LASER TRACKING INSTRUMENTATION

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

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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

1^{rst} 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°/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° 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.

1^{rst} Generation modified

Mount automatic Alt-Az mount open loop encoding

Resolution 13" of arc

Accuracy 20" of arc

Speed 40°/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°

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.

2^{nd} Generation

Mount Alt Az automatic mount closed loop encoding
resolution 1,2" of arc
Accuracy 5 x 10^{-5} rad
Speed 6°/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° 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).

	Single-Parameter Fit			Two-Parameter Fit			
Date	A	B (width)	σ (nsec)	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

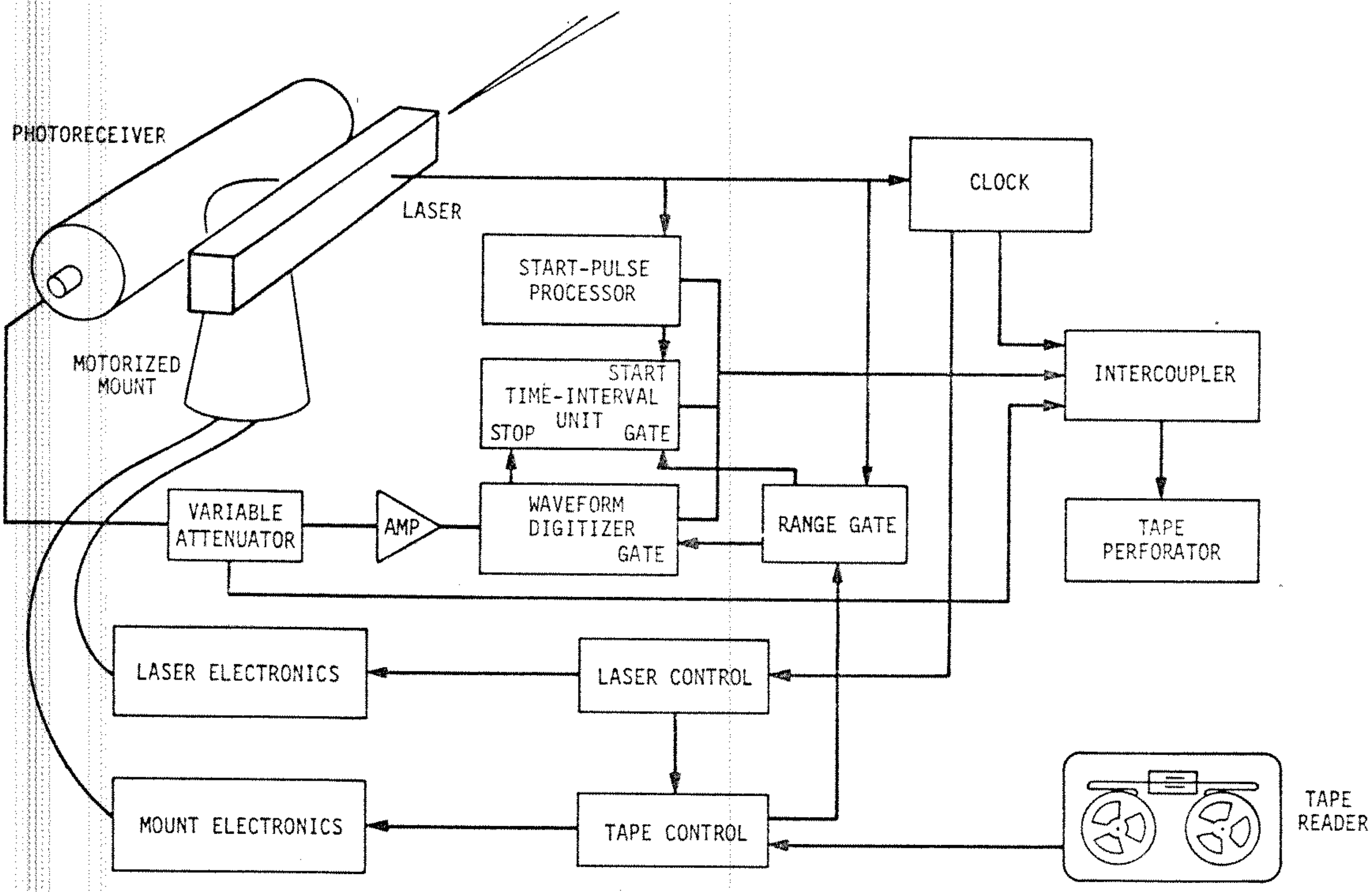

Figure 1. Block diagram of the laser system.

