L A S E R   T R A C K I N G   I N S T R U M E N T A T I O N

Proceedings of the Second Workshop held at
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I.11 WORKSHOP ON LASER TRACKING INSTRUMENTATION (7)

cosponsored by COSPAR and IAG
Prague, Czechoslovakia, 11–15 August 1975

A "Workshop on Laser Satellite Ranging Instrumentation" was held in Lagonissi, Greece, in May 1973. The success of this 1973 workshop let to a COSPAR resolution (8), to "accept the invitation of the Technical University of Prague to arrange another Laser Ranging Workshop, to be held in Prague in August 1975 immediately prior to the IUGG/IAG General Assembly in Grenoble, and to be sponsored by COSPAR in cooperation with IAG."

The IAG will meet the week of 18 August 1975 and the IUGG meeting will start 25 August. Therefore the Workshop will be held during the week of 11–15 August, inclusive.

Rapid progress in laser techniques suggests that although present accuracy levels are quite impressive, they can be substantially improved. Indeed, we anticipate that satellite range measurements with accuracies to 2 cm will soon be available, thereby opening new opportunities in both scientific and applied research. As just one example, it seems clear that, within a few years, we shall be able to measure global plate tectonic and other crustal motions to an accuracy of 1 cm/year. Because of these new capabilities, a widespread interest has developed in the practical questions that arise in designing, building and operating laser systems.

The planned launches of two satellites designed expressly for high accuracy laser tracking lends a timeliness to the Prague Workshop. These are the French Starlette to be placed in orbit in the fourth quarter of 1974, and the U.S. Lageos to be launched in early 1976.

A critical review of the accumulated experience in working with laser systems, particularly the problems encountered, and both successful and unsuccessful methods for dealing with these problems, will be the best foundation for the workshop. To encourage free and open discussion of such topics, the workshop will be conducted on an informal basis, with no formal presentations. This format requires more rather than less preparation and, further, will succeed only if the participants take active part in the discussions.

Attendance will be by invitation only. Suggestions for invitees are requested, but should be limited to those who have been involved in the actual design or operation of satellite laser systems or are seriously contemplating such activities.

The proceedings of the workshop will be published.

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(7) First Circular.

(8) Resolutions and Recommendations adopted by the XVIIth Plenary Meeting of COSPAR, São Paulo, 1 July 1974.

AGENDA FOR THE

WORKSHOP ON LASER TRACKING INSTRUMENTATION

11-15 August 1975 PRAGUE

MONDAY, 11 AUGUST - AM		
	Session 1	Introduction Operating Systems
MONDAY, 11 AUGUST - PM		
	Session 1a	Operating Systems
MONDAY, 11 AUGUST - EVENING		
		Reception
TUESDAY, 12 AUGUST - AM		
	Session 2	System Errors
TUESDAY, 12 AUGUST - PM		
	Session 3	Laser Transmitters
WEDNESDAY, 13 AUGUST - AM		
	Session 4	Pulse Detection and Processing
WEDNESDAY, 13 AUGUST -PM		
	Session 5	Other System Components (Filters, Computers, Mounts, Automation etc.)
THURSDAY, 14 AUGUST - AM		
	Session 6	Satellites in Orbit (incl. planned) Prediction
THURSDAY, 14 AUGUST - PM		
	Session 7	Reliability Laser Hazards
FRIDAY, 15 AUGUST - AM		
	Session 8	Future Systems Sci/Tech Programmatic
FRIDAY, 15 AUGUST - PM		
	Session 9	Open Discussion

LASER STATIONS CNES/CRGS

Jean Ch. Gaignebet

1rst Generation

This station was developped around an old military cine-theodelite with only optical tracking possibilities.
The main characteristics are:

Mount Alt-Az with a seat for the tracker. Hydrolic mouvements via a joysteck.
Maximum speed $20^{o}/s$

Laser Ruby, 1 joule, 30 ns FWHA pulse, 1 Hz repetition rate. Beam divergence 2×10^{-3} rad. /Half energy/

Laser optics
3 afocal systems with focal ratios of 2, 3, 5 and 7

Receiver optics
Schmitt Cassegrain telescope
36 cm aperture f/10 with gold plated mirrors
20 Å Band pass filter 40% transmission

Detection 56 TVP type of PMT with a S 20 photocatode /QE 2% at 0.7 microns/
Gain 10^{8}

Tracking Scope Refractor with an aperture of 20 cm f/S
3^{o} field

Electronics
10 ns resolution counter, Stop input gated.

Time keeper
Quartz crystal 10^{-9} stability. VLF reference and reset by a portable clock
An accuracy of ± 25 μs over periods of more than 6 months is reached.
The resolution of the datation system is 100 μs

Data acquisition
Telex punched tape and hard copy

The Station is in-egrated on a mobile van.
Performances RMS 1,2 m.

1rst Generation modified

Mount automatic Alt-Az mount open loop encoding

Resolution 13" of arc

Accuracy 20" of arc

Speed 40^{o}/s maximum

The mount is computer driven with an option of jaystick or punch tape.

Laser The Laser has been modified by use of a dye cell to have a pulse width of 12 ns FWHA

Detection the 56 TUP PMT is used only for day tracking and an RCA 3103A A is used by night connected with a 40 db Amplifier and a 3 Å 30% filter

Tracking scope

We replaced the edge piece by a TV Camera /Nocticon Thomson tube/ coupled with a monitor-

A 12 to 13 magnitude is seen in a nonintegrating mode. Field 1^{o}

Electronics

1 ns resolution counter. Stop channel is controlled by an automatic gate

Epoch firing time of the Laser is controlled by an early/late adjustment to correct far long track errors /1 μs to 10 s/

Computer A WANG 2200 is used to compute in real time the coordinates of the satellite /Keplerian mouvement/ Alt, Az, range time and the corresponding speeds and accelerations are computed from previously entered sets of orbital elements

Performances 75 cm RMS

Future plans call for the installation of a pulse digitizer and recording the data on magnetic tape.

The expected accuracy should be letter than 40 cm RMS.

2nd Generation

Mount Alt Az automatic mount closed loop encoding
resolution 1,2" of arc
Accuracy 5×10^{-5} rad
Speed 6^{o}/s maximum
The mount is computer driven with an option of joystick

Laser Ruby Single mode diffraction limited Laser with the following performances
2 J per ns pulse width
4 J, 2 ns to 20 J, 10 ns
repetition rate 0.25 Hz
0,75 J per ns pulse width
1,5, 2 ns to 7,5 J, 10 ns
repetition rate 0,5 Hz
The Laser can be mode locked with a train of 7 pulses of 0,8 ns

Laser optics Variable afocal system with a focal ratios from 1 to 10

Receiver optics 1 m Cassegrain telescope Al plated

Detection RTC P 1210 PMT for daylight tracking
RCA 31034 A by night. A filter of 3 Å is used in connexion.
All the detection is conceived in a modulated way and with two channels possibilities

Tracking scope
18 cm refractor associated with a TV camera /Nocticon Thomson CSf tube/
Field 1^{o} 12 magnitude possibilities on a non integrating mode.

Electronics 100 ps resolution counter. Stop channel gated

Computer
Telemecanique T 1600 computer working in a two pass way /Orbital elements to position and interpolation on line/
A digitizer is used /Thomson System adaptable on a Tektronix 7903 scope/

Performances

25 cm without digitizer

5 - 7 cm with digitizer

Lunar Ranging

Only the mount and telescope are now studied and ordered.

Mount Al-Az automatic mount open loop encoding

Resolution 0,3" of arc

Accuracy 3" of arc.

Receiving telescope 1, [illegible] m Cassegrain telescope f/6

THE SMITHSONIAN SATELLITE RANGING LASER SYSTEM

M. R. Pearlman, C. G. Lehr, N. W. Lanham, and J. Wohn

1. INTRODUCTION

Four Smithsonian Astrophysical Observatory (SAO) satellite ranging systems, originally designed for the particular requirements and needs of the Observatory's program in satellite geodesy, have been in continuous operation for more than four years; these systems are located in Natal, Brazil; Arequipa, Peru; Olifantsfontein, South Africa; and Mt. Hopkins, Arizona. During this period, they have provided routine tracking data at a meter accuracy level in support of several geodetic programs. The systems are now being upgraded to meet new requirements in geophysics.

The major thrust of the present activity is to improve the accuracy and performance of the ranging systems to support the tracking requirements for Geos 3 and Seasat and also for earth-dynamics projects based on satellites such as Starlette. Under the current upgrading program, the SAO laser systems are being equipped with pulse choppers to reduce the laser pulse width and with electronic pulse processors to improve range measurement accuracy. We anticipate that the ranging-system hardware will have decimeter accuracy when the upgrading is completed in early 1976.

2. HARDWARE

The laser ranging system shown in Figure 1 has a static-pointing mount (or pedestal) that is aimed by means of computed predictions of satellite azimuth and altitude. This method of steering permits the system to operate during the day as well as at night. A static-pointing mount was selected because it is economical and operationally simple and can be maintained indefinitely at remote locations.

2.1 Laser Transmitter

The laser, a ruby system built in an oscillator-amplifier configuration, generates an output of 5 to 7 joules in a 25-nsec pulse (half-power, full width). The system uses a Pockels cell and a Brewster stack for a Q-switch and operates at 8 pulses per minute (ppm). Both the 0.95-cm (3/8-inch) diameter oscillator ruby rod and the 1.59-cm (5/8-inch) diameter amplifier ruby rod are mounted in 15.24-cm (6-inch) double elliptical cavities, each containing two linear flashlamps. The optical cavity of the oscillator is formed by a flat rear mirror, with a reflectivity of 99.9%, and the uncoated front of the oscillator rod.

The oscillator output of 1 to 2 joules is coupled into the amplifier through a small beam-expanding telescope. The amplifier has a single-pass gain of about 5. Both ends of the amplifier rod are antireflective-coated. The amplifier output is expanded to fill the 12.7-cm (5-inch) objective lens of a Galilean telescope: The diameter of the output beam divergence can be adjusted from 0.5 to 5.0 mrad. Mounted at the output of the laser, photodiodes pick up atmospherically scattered light from the outgoing pulse and send an electrical start signal to the ranging system electronics. Additional details on these lasers are given elsewhere

To meet upcoming requirements, the SAO lasers are being equipped with a pulse chopper to improve ranging accuracy. The first unit is now being installed at Mt. Hopkins. The chopper has been designed to fit between the present laser oscillator and amplifier sections thus minimizing installation impact in the field. It is basically a spark-gap-activated Pockels cell with appropriate polarizers providing the necessary transmission and isolation. The pulse width will be adjustable, but the laser is expected to produce 0.5 joules at a pulse width of 6 to 7 nsec.

2.2 Ranging-System Electronics

The ranging-system electronics consists of a clock, a firing control, a range-gate control, a processing system for the start and stop (return) pulses, a time-interval unit, and a data-handling system (intercoupler) (see Figure 1). The clock, sychronized to within ±1 μsec of the station master clock, controls the firing time of the laser and provides the epoch of observation. Both firing rate and the time of the laser firing are controlled by the laser control unit; the latter can be shifted manually by multiples of 0.001 sec, with a maximum of ±3 sec, to account for the early or late arrival of a satellite at a predicted point in its orbit.

The range-gate control unit provides a delayed pulse of adjustable width to gate the counter and the pulse-processing system. This range gate protects against triggering by sky background or electronic noise. The time-interval unit, which has a resolution of 0.1 nsec, is triggered on and off by outputs from the pulse-processing system.

Range measurement errors introduced by normal fixed-threshold detection techniques have been combatted by adding pulse-processing electronics. With fixed-threshold detection, irregularities in return pulse size and shape and changes in laser output energy and pulse width can introduce both random and systematic range errors comparable in size to the laser output pulse width. For range timing reference, the processor has been designed to make use of the transmitted- and return-pulse centers, as these are more stable than fixed-threshold points and can be extracted in a straight forward manner.

The pulse processor is divided into two sections, the start and stop channels (see Figure 2). A threshold-activated pulse of constant size and shape furnished by the start channel starts the time-interval unit and supplies DC signal levels that measure the transmitted pulse width (at the preset threhold level) and area (energy). The pulse information is later used to extrapolate the range measurement to the center of the start pulse. The stop channel digitizes the return-pulse waveform, providing a pulse of fixed size and shape that stops the time-interval unit. This stop pulse is synchronized to a fixed time reference point on the waveform.

During data preprocessing, the waveform information is used to determine the offset of the return-pulse centroid from the fixed time reference on the waveform. The start correction is calculated by using the transmitted pulse information and algorithms developed during electronic calibration. The time-interval unit reading C_T, the return-pulse centroid offset C_S, and the start correction C_0 are added to give the raw range measurement.

