Peru	7/5	8.8	78
Brazil	7/5	16.0	43
Brazil	7/6	12.5	41
Peru	7/6	22.4	63
Peru	7/6	16.8	70
Australia	7/6	9.4	14
Australia	7/6	21.1	13
Australia	7/6	21.7	32
Peru	7/7	15.4	68
Peru	7/7	23.1	46
Australia	7/7	18.9	33
Peru	7/7	22.6	49
Australia	7/7	39.8	13

Figure 6
(cont.)
LAGEOS
Final Data
July 1 - 7
(1981)

Station	Date	RMS (cm)	Number of Points
Brazil	7/1	40.4	21
Peru	7/2	31.4	118
Peru	7/2	45.8	39
Peru	7/3	26.2	98
Peru	7/3	39.8	119
Brazil	7/4	32.8	98
Peru	7/4	27.2	102
Australia	7/4	39.4	113
Australia	7/5	50.0	24
Peru	7/5	30.9	147
Peru	7/5	31.9	90
Peru	7/6	35.5	39
Peru	7/6	32.9	107
Australia	7/6	41.6	117
Australia	7/6	51.9	98
Peru	7/7	37.0	101
Australia	7/7	34.9	77

Figure 6
(cont.)
GEOS-C
Final Data
July 1 - 7
(1981)

Station	Date	RMS (cm)	Number of Points
Peru	7/1	6.8	66
Brazil	7/2	27.5	55
Peru	7/2	7.0	79
Peru	7/2	10.5	47
Peru	7/2	9.8	65
Peru	7/2	31.4	118
Peru	7/2	45.8	39
Peru	7/3	26.2	98
Peru	7/3	4.8	69
Brazil	7/3	8.0	43
Peru	7/4	10.1	32
Peru	7/4	7.5	75
Brazil	7/4	9.6	62
Australia	7/5	45.4	21
Brazil	7/5	18.9	50
Peru	7/5	9.4	74
Australia	7/6	10.6	45
Peru	7/7	8.2	35
Peru	7/7	10.1	57
Peru	7/7	9.8	74
Australia	7/7	54.3	7