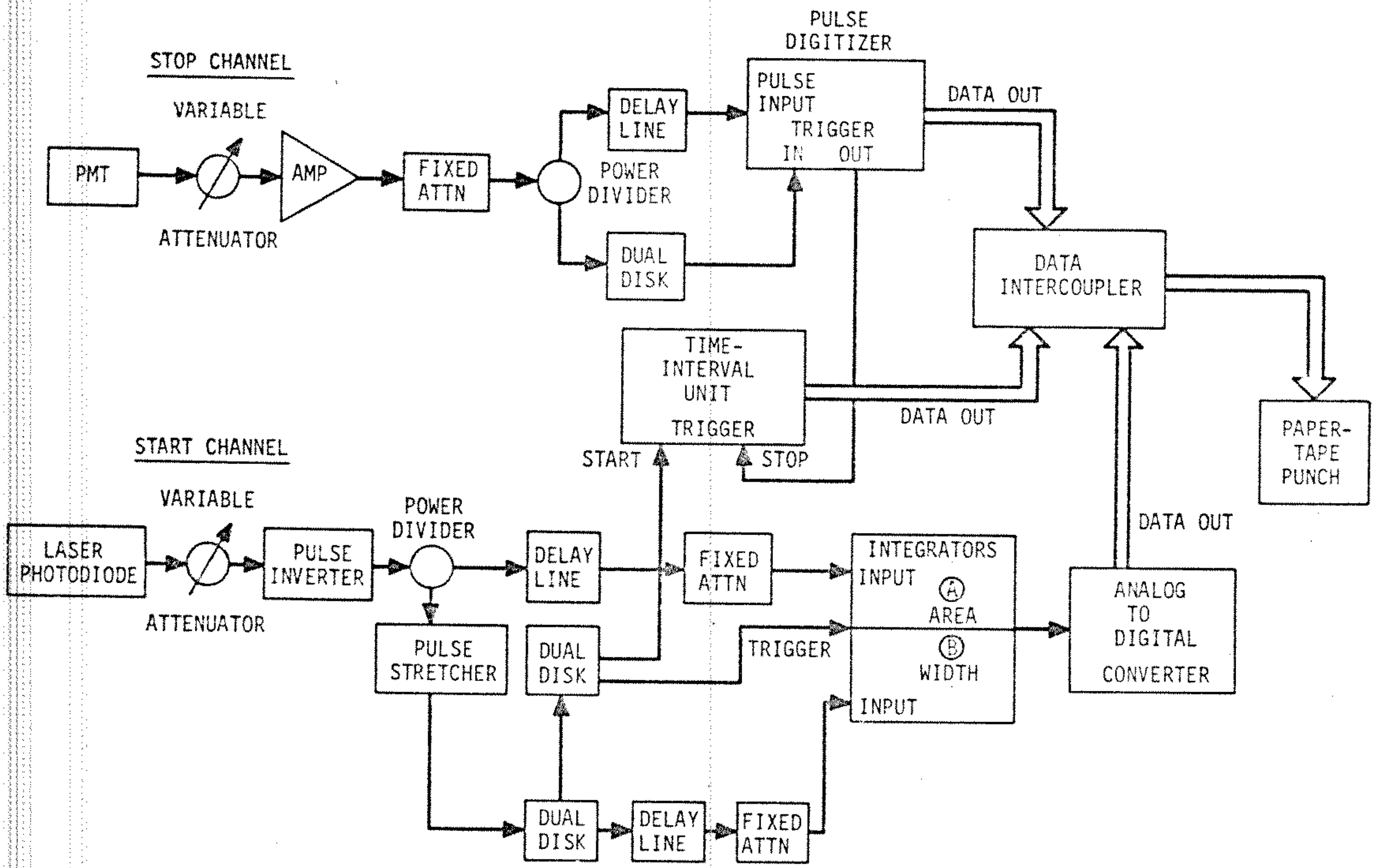

Figure 2. Pulse-processing system.