The start channel is based on commercially available dual discriminators and pulse integrators (see Figure 2). The pulse data are digitized and fed to the data intercoupler in BCD format. We found that the particular discriminators used in this system were not very sensitive to pulse widths less than 5 nsec, so we included a "pulse stretcher" in the circuit to operate the components in more favorable regions. In the pulse stretcher, the incoming pulse is split, one component is delayed by a few nanoseconds, and the components are then summed back together again. We have been able, by means of this device, to extend the system sensitivity to a few nanoseconds.

The stop channel is centered around a commercially available waveform digitizer, which provides a visual and BCD display of the return pulse. The digitizer has 20 sampling channels with spacing adjustable in steps from 1 to 25 nsec. The digitizer is activated by the output of a dual discriminator, which is threshold triggered. The stop pulse to the time-interval unit is provided by the time base of the digitizer; in our system, we use the gate for the 11th channel as a reference.

2.3 Mount

The azimuth-altitude static-pointing mount has a pointing accuracy of better than ± 30". The system is driven by stepping motors in an open-loop mode. The stepping-motor drive-system gears allow for slewing speeds of 2^{o} sec^{-1} and positioning increments of $0\overset{o}{.}001$. Predictions, including pointing angles and range-gate settings, are entered in the system on a point-by-point real-time basis.

2.4 Photoreceiver

The receiving telescope is a 50.8-cm (20-inch) Cassegrain system with additional optics designed to focus an image of the primary mirror on the photocathode of the photomultiplier tube (RCA 7265). The optics following the flat secondary mirror passes the collimated return signal through a 7 Å filter that is both tilt- and temperature-dependent. Effects of age and temperature are compensated for by means of a micrometer tilt adjustment that tunes the filter. Adjustable field stops and a provision to insert combinations of neutral-density filters are available.

2.5 Minicomputer

The SAO laser stations have been equipped with minicomputers for generating pointing predictions from orbital elements and preprocessing calibration and satellite ranging data. The system is now operated in a "stand-alone" mode which is independent of the laser hardware. The current plan is to connect the minicomputer directly to the ranging system during the next year.

3. CALIBRATION AND SYSTEM STABILITY

3.1 Start-Channel Calibration

The calibration of the start channel is developed from the dependence of the system delay on output-pulse characteristics which are derived from the start-channel parameters. Calibration is performed electronically by entering pulses of varying widths into both the start and the stop channels and then varying the pulse amplitudes at the start-channel input. In each run, pulse widths and amplitudes are varied about the normal laser operating conditions.

Typical examples of calibration runs using width alone as the independent variable for both the wide (25-nsec) and the narrow (6-nsec) regions appear linear, with a standard deviation of a few tenths of a nanosecond. Both however, have structures that can be attributed to the variations in pulse amplitudes used during calibration.

Regression analyses using two independent variables-pulse height and amplitude (pulse area divided by pulse width)-yield improvements by as much as a factor of 2 to the fit for the narrow-pulse case. Some examples are shown in Table 1, where B and C are the coefficients of the independent variables, width and amplitude, respectively. The standard deviations have been reduced to 0.2 nsec or less, and variations in the coefficients are typically 10%. The slopes B and C of the curves are ultimately the critical parameters. The constant A is included in an overall constant term for the system delay, determined on a pass-by-pass basis through target calibration. Typical variations in pulse width (in digitized units) are of the order of 10, and those in amplitude of the order of 0.05. The calibrations show the system to be relatively stable, with small daily changes in slopes contributing uncertainties of about 0.1 nsec or less in each component. The two-parameter fit also provides some improvement in the wide-pulse case; however, it has not been implemented operationally, because other error sources dominate in this mode (see Section 4).

3.2 Extended Target Calibration

Target calibration is used extensively in the SAO operating procedures to measure system delay and to verify system stability. In fact, approximately half the pulses fired by the SAO lasers are in support of calibration.

Detailed target calibrations over the full dynamic range of the system (one to several thousand photoelectrons) have shown that the system calibration is dependent on return-signal strength. A typical example based on 2000 laser measurements is presented in Figure 3. Runs consistently show an increase of a few nanoseconds in the calibration constant at high signal levels. In fixed-threshold detection systems, the signal-strength dependence, which is the result of leading-edge "walk," could amount to range deviations as large as the 25-nsec pulse width.

The dependence at high signal strengths appears to be from saturation effects within the photomultiplier. The structure at low signal strengths, if real, may be caused by the triggering circuits within the stop channel.

Once system stability has been verified, extended target calibrations are taken weekly. For data processing, SAO is currently using a piecewise linear model for system calibration. The model, based on the data in Figure 3, assumes a constant system delay for signal strengths up to about 400 photoelectrons and then a straight-line fit to the data above that value. More detailed analysis on the calibration data is underway.

3.3 Prepass and Postpass Target Calibrations

In addition to the signal-strength dependence, changes in system configuration from time to time will shift the system calibration curve up and down. A change in cables, components, subsystems, and even subsystem calibration can have a very dramatic effect on overall system calibration.

In satellite ranging operations, target calibrations of 25 pulses each are performed before and after each satellite pass. These precalibrations and postcalibrations, which are performed at a prescribed reference signal strength (about 100 photoelectrons), are submitted to processing along with the satellite range data. The system-calibration relation (determined by the extended target-calibration analysis) is normalized on a pass-by-pass basis from the mean value of the two calibration runs. The difference in the values of the precalibrations and postcalibrations is used to estimate an upper bound on the short-term system stability during a satellite pass; this difference is stored with the data for reference during analysis.

Data taken during the last six months at Mt. Hopkins show this calibration difference to have a standard deviation of about 1.0 nsec.

These data reflect measurement errors due to the 25-nsec pulse width and to the finite number of data points in each calibration measurement. The σ associated with individual pre- and post-target calibrations is typically of the same size. Hence, the precalibration and postcalibration differences are overestimations of system stability. With a narrower pulse, we expect to obtain better estimates of system stability.

4.0 SYSTEM PERFORMANCE

System performance has been examined through analysis of extended target calibration and satellite ranging data. Although the upgrading is at an interim stage because the pulse chopper has not yet been implemented, some system improvements have already had a very positive effect on the range data.

Ranging errors are introduced by the system from three sources: the laser transmitter, the detection system, and calibration. We will restrict this discussion to the ranging system hardware alone and leave other areas such as refraction, timing, and spacecraft retroreflector array characteristics for discussion elsewhere.

4.1 Laser Transmitter

In its present wide pulse operating mode, the laser transmitter may introduce range errors due to wavefront distortion. Experiments conducted at Mt. Hopkins showed that the wavefront had a structure amounting to several nanoseconds across the laser beam, and that the structure was impossible to forecast or model effectively through calibration techniques.

The wavefront effect results from the large number of transverse modes that are excited when the laser is pumped well above threshold. There are two manifestations of the moding. The first is a variation in intensity over the cross section of the laser beam. The second is a local variation in the emission time of the laser pulse. Both these effects can vary with time and operating conditions.

4.2 Detection System

The pulse processing system has already demonstrated that it significantly reduces both systematic and random ranging errors.

Target calibrations taken simultaneously with the new pulse processing system and the original fixed threshold system. show that bias errors can be reduced by an order of magnitude with pulse processing techniques.
The fixed threshold system shows excursions due to leading edge walk of 3 m (21 nsec) or more over the operating range of signal strengths. The pulse processing system, on the other hand, was able to operate at decimeter accuracies over most of this region.

Target calibrations have also been used to measure system noise without the influence of satellite geometry. The results for the pulse processing system shown in Figure 8, are typical. The ranging error per observation goes from 10 nsec at the single-electron level to a value of about 1 nsec at 1000 electrons. For a single electron, the error is consistent with the standard deviation of a 25-nsec pulse. At the high signal level, however, the error is probably due in part to jitter and quantization in the photoreceiver, and to the finite sampling interval used in the pulse detection system. For the wide pulse width operation the sampling channels in the waveform digitizer are 10 nsec apart.

The improvement in system noise can also be seen from satellite range data taken simultaneously with the threshold and pulse processing systems. In these tests, data were taken with each technique and processed separately. Short arc fits were made through each set of data and range residuals were computed. Some results are shown in Figure 4. In general, noise levels are improved by a factor of two to three with pulse processing.

4.3 Calibration

Ranging errors are introduced into the data through uncertainties in the system calibration characteristics and through calibration normalization.

The extended target ranging data that are used to develop the system calibration characteristic show system delay variations over much of the range in signal strength (see Figure 3). It is not clear if all this structure is real, nor has a fully satisfactory explanation for the structure been found. Rather than fitting a potentially ficticious curve to the data, we use the piecewise linear model (discussed in Section 3.2), which seems more plausible physically. In recognition of variations in the data, however, we ascribe an uncertainty to the calibration characteristic of 1.0 nsec, Calibration normalization is developed on a pass-by-pass basis through pre- and post-target calibrations (see Section 3.3). The error introduced by this procedure is constant per pass and can be estimated by the observed σ = 1.0 nsec for the pre- and post calibration differences. This value also includes any system drift that occurs during the measurement period.

Some ranging uncertainties are also introduced by the calibration of the start channel. However, these are only about 0.2 - 0.4 nsec (see Section 3.1).

4.4 System Accuracy

Each of the major sources of error, the wavefront distortion, photoreceiver and detection system, calibration characteristics, and calibration normalization, introduces a range error of about 1 nsec at high signal strengths. At lower signal levels, the larger errors due to photon quantization introduced by the photoreceiver and the detection system are random, and averaging over a satellite pass should reduce their influence to the 1-nsec error found at high signal strengths. Since these are uncorrelated the total system accuracy is about 2 nsec. The implementation of the pulse chopper is expected to reduce uncertainties in all four areas. The chopper will regulate the final emission times for all the laser modes and should therefore, alleviate most of, if not all, the wavefront problem, The duction in pulse width will decrease the random range error due to photoquantization, particularly at low and intermediate signal strengths. It will also permit finer sampling channel spacing to be used with the waveform digitizer, which should improve system noise in the high signal strength region. For similar reasons, the narrow pulse operation should reduce the error in calibration normalization and should give better definition of the calibration characteristic from detailed target ranging.

Table 1. Start calibration (narrow-pulse region).

Date	Single-Parameter Fit A	B (width)	σ (nsec)	Two-Parameter Fit A	B (width)	C (amplitude)	σ (nsec)
4/16/75	23.35	0.106	0.325	22.04	0.089	2.02	0.164
4/17/75	23.25	0.107	0.323	22.00	0.09	1.93	0.172
4/21/75	22.79	0.116	0.315	21.54	0.092	2.07	0.197
4/22/75	23.33	0.103	0.375	21.65	0.084	2.49	0.205
4/23/75	23.33	0.101	0.367	21.70	0.087	2.35	0.193
4/24/75	22.81	0.115	0.326	21.60	0.096	2.02	0.190
4/25/75	23.11	0.107	0.374	21.54	0.088	2.42	0.198
4/30/75	23.38	0.102	0.364	21.84	0.083	2.40	0.181
5/01/75	23.62	0.099	0.367	22.18	0.082	2.20	0.205
5/05/75	22.92	0.114	0.339	21.79	0.091	2.07	0.214
5/06/75	22.97	0.117	0.314	21.83	0.094	2.07	0.172
5/08/75	22.89	0.117	0.336	21.69	0.097	2.00	0.205
5/12/75	23.28	0.113	0.294	22.18	0.090	1.98	0.172
5/15/75	23.00	0.116	0.322	21.91	0.096	1.89	0.194