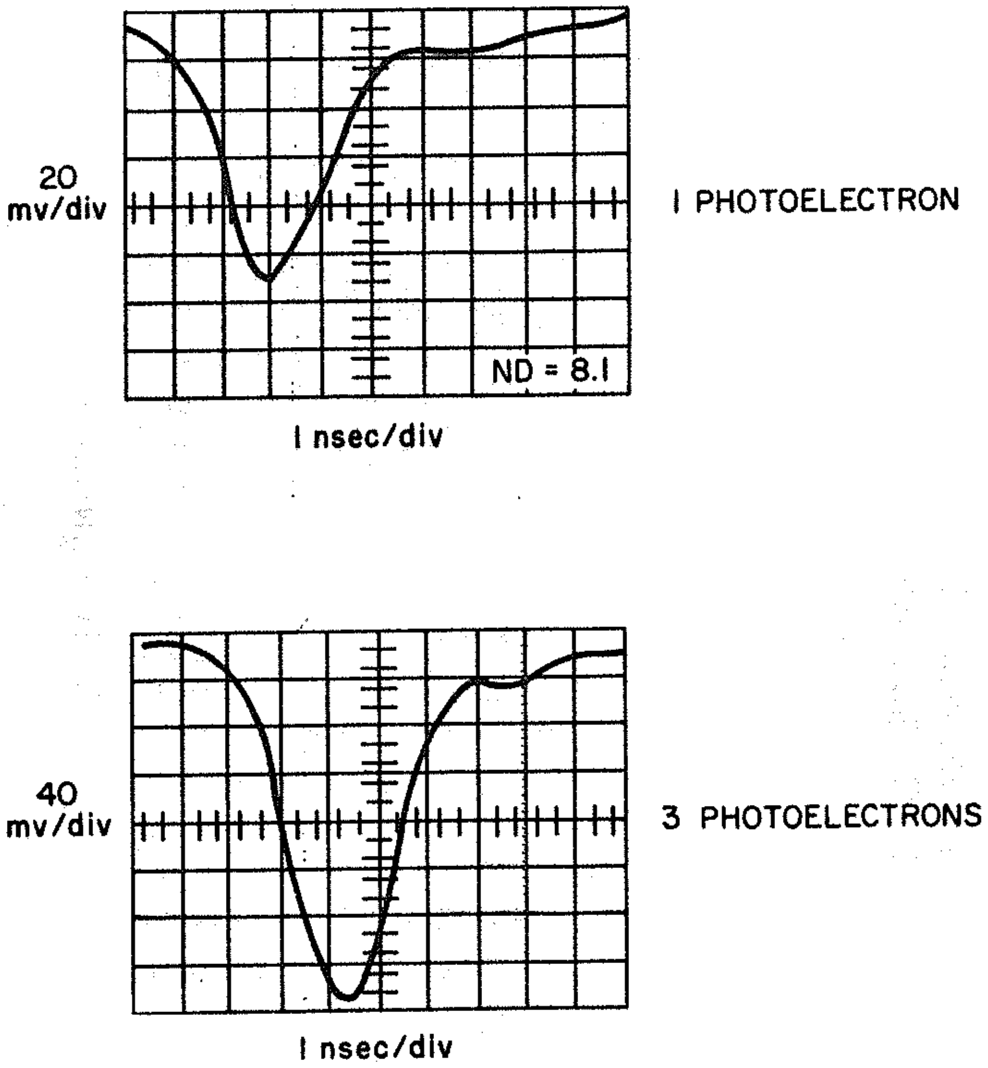

Figure 7.

Pulse response of the Amperex 2233 PMT with EMI Gencom base using 130 picosec. light pulse input.