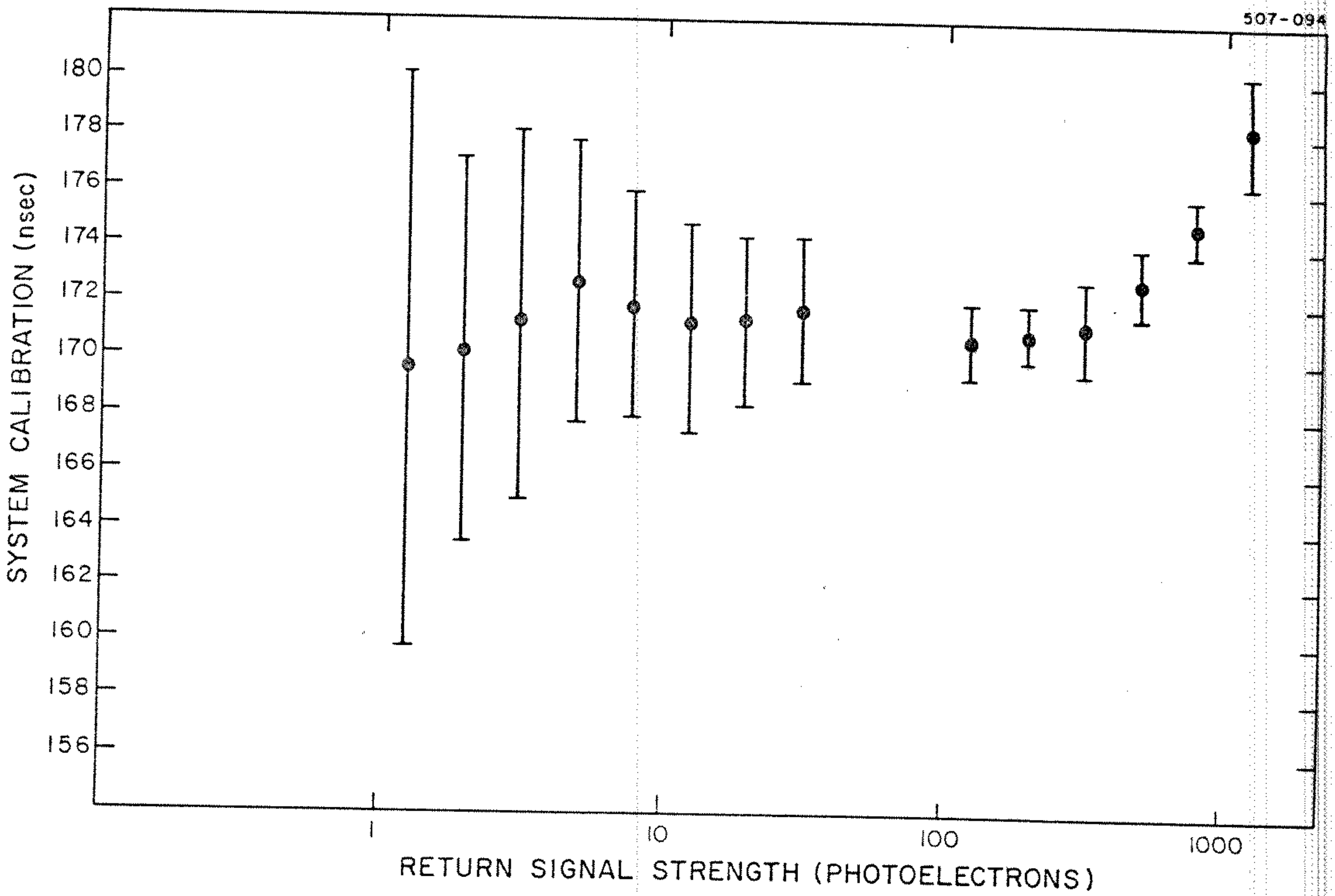

Figure 3. Detailed system calibration at Mt. Hopkins, April 18, 1975. Error bars denote the standard deviation of all the data in the signal-strength interval. A log signal strength of about 3.0 is equivalent to 1 photoelectron.