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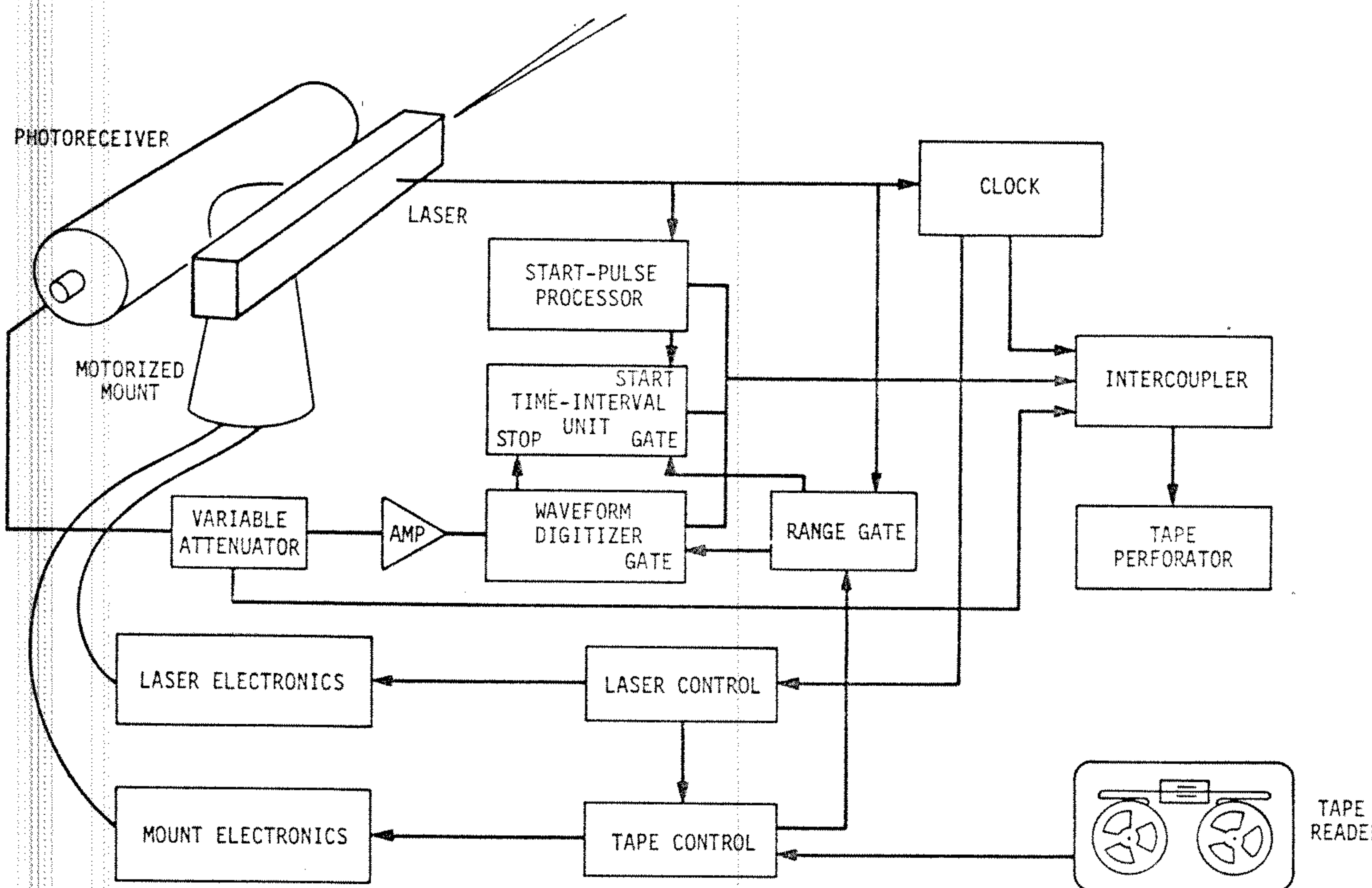

Figure 1. Block diagram of the laser system.

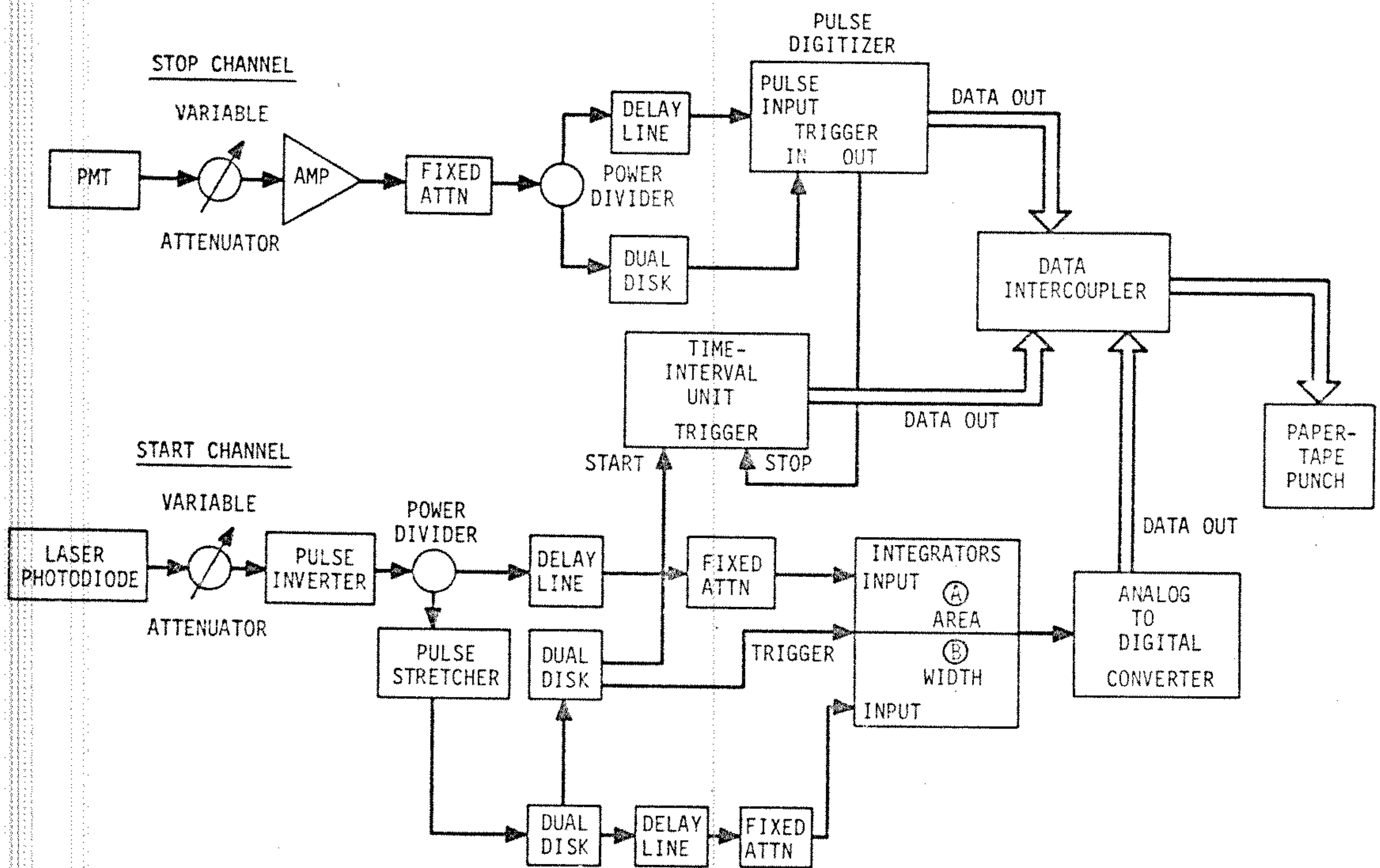

Figure 2. Pulse-processing system.

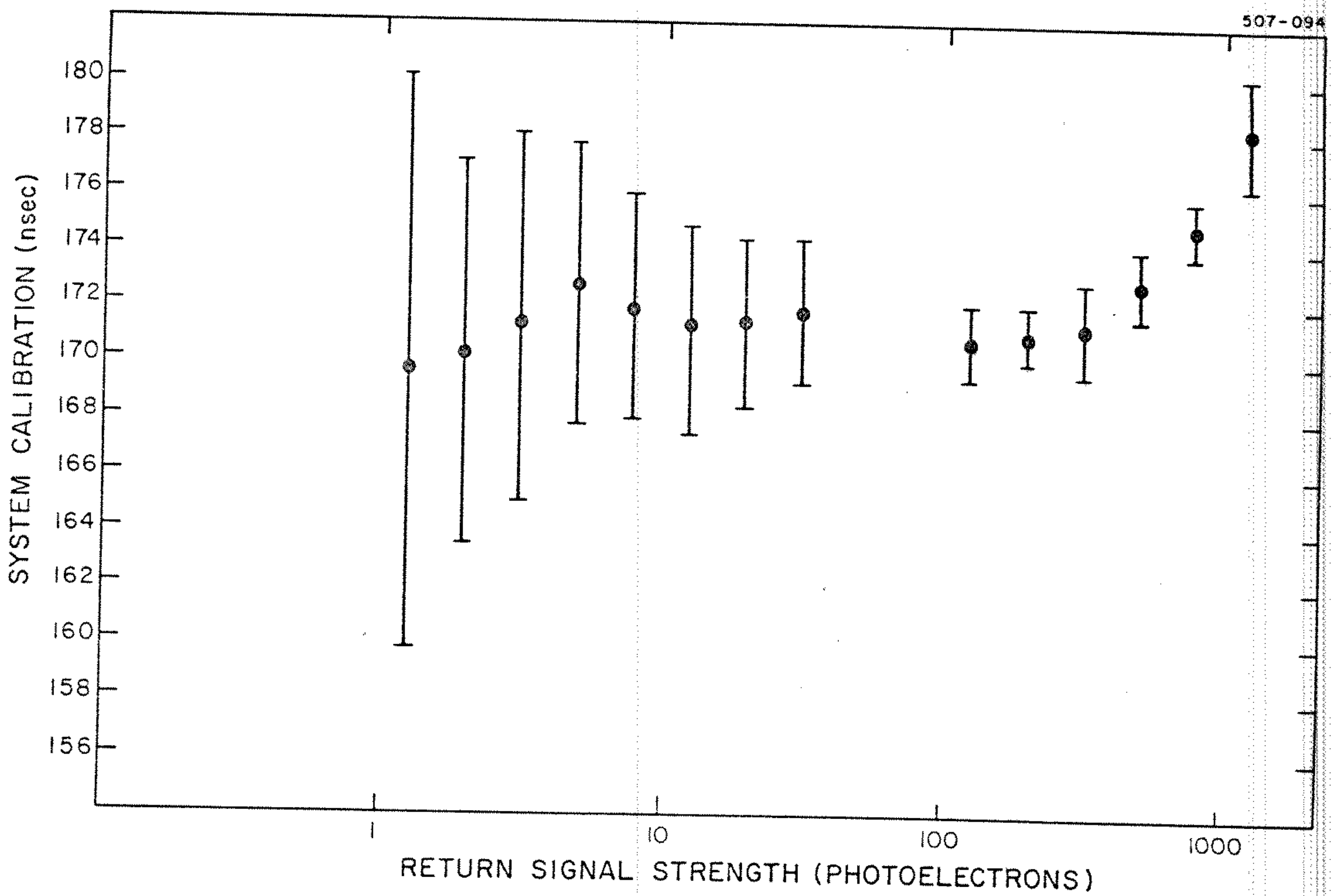

Figure 3. Detailed system calibration at Mt. Hopkins, April 18, 1975. Error bars denote the standard deviation of all the data in the signal-strength interval. A log signal strength of about 3.0 is equivalent to 1 photoelectron.