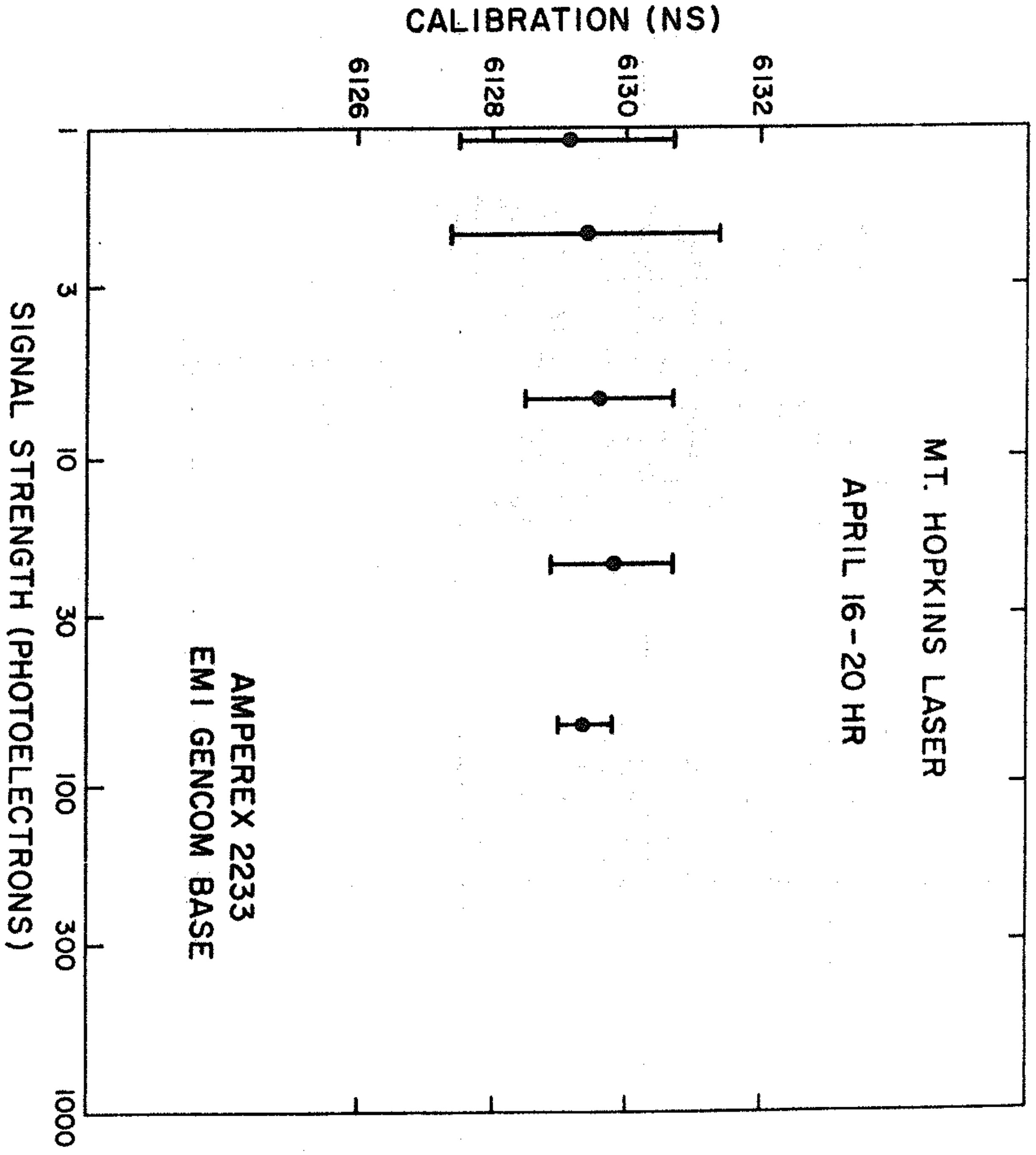

Figure 8.
Extended target calibration using the Analog Pulse Processor.

THE TLRS AND THE CHANGE IN MOBILE STATION DESIGN SINCE 1978

BY

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We have witnessed a tremendous revolution since 1978 concerning the characteristics of transportable laser stations fueled by the necessity to develop cost-effective systems for geodesy. At the last workshop we had a number of movable stations in field operation, but none which were truly mobile. The situation has now changed. One highly mobile system is fully operational, a second even more compact station is close to operational status, and at least two others are currently under construction. The development of these systems has resulted not so much from a technological breakthrough, but through the application of single photoelectron techniques heretofore reserved for lunar ranging. We have had the recognition that the tracking problems presented by LAGEOS are more similar to those which have been solved with the moon than those previously used on lower satellites.

The use of the term single photoelectron ranging should be looked upon not necessarily as an indication that the signal is less than one photoelectron per shot, but as the ability to co-add a number of shots and locate your ranging target by a statistical inspection of the residuals. Earlier satellite ranging required that the satellite be located principally by means of a signal strength greater than the noise in the range gate. Single photoelectron techniques, on the other hand, do not depend on any greater signal but on the fact that the returns from the target will be highly correlated with the prediction ephemerous as opposed to noise returns which are not. The practical necessity of maintaining this approach is due to the fact that any aperture ranging system which can be easily transported (less than 0.5 meters) will not produce a reliable multi-photoelectron return on the LAGEOS satellite with less than about 100 millijoules output energy. Single photoelectron techniques on the other hand can detect LAGEOS even in the presence of high background noise with energies fifty times less. The regulatory environment alone regarding aviation eye safety is reason enough to consider the low power techniques. The added advantages in calibration ease, cost and reliability of the laser system weigh heavily in the direction of these lower-power high-repetition rates systems for applications which concentrate on the LAGEOS target.

The first system to fully realize operational single photoelectron ranging for satellites was constructed by The University of Texas between 1978 and 1980. A special attempt was made to make the station reliable and mobile using a number of special features. The system, dubbed the TLRS, has operating parameters such as shown in the station report forms. One of the unusual aspects is that the TLRS uses a mode-locked laser limited to 3.5 millijoules per burst of pulses and transmits the entire pulse comb rather than pulse selecting as has been the case in the past. High accuracy pointing is critical. In order to be able to work at unprepared sites, the system has a on-site mount orientation routine which is practical to run prior to each satellite pass. The system also employs a feedback calibration system to calibrate the single stop timing electronics. These and other hardware are more fully described another paper in these proceedings. Figure 1 gives a schematic diagram of the system as it is configured at this time.

The operating characteristics of the TLRS can best be shown by describing the first few hours of activity after arriving at any given site. The TLRS van is driven to the site as would any small truck. Most of the auxiliary equipment is contained in a 32-foot office trailer which is pulled by a second vehicle. All of the clocks run off the truck generator during the moves. The van is first driven along side the chosen geodetic marker and positioned within about five centimeters of the ideal location. The van is then manually jacked on 3 cones, leveled and stabilized. If the surface on which the system is being parked is relatively soft, plywood sheets are used under the cones to stabilize the foundation. Power is then hooked to the van (approximately 20 kW, single phase, 220 volt) at which time the clocks automatically switch to the mains. The beam director is then raised through the roof and the entire coude assembly jacked on three more cones so that the optical system is supported independent of the truck chassis. The coude system is levelled by means of an electronic level on the base of the beam director. After the computer is started, the software quizes the crew on the approximate geodetic position of the truck, the azimuth at which it is parked and other initialization parameters. The time in the van is checked by comparing it with a cesium standard which rides in the auxiliary office trailer. Loran C communication is established to monitor the frequency of the clocks during that occupation. At this point the elapsed time is approximately two hours.