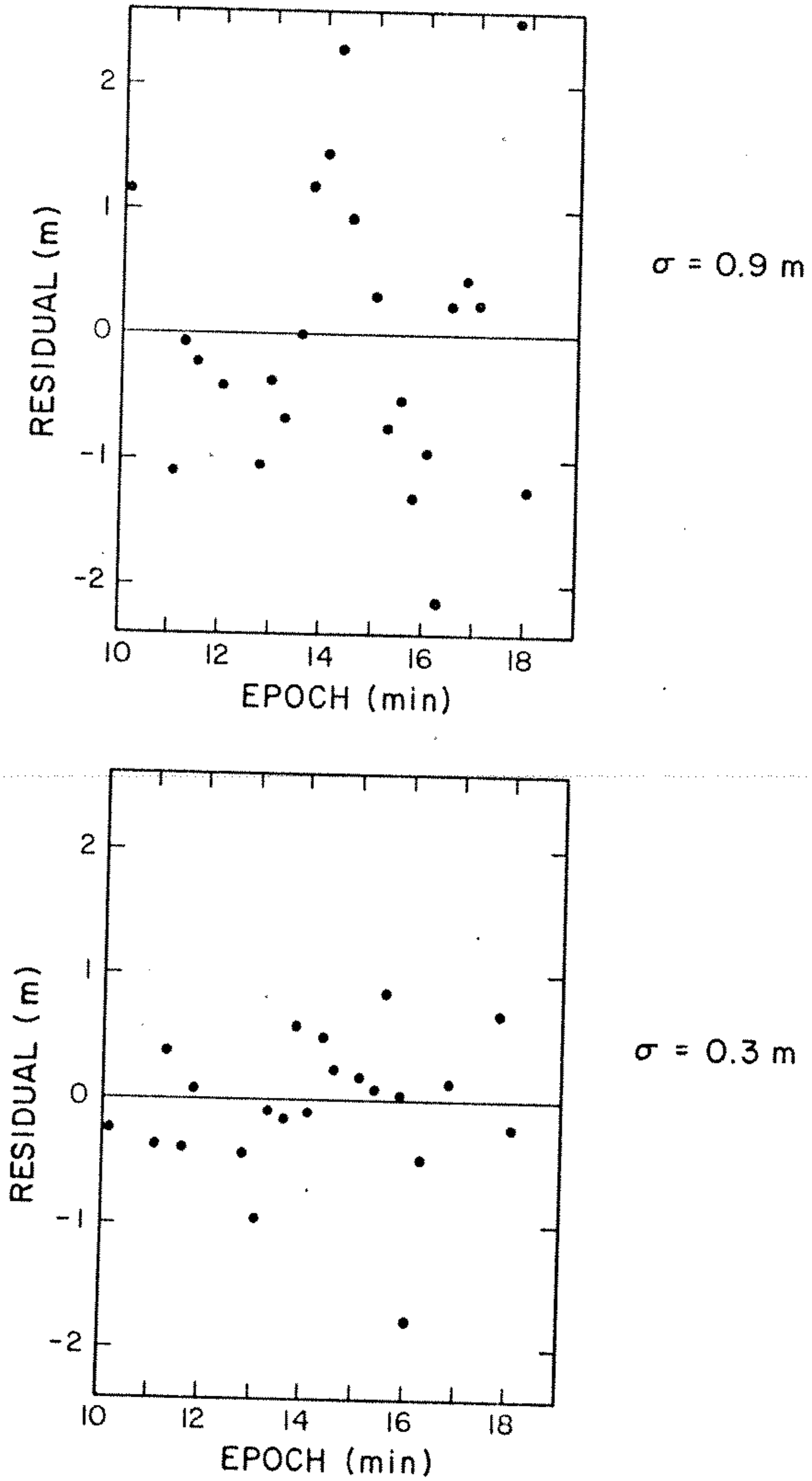

Figure 4. Range residuals to a short arc orbital fit on Beacon-C (30 Nov. 1974, 11^h10^m UT).