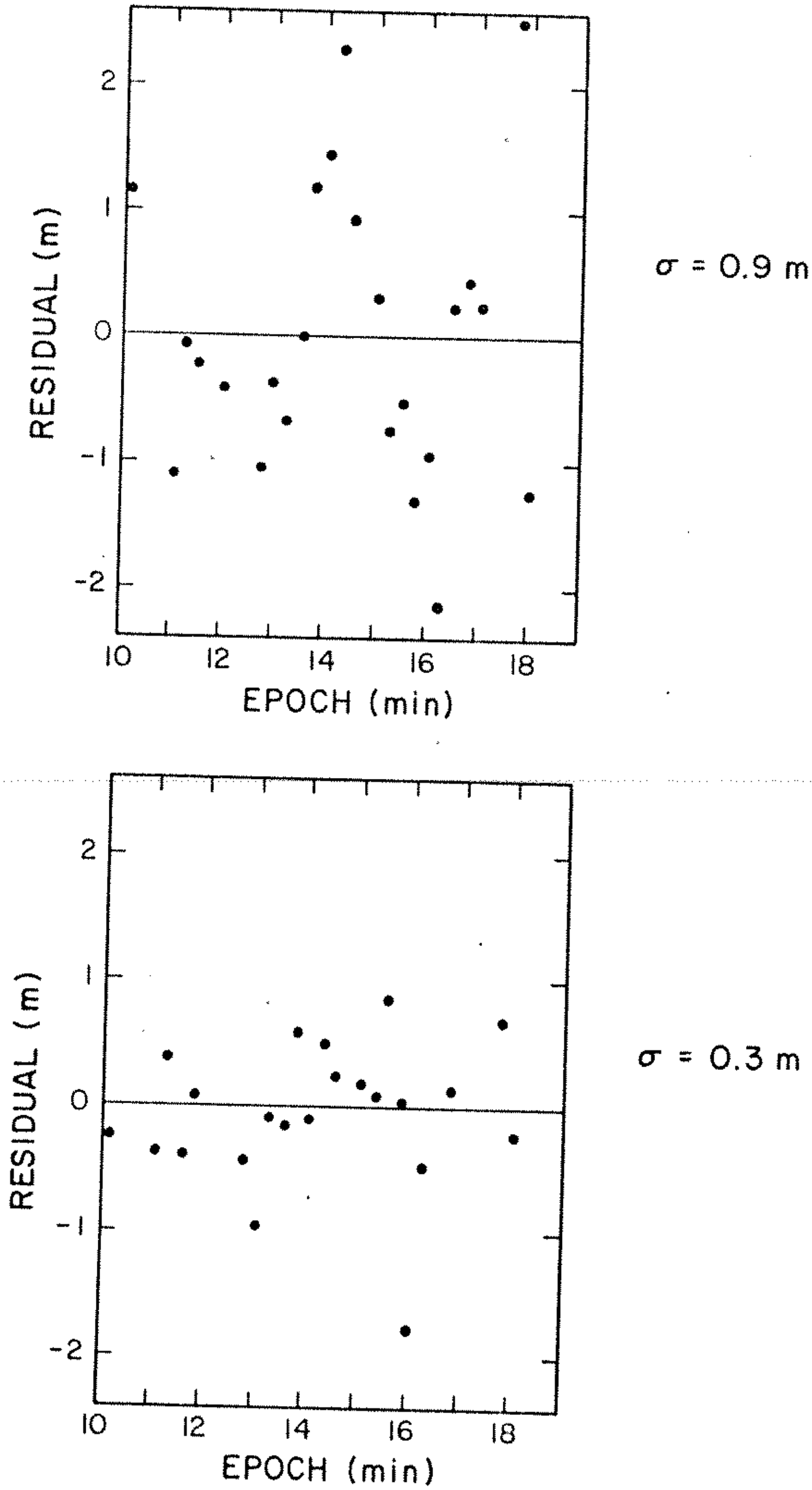

Figure 4. Range residuals to a short arc orbital fit on Beacon-C (30 Nov. 1974, 11^h10^m UT).

SATELLITE LASER RANGING WORK AT THE GODDARD SPACE FLIGHT CENTER

Thomas E. McGunigal, Walter J. Carrion, Louis O. Caudill, Charles R. Grant, Thomas S. Johnson, Don A. Premo, Paul L. Spadin and George C. Winston
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INTRODUCTION

The feasibility of using pulsed lasers to range to artificial earth satellites was first demonstrated by the Goddard Space Flight Center in 1964 when laser returns from the BEACON Explorer Satellite were observed.[1] Since that time, nearly a dozen retroreflector equipped satellites have been launched and tracked with ever increasing precision. The system accuracy has improved from the several meter level of the first systems to better than 10 cm in regular satellite tracking operations. The ranging data has been used for precise satellite orbit determination,[2] for determining polar motion,[3] earth tidal parameters,[4] for measuring with great precision the distance between laser sites[5] and for calibration of spaceborne radar altimeters.[6] The purpose of this paper is to describe the systems presently being operated by the Goddard Space Flight Center, their range and accuracy capabilities, and planned improvements for future systems. In short, GSFC is currently operating one fixed and two mobile laser ranging systems. They have demonstrated better than 10 cm accuracy both on a carefully surveyed ground range and in regular satellite ranging operations. They are capable of ranging to all currently launched retroreflector equipped satellites with the exception of Timation III. A third mobile system is currently nearing completion which will be accurate to better than 5 cm and will be capable of ranging to distant satellites such as Timation III and the soon to be launched LAGEOS.

SYSTEM DESCRIPTION

Very simply stated, a pulsed laser ranging system determines the range to a target by measuring the time of flight of a short pulse of intense light to the target and back. The time of flight is then multiplied by the velocity of light to give the range to the target. The block diagram of the systems currently in use by the Goddard Space Flight Center is shown in Figure 1. A precision timing system produces a pulse once each second which initiates the firing of the laser transmitter. A small sample of the transmitted energy is detected by a photodiode. The output pulse from the photodiode is used to trigger a fixed threshold discriminator which starts the range time interval unit. Similarly, the return pulse from the target is detected by a photomultiplier tube which also triggers a fixed threshold discriminator stopping the range time interval unit. Because the precise time of starting and stopping the range time interval unit is a function of the amplitude and shape of the leading edge of the transmitted and received pulses, small corrections to the gross range word are made by sampling and recording the exact shape and amplitude of the transmitted and received pulses using the waveform digitizers. Thus the center of the transmitted and received pulses is used as the reference point on the pulse. The beginning of the sweep of the appropriate waveform digitizer is controlled by the same pulse which starts or stops the range time interval unit. The epoch time interval unit is used to record the value of the variable time delay between the occurrence of the 1 pps signal from the time standard and the actual firing of the laser. The computer performs the dual role of calculating the azimuth and elevation signals required to drive the telescope mount and of formatting and recording the ranging data for each range observation. Actual preprocessing or reduction of the data is then performed at a central computing facility at Goddard after the data records have been transmitted (usually by mail) from the remote sites. Each site does have the capability of performing a "quick-look" analysis and editing of the data for rapid transmission by teletype to GSFC, however the accuracy of this "quick-look" data is not of the same quality as the final preprocessed data.

MAJOR SUBSYSTEM DESCRIPTION

1. Laser Subsystem

The laser transmitter is perhaps the most important single element of a pulsed laser ranging system. The Goddard systems use a ruby laser which was designed and manufactured by Korad, a division of Hadron, Inc. The lasers have a pulsewidth at the half maximum points of 4 nanoseconds. They operate at a repetition rate of one pulse per second with an energy of 0.25 joules per pulse. In order to achieve this relatively narrow pulsewidth, the lasers are operated in a Q-switched, cavity dump or pulse transmission mode. See Figure 2. In this mode of operation the laser is electro-optically Q-switched after the lamp is flashed by using a Pockel's cell/polarizer combination arranged so that no energy is coupled out of the cavity. When the energy in the cavity has reached a maximum value, the voltage on the Pockel's cell is removed, and the stored energy is entirely

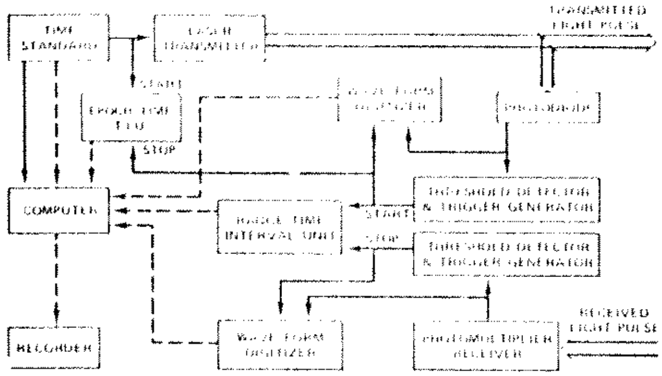

Fig. 1. Laser Ranging System

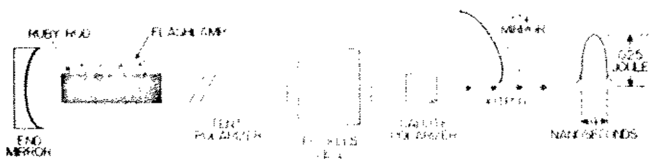

Fig. 2. Cavity Dump Pulsed Ruby Laser

coupled out or "dumped" from the cavity within a four nanosecond period. Thus, the four nanosecond pulse is produced. The advantage of using the cavity dump technique in the ranging application appears to be two-fold. The first and most obvious advantage produced by this technique is that the shorter pulse permits higher resolution in determining the time of flight of the pulse to the target and back. Perhaps the more important advantage, however, is that all of the multiple transverse modes of oscillation which occur in a high energy laser of this type are synchronized by the operation of the cavity dump Pockel's cell to leave the system at the same instant of time. The extreme importance of the synchronizing effect arises from the fact that each oscillatory mode has a slightly different radiation pattern from the laser rod. Thus at any point in the far field of the laser transmitter radiation pattern, a unique ensemble of modes exists which is a superposition of the slightly different radiation patterns of each oscillatory mode. In the ranging application, this is no problem if all of the modes started at precisely the same time. However, if the modes do not start at precisely the same time, then the measured time of flight to a target will vary depending on where that target is located in the overall radiation pattern of the laser. The importance of this effect in precision laser ranging systems is perhaps best understood by reviewing the evolution of the various laser systems used by GSFC in achieving the present system accuracy of better than 10 cm. Initially, it was felt that our accuracy goal of 10 cm could be met by using a conventional Q-switched laser with a pulse-width of nominally 20 nanoseconds in combination wit an improved receiver which used the centroid detection technique.[7] However, although the precision of the system improved, the results of satellite tracking tests with two collocated systems were disappointing. We discovered in ranging to a small corner cube on a carefully surveyed ground range that bias errors as large as one meter could be produced by the systems depending upon where the target was located in the transmitter radiation pattern. This problem was solved on an interim basis by installing a commercial available electro/optical shutter produced by Apollo Lasers, Inc. following our 20 nanosecond Q-switched laser. The electro/optical shutter was adjusted to take a slice of the wider laser pulse when it reached a maximum value and it therefore produced a shorter pulse of approximately 5 nanosecond. It also produce the desirable effect of synchronizing the multiple tran verse modes to leave the laser/shutter combination a the same instant of time. After the installation of the electro/optical shutter no angle dependent biases wer measurable, and the system precision was also improved. Because of the rather low energy output of the narrower pulse and a rather cumbersome operational layout, we have now installed the cavity dump lasers described above in all of our systems.

2. Optical/Mechanical Subsystem

The role of the transmitter portion of the optical/ mechanical subsystem is to collimate the output of the laser and to point the collimated beam at the satellite being tracked. The receiving telescope collects the energy reflected from the satellite and focuses it onto the cathode of a photomultiplier tube.

The transmit optical system employs a coelostat type of arrangement for pointing the transmitted bean This arrangement of two fixed and two movable flat mirrors then permits the laser to be mounted in a fix position with rigid connections to the laser cooling system and power supplies. Two collimators are use to narrow the beam divergence of the laser from 4 milliradians to the desired 0.2 milliradians. A four power Galilean collimator is fixed in position at the output of the laser. This collimator expands the spot size from 3/8 inch to 1.5 inches lowering the energy density to which the coelostat mirrors are exposed. The last movable mirror of the coelostat is followed by a five power Galilean collimator which moves with the receiver telescope. The use of this collimator after the moving mirrors diminishes by a factor of five the alignment precision required of the coelostat.

The receiver telescope used is approximately twenty inches in diameter and uses a Cassagrain

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mirror arrangement with the photomultiplier tube mounted at the prime focus at the rear of the primary mirror. In the ranging application the telescope serves merely as a photon bucket so that diffraction limited optical quality is not necessary.

The mount for the transmit and receive telescopes in the fixed station at GSFC is a special X-Y mount while the mobile systems use extensively modified NIKE-AJAX Az-El mounts. Twenty-two bit inductosyn type encoders are used in conjunction with both types of mounts. After the mounts have been aligned in the conventional way, final calibration is performed by recording the error in position of a series of approximately fifty well distributed stars. These errors are then used in developing an error model for the mounts which is retained in the memory of the digital computer. Using this technique, better than five arc second absolute pointing can be achieved.

3. Receiver Subsystem

The purpose of the receiver subsystem is to detect the light pulses from the laser transmitter and receiver telescope, and to measure precisely the time of flight of the light pulse to the target and back. The main elements of the receiver subsystem are the photodiode for detecting the transmitted pulse, the photomultiplier tube for detecting the much weaker received pulse, two fixed threshold pulse height discriminators, two waveform digitizers and finally a time interval unit. See Figure 1.

There are no special requirements on the photodiode and any of a number of standard units will suffice. The photomultiplier used in the Goddard systems is an Amperex 56TVP. Although this is an old design, it combines a number of characteristics useful in the ranging application. It has high gain, high output current capability, it can be readily range gated to control average background, it has relatively good transit time stability, and it is rugged and low in cost.