If all features are functional to this point, the laser is aligned and tested. The finder telescope of the beam director is used to locate a bright star which is centered in the field so as to determine the basic azimuth offsets of the instrument. A second star is then located at which time it is possible to solve for the tilt and azimuth of the tower. This process continues until about ten to fifteen stars are acquired and an exact 8-10 parameter mount model is determined. (Further information on this mount model is given in these proceedings.) If the geodetic position which was entered by the operator is in error, the mount solution will show a significant tilt in the tower relative to the electronic level. This allows the operators to determine whether or not their location guess is sufficiently accurate for a satellite acquisition. The efficiency of the optical system is usually checked at this point by monitoring the count rate on a bright star. The exact offsets to the geodetic marker are then read from a small vertical-looking telescope which is poised near the driver's door.

The ephemeris for LAGEOS, with the position and velocity of the satellite at three-hour intervals, is mailed to the TLRS several months in advance. On command the computer will predict the azimuth and altitude of subsequent passes from the nearest prediction point. After the pass is integrated the system is ready to range. Normally the crews tailor their mount models to each pass by selecting a few stars along the expected arc prior to the event; however, each team may use a slight variation on this technique depending on their previous experience. The elapsed time at this point can be as little as four hours, but is frequently longer if it is necessary to wait for darkness in order to develop a proper mount model. The TLRS will continue to range at a site with two men crews, sending the data to the data reduction center in one-week segments, until approximately 600 minutes of tracking have been derived. If practical, phone communications are installed in the TLRS for their month-long occupations.

Based on early observations the TLRS has proven to be a reliable and quite accurate device for ranging the LAGEOS satellite. The quality of the data which is possible with this system is indicated in Figure 2, where we have plotted the residual deviations from a low order of polynomial versus the number of range observations which were averaged to achieve these normal points. The best passes of the TLRS have over three thousand single photoelectron hits with an RMS from the best fit orbit of about 7-8 centimeters. One hundred point return normal places fit to these data show a scatter from the best arc approaching one centimeter. Since the system is highly mobile, the occupation time at any given location is limited only by the number of tracks which are necessary on the target and not in general the logistics of moving the station between the sites. Clearly this one station alone represents a drastic change in the compliment of laser ranging equipment since 1978. In the next few years the extent of crustal dynamics studies should fuel this evolution to the point where several truly mobile stations are in the field gathering data from orbiting satellites.

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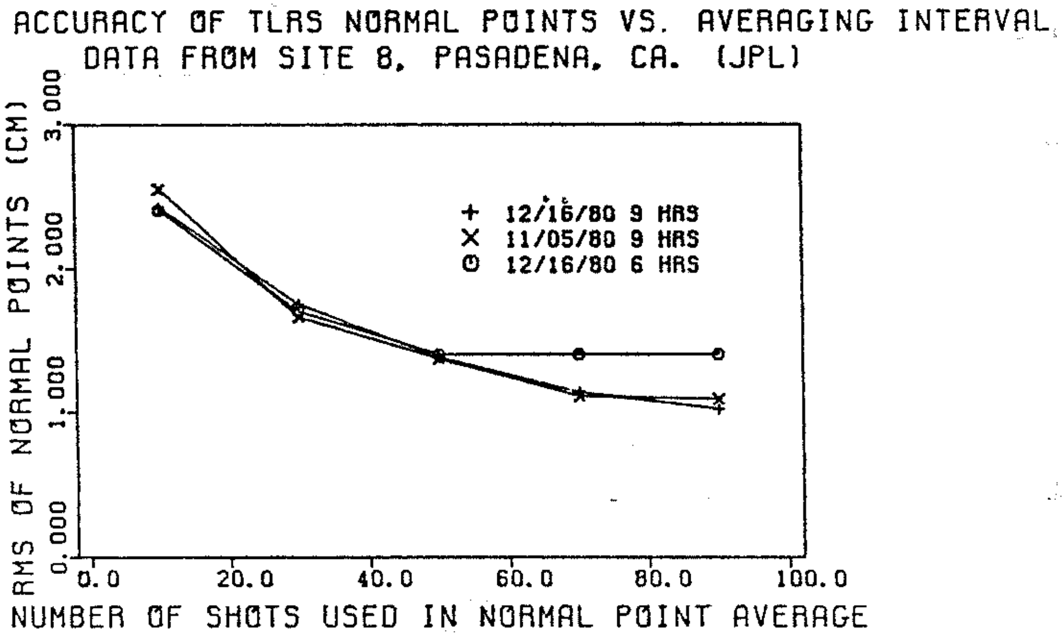

Figure 2: Normal points were formed from several strong passes to determine the precision limits of the current TLRS. Starting with a single point RMS scatter of 8cm, the data improved nearly as predicted for a gaussian distribution of residuals.