SATELLITE LASER RANGING WORK AT THE GODDARD SPACE FLIGHT CENTER

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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. Th 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

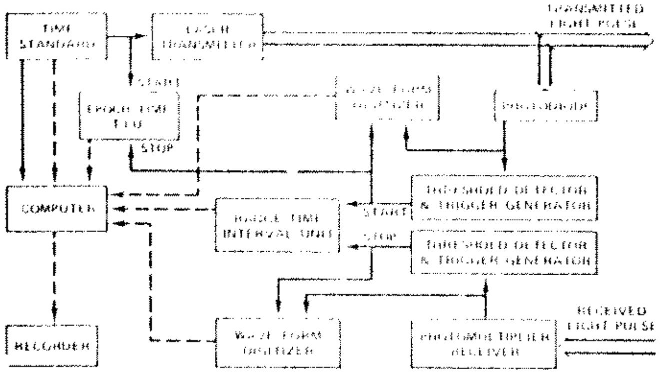

Fig. 1. Laser Ranging System

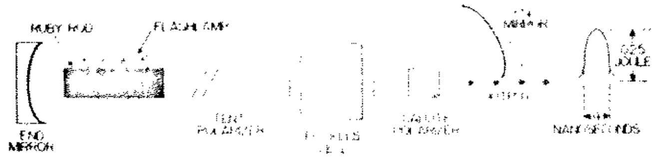

Fig. 2. Cavity Dump Pulsed Ruby Laser

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 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, thumbwhe 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

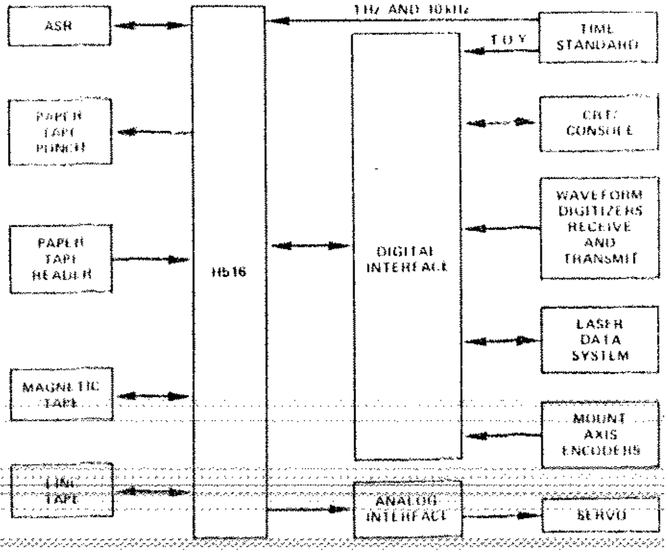

Fig. 3. Computer Hardware System

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 laser 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 prime 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

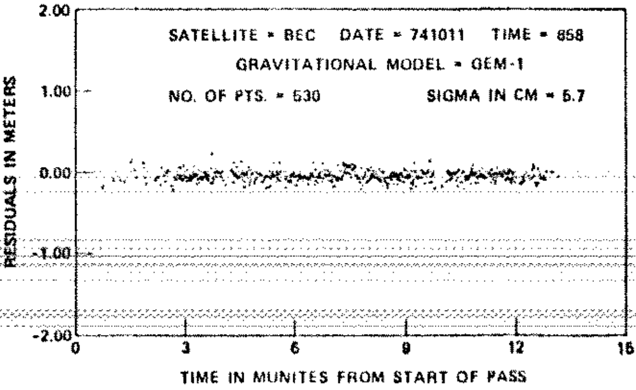

Fig. 4. Stalas Range Residuals Vs. Time

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 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 approximately 200 feet square with a 25 foot by 50 foo 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 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.