The output of both the photodiode and photomultiplier tube is power divided with part of the signal being used to trigger a fixed threshold discriminator. This discriminator then produces a noise-free step-function output which starts or stops the time interval unit and also starts the sweep of the appropriate waveform digitizer. The second half of the output of the photodiode or photomultiplier, after an appropriate delay, is then sampled by the waveform digitizer and recorded permitting an analysis of the exact shape and amplitude of the pulse. This information about the exact shape and amplitude of the pulse will then be used to make small corrections to the gross range information measured by the time interval unit. The time interval unit is a commercially available computing counter (HP Model 5360A) with 0.1 nanosecond resolution. The time base for the time interval unit is supplied externally by the cesium beam frequency standard which is part of the timing subsystem.

4. Computer/Software Subsystem

With one exception the ranging systems use Honeywell H-516 computers. A Raytheon R520 was used in one system due to equipment availability at the time the systems were built. The significant unique features of the R520 are that it has a 24-bit word length and 8 K of memory, otherwise the hardware and software are functionally similar to those of the H-516 systems. This description will be specifically that of the H-516 systems.

Computer Hardware. The computer hardware is indicated in Figure 3. The H-516 has a 16-bit word length, 16 K of core memory and a 0.96 microsecond memory cycle time. It is equipped with high speed arithmetic, realtime clock and priority interrupt options. Software timing is controlled by a one per second interrupt and for lesser time intervals by a realtime clock interrupt based upon a 10 kHz signal from the time standard.

The digital interface multiplexes up to thirty-two 16-bit input words and thirty-two 16-bit output words to the input/output bus. Console displays and controls consist of discrete pushbuttons and lamps, thumbwheel decimal-digit switches as well as a CRT data display and input keyboard. Also input via the digital interface are the time-of-year, the mount pointing angles (encoders), digitized samples of the transmitted and received laser pulses and various measurement and

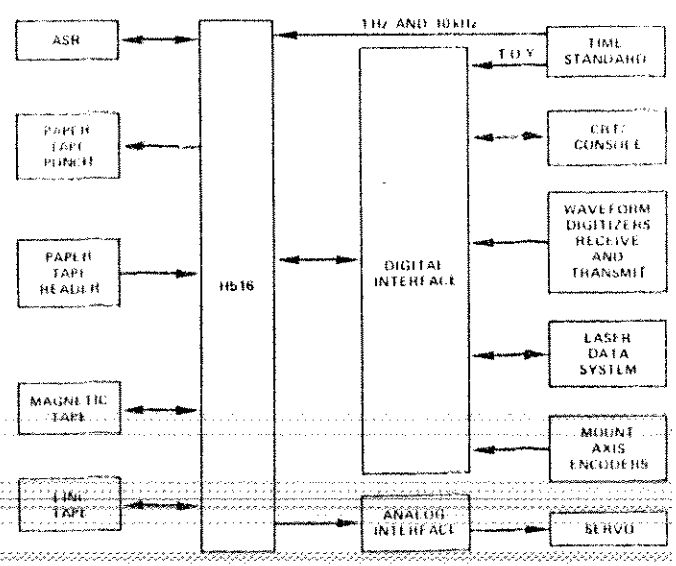

Fig. 3. Computer Hardware System

status data from the laser data system. Predicted range is output to the laser data system. Mount drive signals are output via an analog interface. A teletypewriter is used for non-realtime system initialization, diagnostics and software system generation as are a paper tape punch and paper tape reader. An industry compatible magnetic tape, a file addressable magnetic tape and 8K of the computer memory are recent hardware additions intended to increase system capability and improve the operation.

Software. The present software system is paper tape based both for application programs and for data recording. It requires 8K of computer memory. The additional memory and magnetic tape hardware mentioned earlier will, when software modifications are complete, allow the addition of many useful features and will provide a more desirable data media.

The software system consists of a number of stand alone programs each designed to perform a specific function as described below.

a. Telescope Initialization Program (TIP). Orbit prediction data is received from GSFC by teletype in the form of three dimensional, short-arc, polynomial fits to the predicted orbit. TIP reads the teletype paper tapes for the various satellites and merges and sorts the passes chronologically for a week's operation. A daily operating schedule is typed on the teletypewriter giving all passes to be tracked. Also, prepass computations are performed and an array of initialization and prediction data for each pass is written on tape. This tape is read by the realtime tracking program, TOP, and reduces the set-up operations necessary prior to each pass.

b. Telescope Operating Program (TOP). TOP is the realtime system control program. After once reading the initialization data tape TOP generates the telescope pointing command angles (AZ-EL or X-Y), computes the servo drive signals and the predicted satellite range, interfaces with the operator via the control console and with the hardware system via the analog and digital interfaces and records measurement and status data on tape, all in realtime throughout the tracking operation. Functions having to do with pointing angle computation, operator interface, and data collection and recording are performed at a one-per-second rate. Pointing angle interpolation and mount servo control functions are performed at a 50 millisecond interval synchronized to the one-per-second rate by signals from the time standard.

c. Star Operating Program (SOP). It is usually not cost effective nor practically feasible to build transportable, field operated telescopes and tracking mounts with the maintainable pointing accuracy required in narrow beam laser ranging systems. Systematic errors in the opto-mechanical system can be greatly reduced by a calibration process based upon star observations. SOP is functionally similar to TOP except that it points the telescope to the computer positions of a set of stars scattered throughout the hemisphere and records the pointing error at each star. These data are then processed in non-realtime to determine the coefficients of a mathematical model of the pointing errors. The resulting error model is evaluated in realtime in TOP to transform the shaft angle encoder readings to telescope optical axis angles.

d. A number of supporting programs have been written for hardware testing, software system generation, and for various system development and verification purposes.

5. Timing Subsystem

In order to make optimum use of the highly accurate laser ranging data, it is necessary to time tag the data from the laser stations very accurately. In applications where the data from two or more stations will be merged to determine baselines, polar motion, etc., it is necessary that the clocks at the several stations be synchronized to better than 5 microseconds. Although it is not normally necessary to synchronize this precisely to UTC, the primary time standard maintained in the U.S. by the U.S. Naval Observatory, as a practical matter most of the intercomparison techniques used will accomplish this as well.

The timing system used at the laser ranging system employs a cesium beam frequency standard as the primary frequency reference. Depending upon the geographic location of the station a variety of techniques are used to set clocks initially and to maintain the required synchronization. The systems are equipped with LORAN-C and VLF receivers and we have used portable atomic clocks where necessary to perform this function.

6. Laser Data Preprocessing

After the laser ranging station has completed a satellite pass, the recorded data is sent to the Goddard Space Flight Center for preprocessing. This is the process by which raw laser ranging data is analyzed, edited, reformatted and made available to the community of users. The basic steps in this process include:

a. applying calibration corrections derived from the prepass and postpass calibration over a known path.

b. applying atmospheric corrections.

c. applying corrections determined by an analysis of the waveform digitizer values.

d. editing of the data to discard obviously invalid points.

e. fitting a short arc orbit to the remaining data.

f. discarding points with errors larger than 3 standard deviations and finally,

g. outputting the data in the desired format to users.

Figure 4 is a plot of the data for a typical satellite pass after it has been preprocessed following the steps outlined above.

In addition to the ranging data, angle data is also made available to the users. The angle measurements are simply the corrected outputs of the precision angle encoders for those observations when returns were received from the satellite, therefore their accuracy is only approximately one half of the transmitted beam divergence or 0.1 milliradians.

OPERATIONAL CONSIDERATIONS

1. Present Operational Systems

At the present time GSFC has three operational laser ranging systems:

Systems	Location
Stalas	GSFC
Moblas 1	Bermuda
Moblas 2	Grand Turk Island

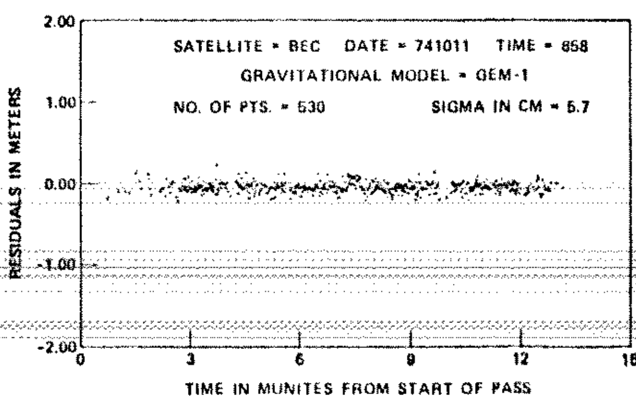

Fig. 4. Stalas Range Residuals Vs. Time

The Moblas 2 laser ranging system is illustrated pictorially in Figure 5.

A third laser ranging system (Moblas 3) is nearing completion and is scheduled to be ready for operation early in 1976. In addition, the Air Force Easte[rn] Test Range is assembling a laser ranging system at the Patrick Air Force Base in Florida. The system, which will be called RAMLAS, will support GEOS-C and other NASA programs starting in August 1975.

2. Mobile Station Layout

A typical mobile laser site requires a fenced are[a] approximately 200 feet square with a 25 foot by 50 foo[t] concrete pad for the laser van. A survey marker isolated from the concrete system pad is required for precisely locating the laser ranging system. Althoug[h] we also used isolated piers for supporting the laser mount in the past, experience has shown that they are not necessary and we do not plan to use them at future mobile sites.

Typically, five vans are required at a remote mobile laser site. These are:

1. Telescope and laser van
2. Electronics van
3. Radar van
4. Storage and shop van
5. Comfort van

If commercial power is not available, a power generating van is required in addition.

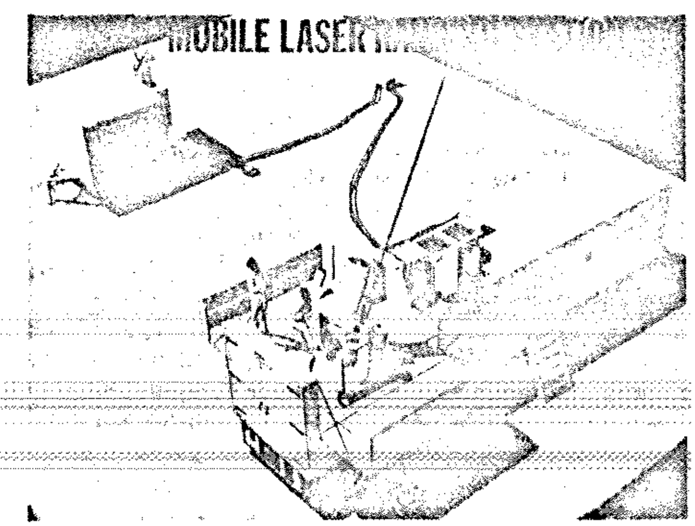

Fig. 5. Mobile Laser Ranging Station

3. Manpower Requirements

There are three operating positions that must be manned in order to take a satellite pass. These are the console operator, the mount operator and the radar operator. A surveillance radar is required to insure that no aircraft in the vicinity of the laser system intercepts the laser beam because of the possibility of eye damage to aircraft occupants.

A typical crew for conducting laser ranging operations on a regular basis is as follows:

1. Crew chief
2. Computer technician
3. Electronic technician
4. Optical/Mechanical technician
5. Radar technician

If more than 40 hours per week of operations are regularly scheduled, additional crew members are needed for efficient operation.

4. Transportability

Moblas 2 and Moblas 3 telescopes are trailer mounted and can be towed over the highway. The Moblas 1 telescope must be transported on a flat bed trailer. The electronics vans can be towed, but the radar and shop vans must be transported on flat bed trailers. The comfort van is normally rented locally and not moved from site to site.

Approximately one week is required to prepare a mobile laser ranging system for transportation to a new site, and about two weeks to set up, align, test and be ready to perform satellite ranging at the new site after arrival. Two weeks should be adequate for a move within the continental U.S. Therefore a minimum of five weeks is required after shut down at one site before ranging can be started at a new site.

PERFORMANCE AND RESULTS

1. System Accuracy

Laser ranging systems are neither primary nor secondary standards of length. Rather, they are instruments which are capable of measuring precisely the time of flight of a short pulse of light to a target and back. Of course, this time of flight is directly related to range when the system delays are known because the velocity of light in free space is known to about 5 parts in 10^8. Thus, the accuracy with which laser ranging systems can be used to measure the distance to a satellite is characterized by a number of factors. First, it is necessary to calibrate the system to a known standard of length to determine the fixed and dynamic (i.e., pulse height dependent) system delays. Second, the "noise" of the instrument or uncertainty in determining the true position of the pulses will limit system performance. Third, the drift or instability of the instrument must not be large compared to the "noise" level. Fourth, since an earth satellite is moving very rapidly, it is essential that the time at which each measurement is made be maintained very accurately. Fifth, since the velocity of light in the atmosphere is different from the free space velocity, atmospheric corrections must be applied. Finally, in a typical spacecraft using an array of corner cubes, the geometric center of the return pulse will be modified by the array.