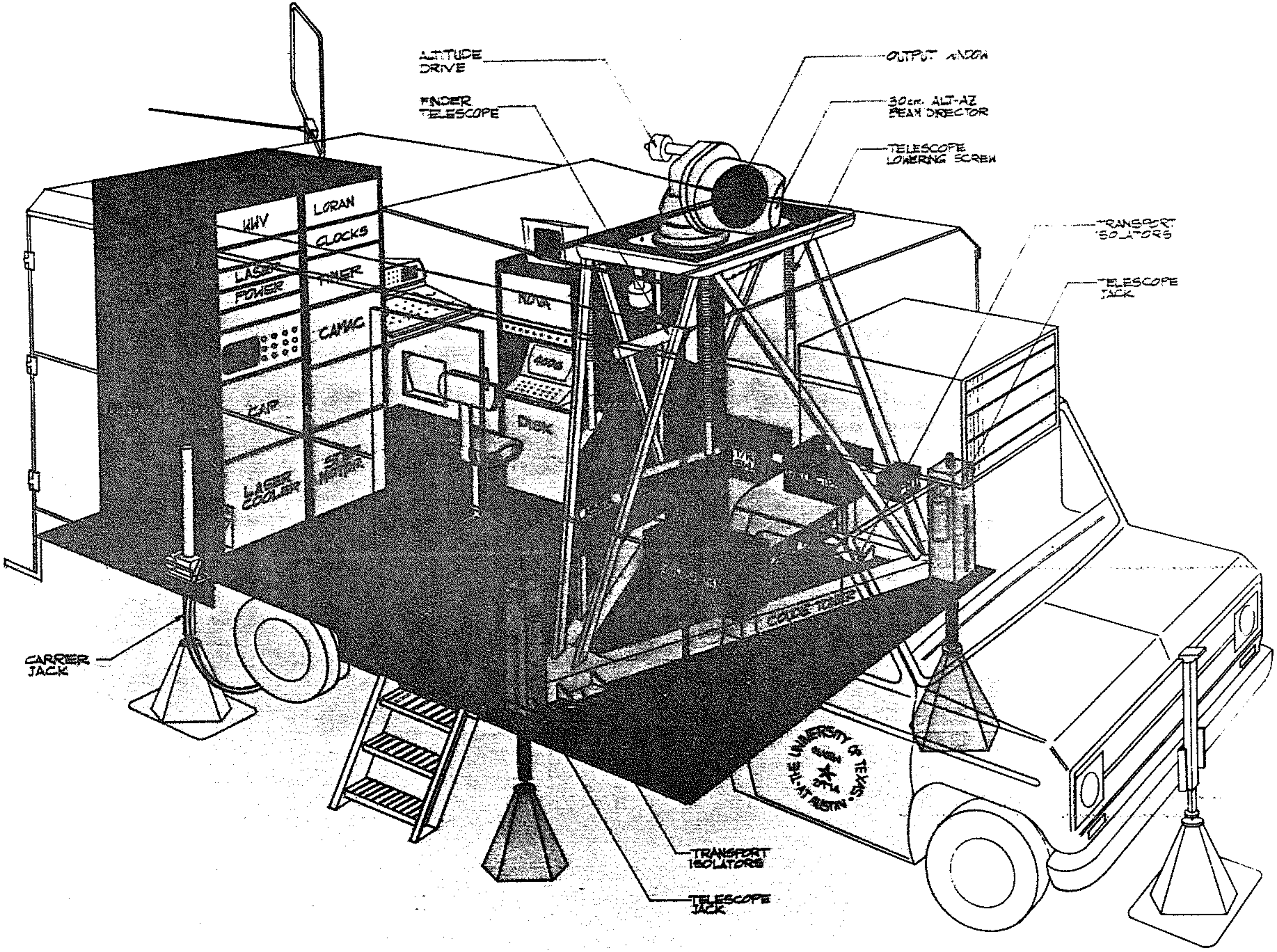

Figure 1: The TLRS is housed in a small single chassis van which is leveled at the site on three jacks. The beam director retracts to below the roof line for transport.