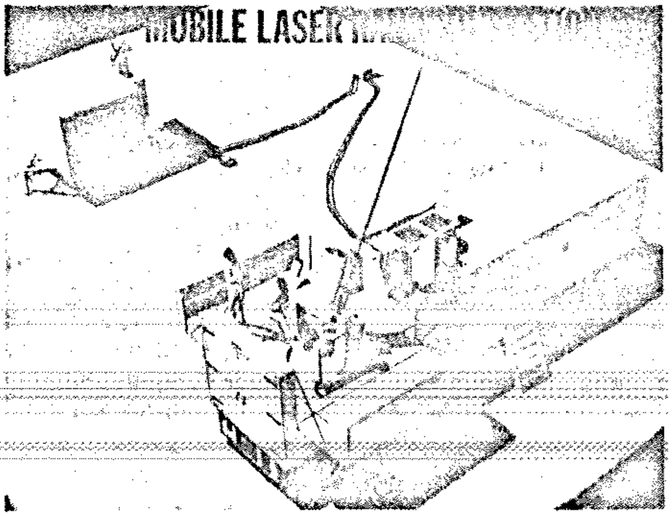

Fig. 5. Mobile Laser Ranging Station

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.

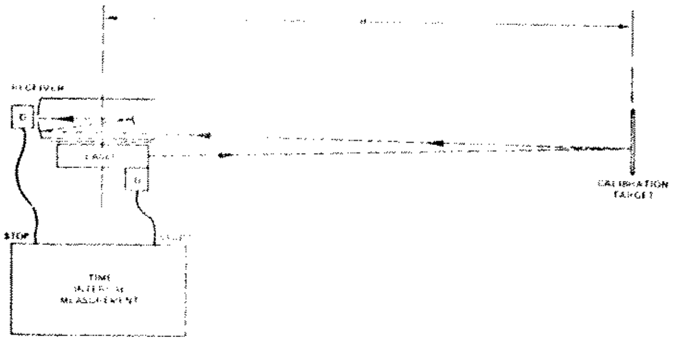

Fig. 6. Laser Ranging System Calibration

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

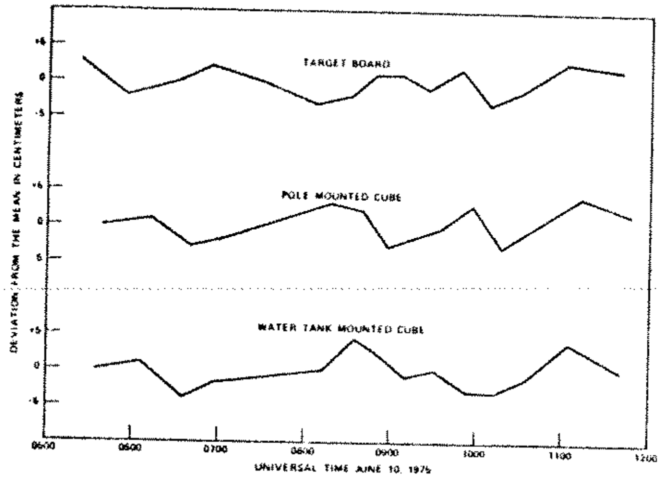

Fig. 7. Stability Test

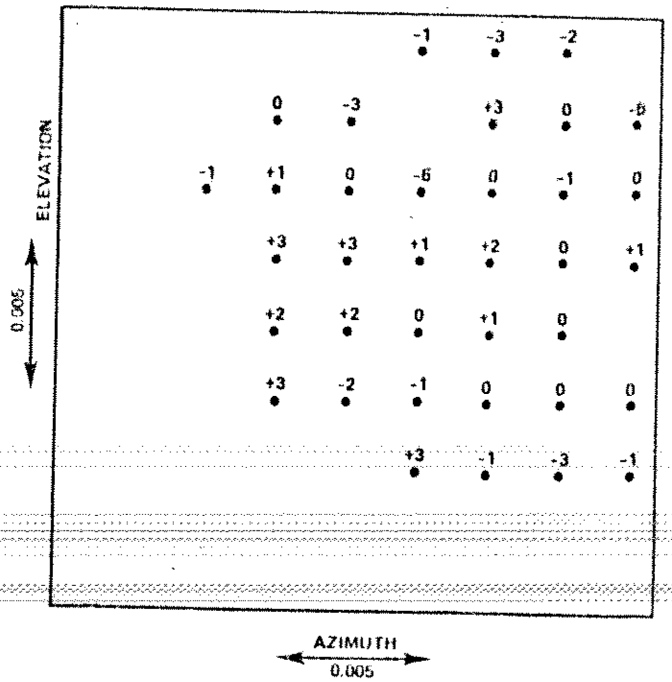

Fig. 8. Range Stability Vs. Pointing Angle

that the overall system stability is within the 1 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 ±5μs 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 ±5μs 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 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.