The error budget for the GSFC systems is given in Table 1. A detailed discussion of each factor in the error budget follows.

Table 1

Laser Ranging Accuracy

	4 ns Laser
Calibration	1.7 cm
Pulse Position Measurement ($10/\sqrt{10}$)	3.3 cm
System Stability	4.0 cm
Clock Synchronization ($5\mu s$)	3.5 cm
Atmospheric Propagation	3.0 cm
S/C Array Geometry ($9/\sqrt{10}$)	2.9 cm
Total RSS	7.7 cm

a. Calibration. The laser ranging system calibration procedure is an end-to-end calibration against a secondary distance standard (Fig. 6). The distance from the laser mount axis to the calibration target is measured with a geodometer. The calibration procedure is to measure the time interval between the transmitted pulse and the received pulse while the signal is attenuated over the entire dynamic range expected on a satellite pass. Approximately 100 points of range data are obtained. Thus, the system is calibrated over a wide range of received pulse heights.

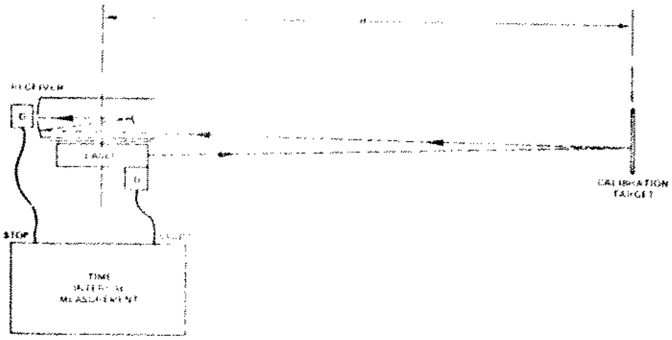

Fig. 6. Laser Ranging System Calibration

This calibration is performed before and after each satellite pass.

The calibration error sources are: the measured distance from the tracker axis to the calibration target, the atmospheric propagation correction, and the precision of the time interval measurement. The accuracy of the measured distance to the calibration target is ±1.5 cm, the accuracy of the atmospheric propagation correction is ±0.6 cm, and the accuracy of the time interval measurement for 100 data points with a measurement RMS of 5 cm is ±0.5 cm. The total calibration error in this case is 1.7 cm taking the root sum square of the various random errors.

b. Pulse Position Measurement. The simplest form of pulse position measurement is a fixed threshold trigger on the leading edge of the pulse. The disadvantage of this method is that the measured position is a function of pulse height and pulse shape.

A better form of pulse position measurement is a constant fraction discriminator on the leading edge of the pulse. This method has the advantage that the measured position is only weakly dependent on pulse height, but is still a function of pulse shape.

The pulse centroid (center of energy) is a better measure of pulse position since it is dependent upon all of the energy in the pulse, rather than upon details of the leading edge. This is the technique currently used in the GSFC systems. In tracking operations we typically achieve single point ranging uncertainties of better than 10 cm. In as much as no unmodeled orbital uncertainties can occur for intervals of less than 10 seconds the single shot uncertainty can be reduced by averaging ten consecutive range readings, thus $10/\sqrt{10} = 3.3$ cm is the uncertainty in determining the range for ten second periods.

c. System Stability. Since the laser systems are calibrated immediately before and after each spacecraft pass, the system must be stable for the duration of the pass if the calibration is to be meaningful. Furthermore, because of the multimode lasers used it is essential to check for angle dependent biases as well as time dependent drifts using small corner cubes which simulate a satellite return more realistically. The system stability of the GSFC systems is shown in Figure 7 for three different targets. The first target is a flat board which is normally used for calibration, and the other two targets are small corner cubes mounted on a pole and a water tank respectively. Figure 8 is a plot of range difference versus transmitter pointing angle. Both these plots confirm

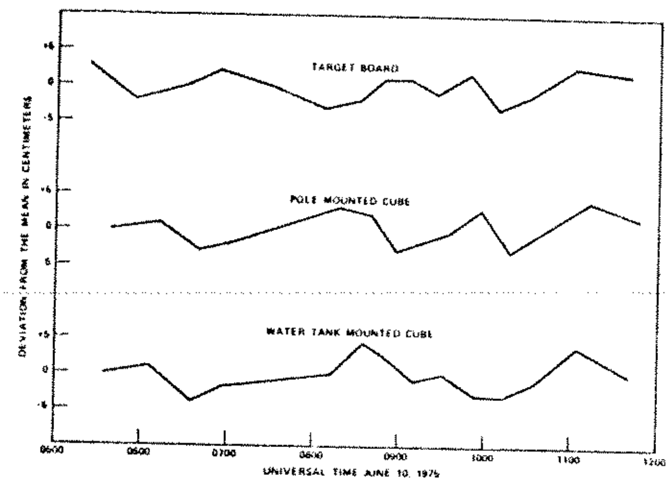

Fig. 7. Stability Test

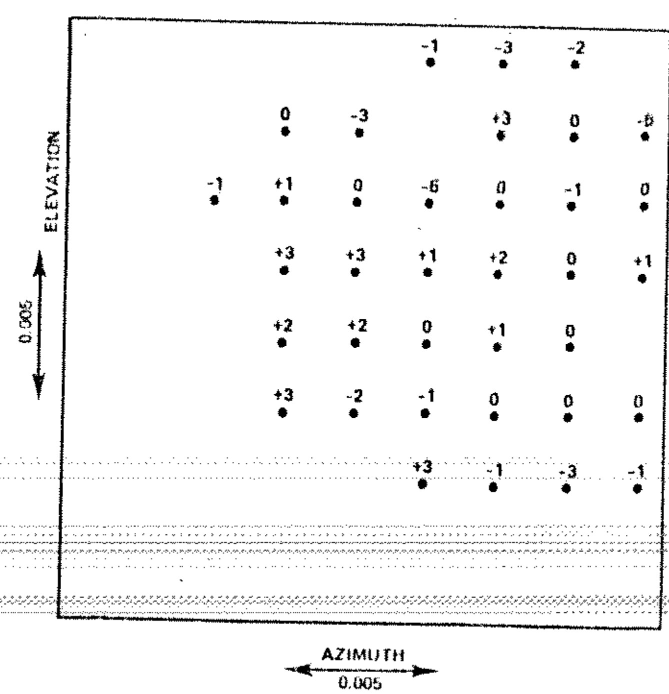

Fig. 8. Range Stability Vs. Pointing Angle

that the overall system stability is within the 4 cm value used in the error budget.

d. Clock Synchronization. The GSFC laser systems are equipped with Cesium standards and LORAN-C receivers. The requirement for time synchronization in the Atlantic calibration area is $\pm 5 \mu s$ between stations. This requirement arises from the fact that a satellite moving in a typical low orbit travels approximately 0.7 cm in one microsecond. Thus, if time is synchronized to within $\pm 5 \mu s$ between sites, the peak error in spacecraft position would be ± 3.5 cm.

e. Atmospheric Propagation Correction. Since the velocity of light is different in the atmosphere than in free space, the ranging data must be corrected for the atmospheric slowing. In general this is done by using an atmospheric model which relates surface pressure, temperature and relative humidity to the total range correction. The model used by the Goddard Space Flight Center was developed by John W. Marini and C. W. Murray, Jr.[8] This model was extensively checked against ray traces using radiosonde atmospheric data and the agreement between the model and the ray traces was better than 0.5 cm even at low elevation angles. Since this intercomparison neglected common mode errors and assumed atmospheric homogeniety, the absolute error is conservatively estimated to be less than 3.0 cm.

System Intercomparison Results. The final and perhaps most complete test of ranging system accuracy is to conduct actual satellite ranging operations with two or more collocated laser ranging systems. Short arc solutions are then made independently using the data from each ranging system. Biases between these two independently determined arcs are then computed. Figure 9 is a plot of the results of a series of intercomparisons of two collocated systems for three different system configurations. Each point on this plot is the result of a separate satellite track by two systems and the error bars represent the uncertainty in determining the bias for each short arc. In general, this uncertainty in determining the bias is dominated by the noise in the data from the individual ranging systems. The first series of 11 tracks were performed in 1971 using the first operational laser systems developed by GSFC.[9,10] These systems used leading edge detection with pulse height correction and the single point uncertainty in the data was typically 50 cm. The second series of 7 tracks were performed in the Fall of 1973 using systems which employed the centroid detection scheme described earlier but using the same lasers (i.e., 20 nanosecond, multimode Q-switched) as the earlier systems. Here, the precision was improved by the

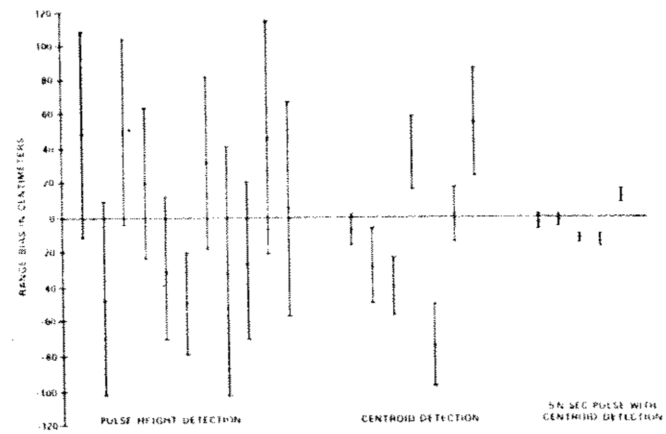

Fig. 9. Laser Ranging Two Station Intercomparison Results

new receiver technique, however, the system biases were approximately the same as the earlier systems. The final series of five tracks were made in late Spring of 1974 using the Moblas 1 and 2 systems with the same Q-switched laser, however, it was now followed by an electro-optical shutter. Here, both the improved precision and reduction in system bias is obvious.

2. System Range Capability

In addition to the accuracy capability of a system, an extremely important characteristic of a laser ranging system is its maximum range. Although it is possible to design systems to operate satisfactorily with less than a single photoelectron average return per shot as in the lunar ranging systems,[11,12] the Goddard systems are not designed to operate in this way. Rather, the centroid detection technique is designed to exploit the higher signal levels available in ranging to targets much closer to the earth. Typically, the threshold is set at a signal level of five photoelectrons per shot to achieve the system accuracy described above. The average number of photoelectrons to be expected for each laser shot can be computed from the well known basic radar equation

$$N = \frac{1}{2\pi} \eta \frac{E_T D_R^2 E_{ff}}{\theta_T^2 h\nu} \cdot \frac{\sigma \alpha_T}{R^4}$$

where:

η = Photomultiplier Tube Quantum Efficiency

E_T = Laser Energy

D_R = Diameter of the Receiving Telescope

E_{ff} = Overall System Efficiency

θ_T = Divergence to 1/e point of the transmitted beam

h = Planks constant

ν = Frequency of the laser radiation

σ = Radar cross section of the target

α_T = Two-way atmospheric transmission

R = Range to the target

The values of the fixed parameters for the GSFC systems are summarized in Table 2.

Table 2

Parameter	Value
η	2%
E_T	0.25 J
D_R	0.51 M
E_{ff}	0.15
θ_T	0.2 milliradians
ν	4.321×10^{14} Hz ($\lambda = 0.6943\,\mu m$)

Peter O. Minott of the Goddard Space Flight Center has calculated and in most cases measured, the cross section of a variety of retroreflector equipped satellites currently in orbit.[13] In the interest of completeness, we have included a summary of his results for the various satellites and the Lunar arrays in Table 3.

The right hand column of Table 3 is a tabulation of the radar cross section for each of the satellites divided by R^4 and is thus an indicator of relative ranging difficulty.

In summary, the present GSFC systems are quite adequate for conducting regular ranging operations to any of the lower satellites including STARLET which is the most difficult of that group. However, improvements will be needed in system capability to reliably range to LAGEOS or Timation.

3. Operational Summary

Upon the completion and testing of the Moblas 1 and Moblas 2 Laser Ranging Systems at the Goddard Optical Research Facility (GORF), they were moved to California for the San Andreas Fault Experiment (SAFE). Moblas 1 was operated at Quincy and Moblas 2 at Otay Mountain near San Diego.