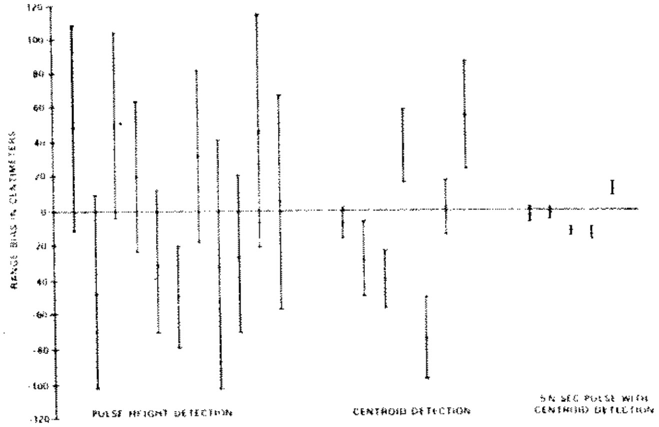

Fig. 9. Laser Ranging Two Station Intercomparison Results

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

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

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 x 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 14, 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 groun 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 chang 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 th 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 nano second 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

The authors would like to express their appreci ation to NASA's Office of Applications, Office of Trac ing and Data Acquisition and Office of Aeronautics an Space Technology for the moral and financial support which made this work possible. We are also grateful to Dr. David Smith and numerous members of his Geodynamics Branch at Goddard who as the primary users of the ranging data have worked with us to develop the full potential of laser systems for a variety of applications. Finally, we are grateful to those employees of the RCA Service Company who serve as the maintenance and operations staff for these systems and who have contributed in innumerable ways to their development, test, and improvement.

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INTERKOSMOS LASER RADAR NETWORK

A.G. Masevitsch, K. Hamal

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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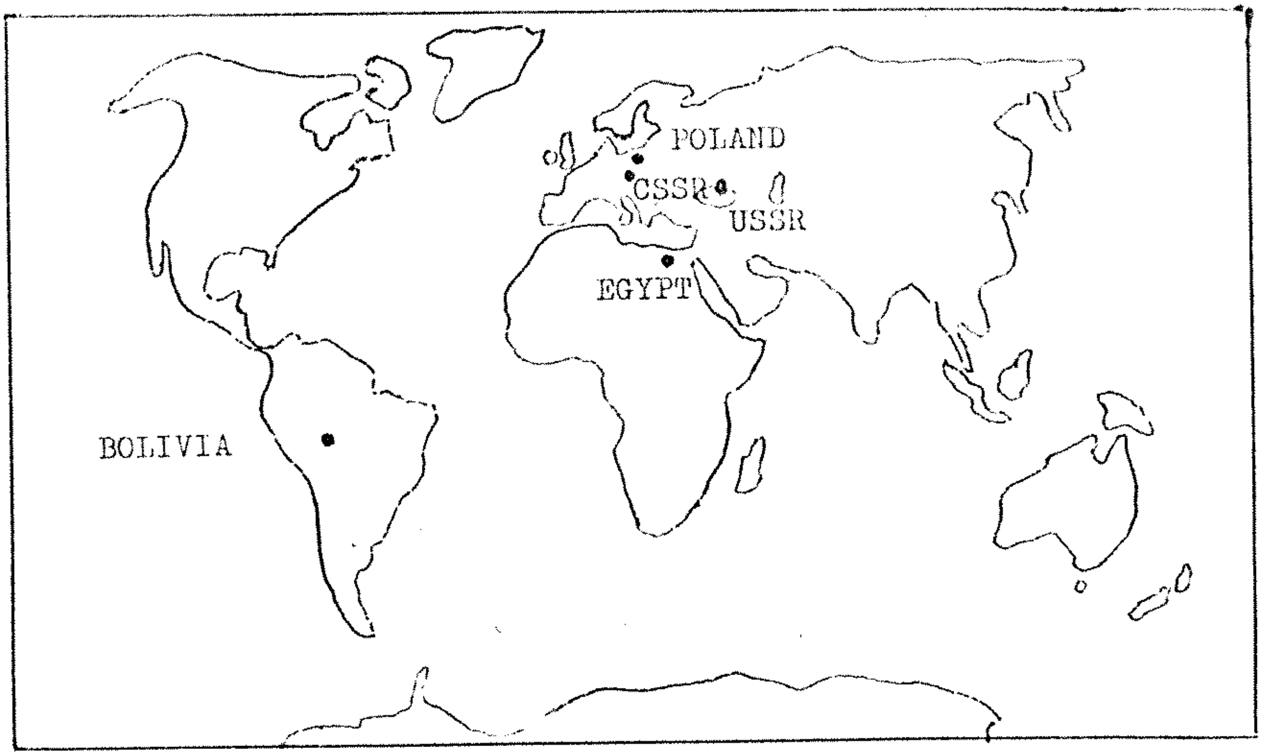