During the period from August 27, 1974 to December 14, 1974 these two systems made range measurements to three retroreflector equipped satellites; GEOS-A, GEOS-B, and BE-C. During this

Table 3

Satellite	Orbital Altitude $M \times 10^6$	Cross Section $M^2 \times 10^6$	Cross Section/(Slant Range)^4	
			Zenith $M^2 \times 10^{-18}$	45° $M^2 \times 10^{-18}$
1. BE-B	1.13	4.60	2.92	0.918
2. BE-C	1.00	4.60	4.60	1.47
3. GEOS I (A)	1.95	57.2-0	3.96	0.026
4. GEOS II (B)	1.53	100-0	18.2	0.127
5. GEOS III (C)	0.93	3-30	4.01	10
6. LAGEOS	5.90	10.8	0.00891	0.00473
7. Lunar Arrays	360	400	2.38×10^{-8}	2.33×10^{-8}
8. STARLET	0.92	0.55	0.767	0.240
9. Timation III	14.0	103	0.00268	0.00183

operational period, the mobile system employed the laser electro-optical shutter configuration discussed earlier.

The stationary laser ranging system, Stalas, at GORF also participated in the SAFE program from October 7, 1974 to December 11, 1974 using the cavity dump laser system.

A summary of the performance of the three systems during the 1974 SAFE operation is as follows:

System	Total No. of Passes	Ave. Cal. Range Residual	Ave. Pass Range Residual	Ave. No. Hits Per Pass
Moblas 1	60	4.7 cm	11.6 cm	77
Moblas 2	141	6.1 cm	10.2 cm	159
Stalas	114	5.5 cm	6.7 cm	229

On several occasions during the 1974 SAFE operations, simultaneous ranging to the BE-C satellite by Moblas 2 in San Diego, Cal. and Stalas at Greenbelt, Md. was accomplished. This permitted an accurate determination of the baseline distance between the two sites.

After completing the 1974 SAFE measurements, the two mobile laser ranging systems were moved to the Atlantic Ocean area to support GEOS-C. Moblas 2 was moved first to Wallops Island, Virginia for a short collocation experiment with the Wallops Island laser ranging system and then to Grand Turk Island. Moblas 1 was moved to Bermuda. The Stalas system has also supported GEOS-C. Korad cavity dump laser systems were installed in Moblas 1 and 2 at the time of the move, replacing the laser/electro-optical shutter configuration.

GEOS-C was launched April 9, 1975 and laser ranging started on this satellite April 19, 1975. Five retroreflector equipped satellites have been tracked by the three laser ranging systems since that time with the highest priority given to GEOS-C. A summary of the laser ranging on these satellites from April 9, through June 25, 1975 is as follows:

Satellite	Moblas 1	Moblas 2	Stalas	Total
GEOS-C	11 passes	60 passes	68 passes	139
STARLET	1	16	32	49
BE-C	9	21	38	68
GEOS-A	3	20	24	47
GEOS-B	7	13	7	27
Totals	31	130	169	330

Preprocessed data on these passes is not available at this time, so the range residuals cannot be listed. Since Moblas 1 and 2 are now equipped with cavity dump lasers, it is expected that the range residuals for these two systems will be improved by nearly a factor of two.

FUTURE IMPROVEMENTS

The thrust of the continuing ground laser ranging technology development at GSFC is twofold: (1) to continue the development of technology which will improve both system accuracy and range capability and (2) to develop the technology of cost effective systems which may not represent the state-of-the-art in terms of accuracy but which meet the requirements of a broader class of users for reliable relatively low cost systems. In addition we are developing the technology necessary for performing laser ranging from spacecraft to ground and to other spacecraft for a host of future applications.

The most pressing requirement for immediate system improvements will come with the availability of NASA's LAGEOS satellite. This satellite will be a perfect sphere, 0.60 meters in diameter and equipped with 426 retroreflectors. It will be launched into a very stable circular orbit with an altitude of 5900 kilometers. The excellent geometry and high orbit of this satellite will require more accurate ground systems to take full advantage of potential applications and will require an improvement of approximately a factor of ten over present systems in range capability. The Moblas 3 system presently nearing completion will have an overall system accuracy of better than 5 cm and will incorporate the necessary improvement in range capability. The most important single change will involve the use of a frequency doubled Nd:YAG laser in place of the ruby lasers now being used. We are currently evaluating two candidate systems for the new laser transmitter. The first is an 0.2 nanosecond pulsewidth laser producing 0.25 J of energy at 0.53μ meters wavelength being built for NASA by GTE/Sylvania. The second candidate will be a 5 nanosecond pulsewidth laser not yet under contract. To realize the optimum potential of either of these lasers various receiver subsystem improvements will also be incorporated. Moblas 3 will then serve as the technical forerunner of a new series of laser ranging systems whose procurement is currently being contemplated by NASA for future network applications.

ACKNOWLEDGEMENTS

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INTERKOSMOS LASER RADAR NETWORK

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Using simultaneous photographic and laser satellite observations /1/, it is possible to determine with a great accuracy the lengths and directions of arcs thousands of kilometers long on the earth´s surface. The method of geodetical Arctica-Antarctica vector enables us to determine with the same accuracy the lengths and directions of arbitrary ground arcs up to the length of earth´s diameter.

The main reason to build the laser radar network /Fig. 1/ was to fullfil the requirements of the Arctica--Antarctica project and East-west vector and some other projects in geodesy and geophysics were considered.

The measurements have been covering úhotographing of artifical satellites and at selected places of this chords the laser ranging has been done.

The principal requirements were the accuracy ± 1,5 m, the transprotability and simple operation. To solve the problem quickly and efficiently, the international laser radar working group was found within the Interkosmos program. The technical project was made in 1971, one station a yaer was expected to build.

Since 1972 Laser Radar I /2/ /Fig. 2/, stationary version, was operating at Ondrejov /Czechoslovakia/. In 1975 this station was moved to Poznan /Poland/ and put to the operating condition in June 1975.

The Laser Radar II /Mobil container version/ was operating since March 1973 in Riga /Soviet Union/. In September 1974 this station has been operating at Helwan /Egypt/. The observatory was built within two days including alignment, preliminary calibration and first satellite tracking experiment. The station cooperated at Geos A, B campaign with 5300 measurements during September, October and November 1974 and at Geos C campaign for three months since May 1975. For overseas observing sites the aircraft transportable Laser Radar III was developed /Fig. 4/. The transportability was checked during the transport to Bolivia - the end station of East--West vector. The container is moduled, the size of modules is matched to commercial plane.

The block scheme of these radars is shown on fig. 2. The 4-axis mount /M/ /see also fig. 4/ is visually tracked. The analog control of the third axis is used. The 10 cm guiding telescope has 1 or 2 degrees field of view. The transmitter consists of the Q-switch ruby laser /L3, L4/, the power supply /L1/, the remote control /L2/ and the cooling system /L5/. The ruby rod of 1 cm diameter and 12 cm long and a linear flash lamp are placed in the ellipsoidal pumping cavity. Q-switching is accomplished by the rotating Brewster angle-Porro prism and the passive dicarbocyanine bleacher /3/. The output energy is 1 J, the pulse length 15 ± 2 nsec, repetition rate 60 shots/min. The solid state driver for the rotating prism motor allows ± 2 μsec synchronization according to UT. The beam divergence of the laser is 3 mrad and using the telescope could be reduced up to 0,5 mrad. Part of the transmitted light is detected /500 MHz bandwidth/ and starts the counter /D3/ and is connected with the chronograph /T2/. The receiving system consists of the 32 cm Cassegrain telescope /R1/, 20 Å interference filter /R3/ with 50% transmission and RCA 8852 photomultiplier /R4/ with 4% quantum efficiency. The received electrical pulse passing the adjustable gate /D1/, the amplifier and adaptive threshold circuit /D2/ stops the 5 nsec resolution counter /D3/. The timing system consists of the chronograph /T2/ connected with the time base /T1/. The outputs from the counter and the chronograph are printed /DT/.

Keeping very high efficiency of the scientific and technical work and taking in account considerably wide cooperation in both preparing and exploitation of the stations, each laser radar proceeds following steps: the completation at coordinator centre /takes approximatelly 14 days of common work of 5 - 8 experts of cooperating countries/, packing of station, transport building and calibration.

The training centre was built to traine the operators.

Advanced station

To increase the accuracy and universality the second generation of the laser radar has been considered. Four axis mount /4/ :Fig. 5/ allows simple visual tracking and the carefull design gives the possibility of automatic tracking either. The overall pointing accuracy within 1 mrad was achieved. The ruby laser exploiting two Pockells cells gives 2 nsec long pulses /Fig. 6/, the repetition rate may be increased up to 180 pulses/min. The range time interval unit is based on the expander technique /6/. The time resolution is better than 0,3 nsec. To allow measurements at very low signal level the range time interval unit has three stops. We plan to exploit an online computer generating ephemeris and controling two stepping motors in the third and forth axis. The computer will collect measurements within the calculated range gate.

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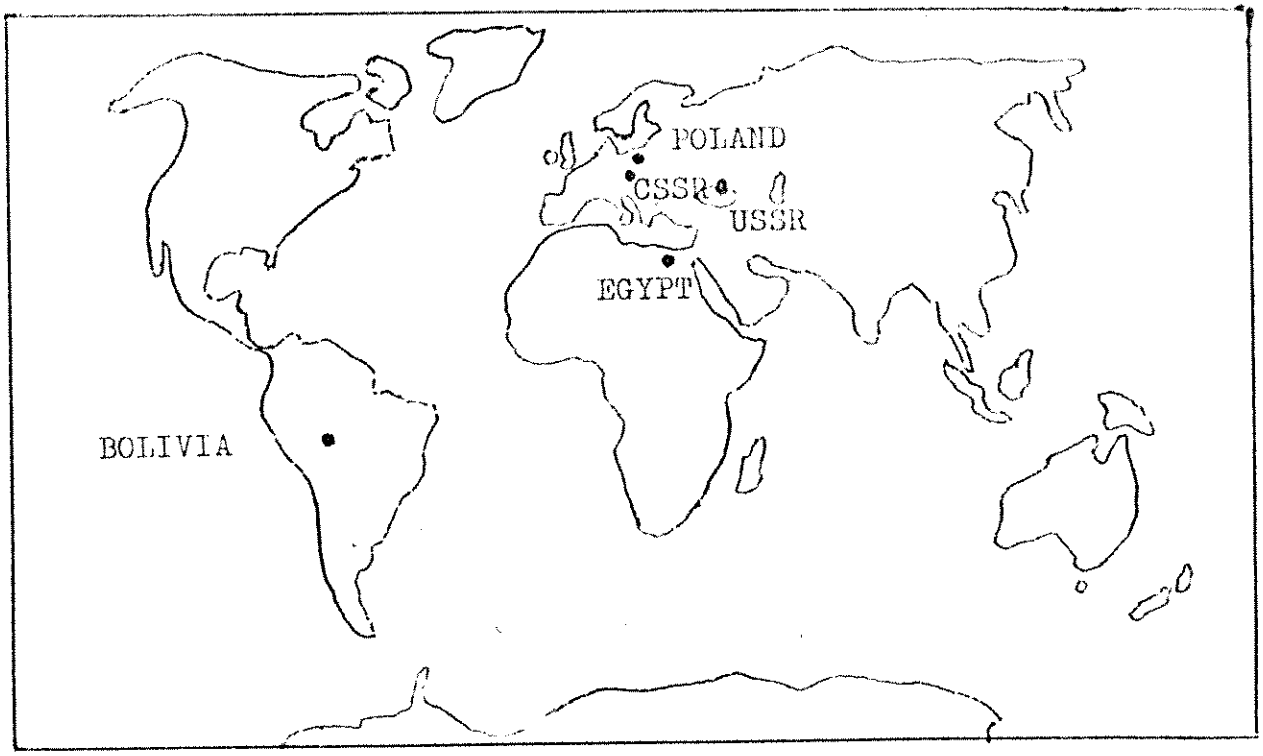

Fig. 1. INTERKOSMOS Laser Radar Network

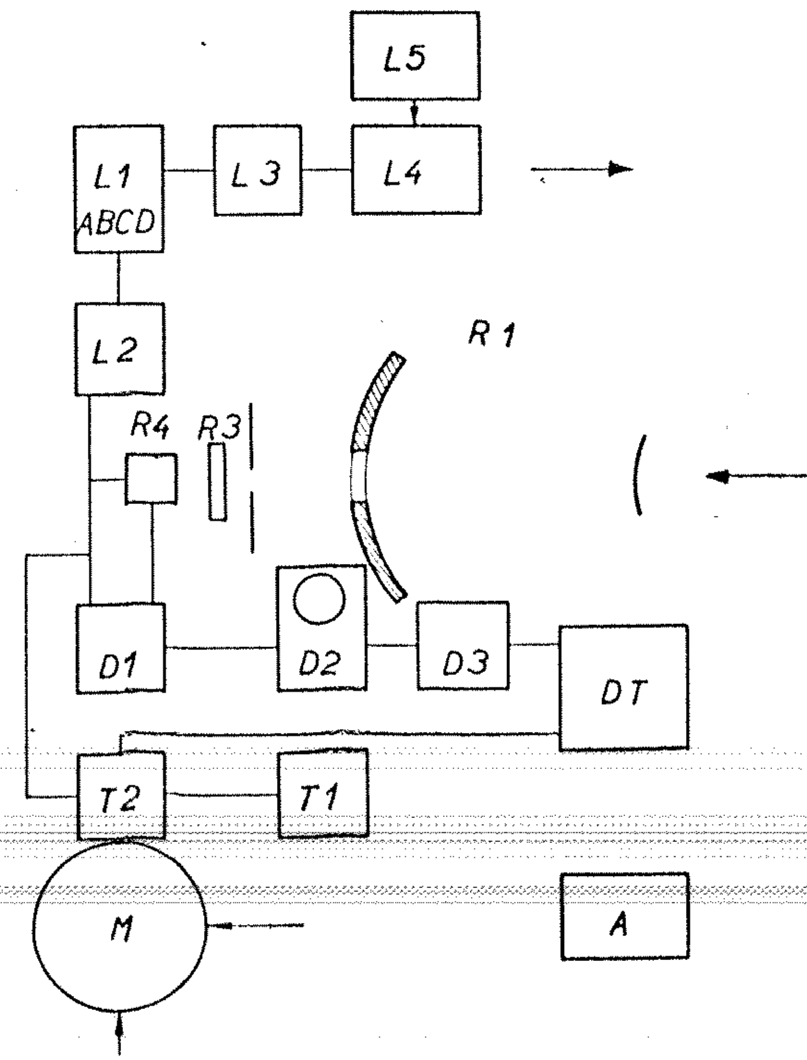

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Fig. 2. Laser radar block diagram

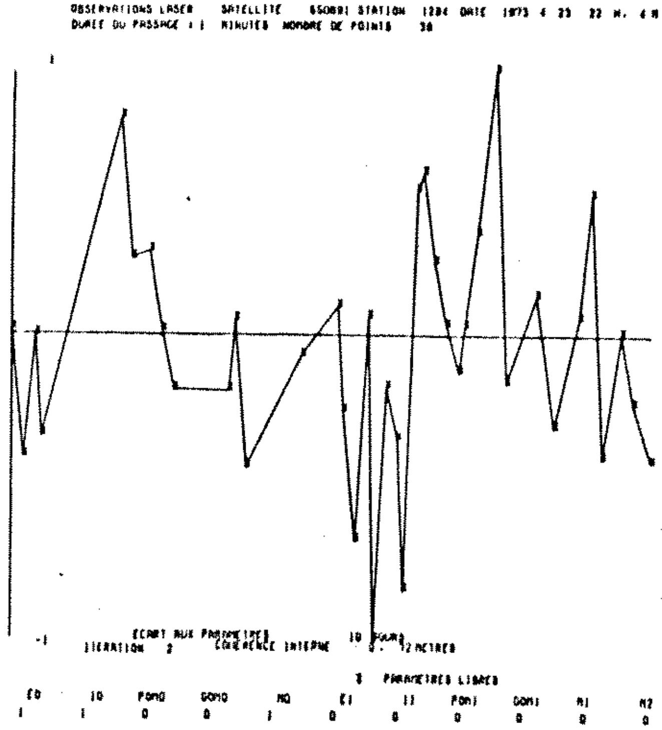
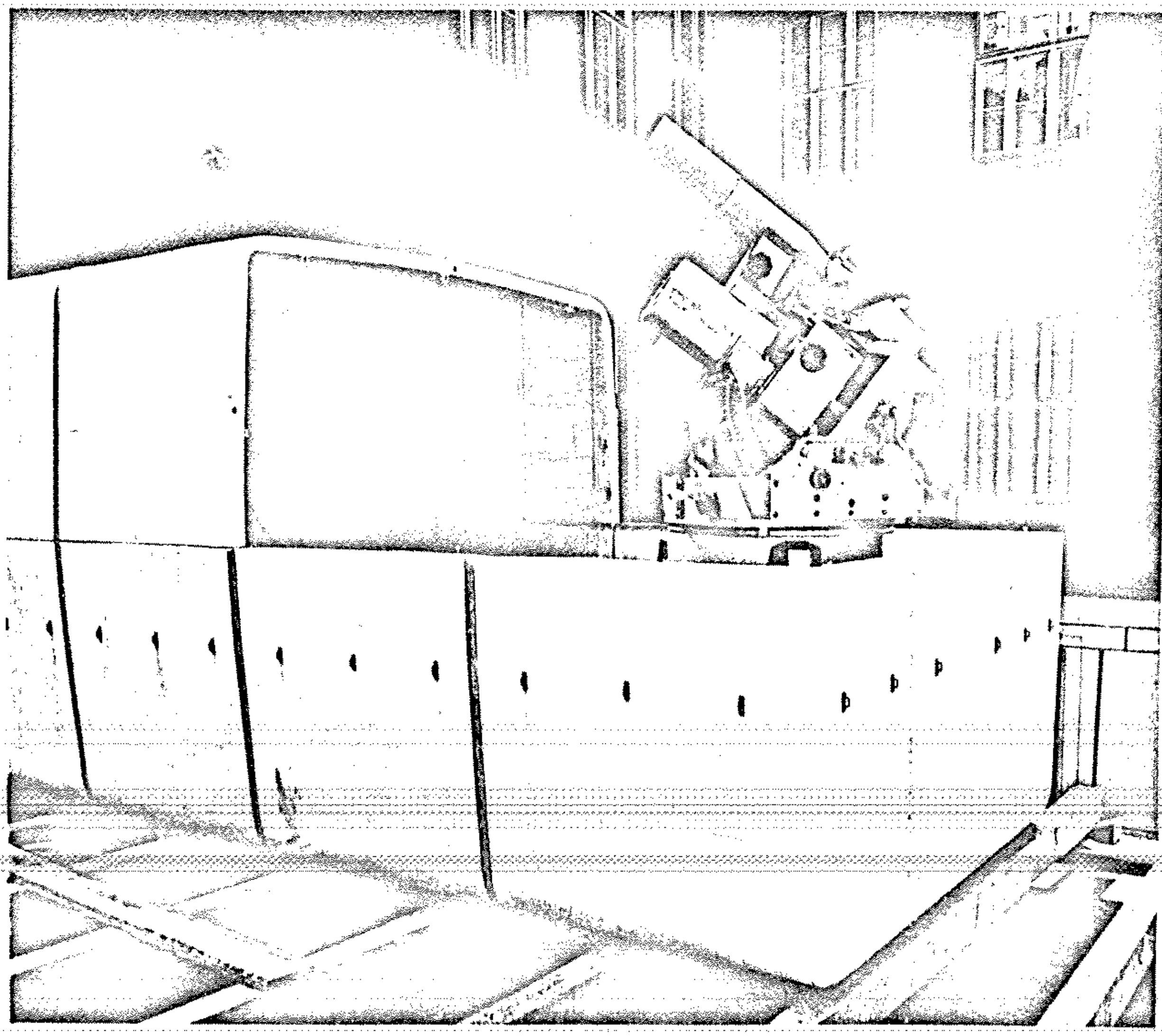


Fig. 3. CRGS CNES internal coherence computation



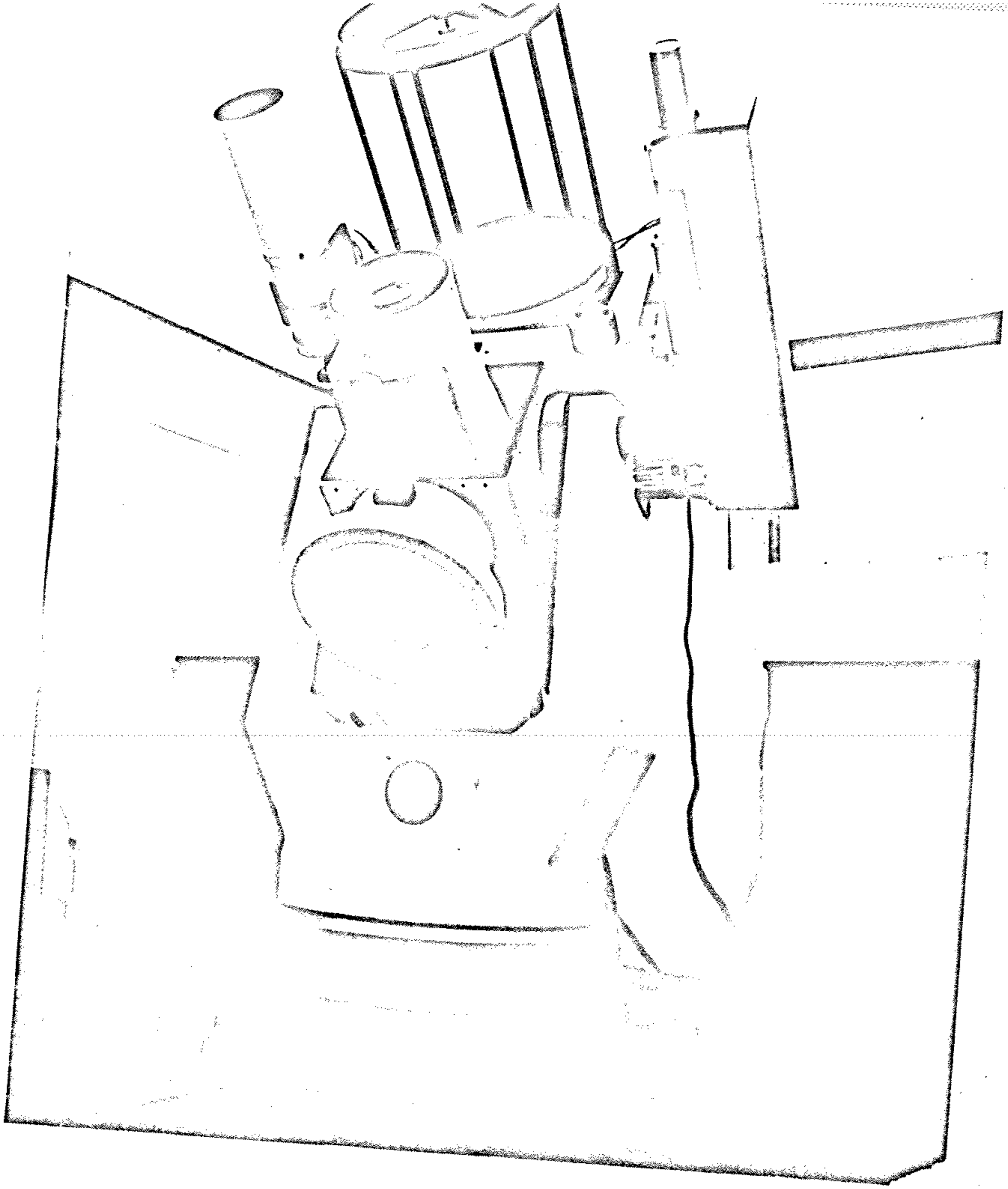


Fig. 5. Automatic 4axis mount

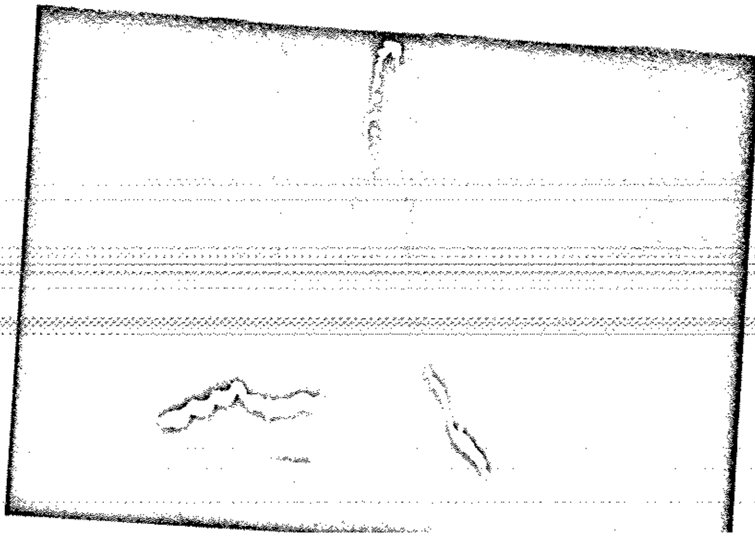


Fig. 6. Laser pulse 5 nsec/div