Fig. 1. INTERKOSMOS Laser Radar Network

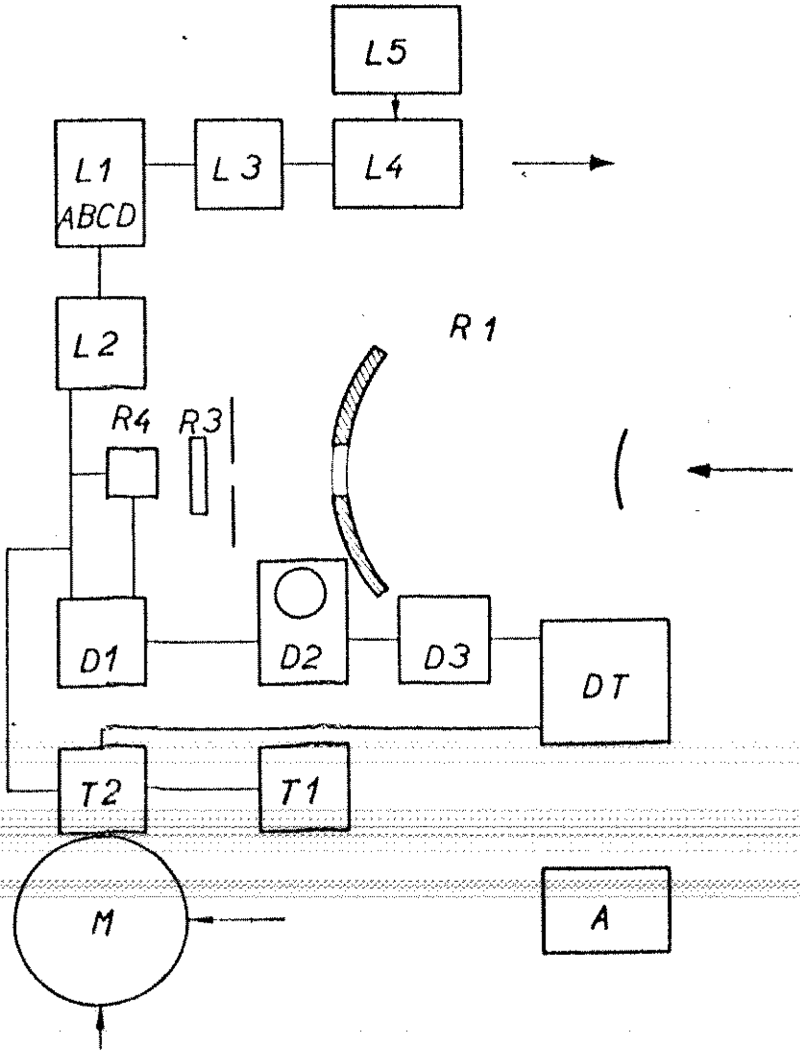


Fig. 2. Laser radar block diagram

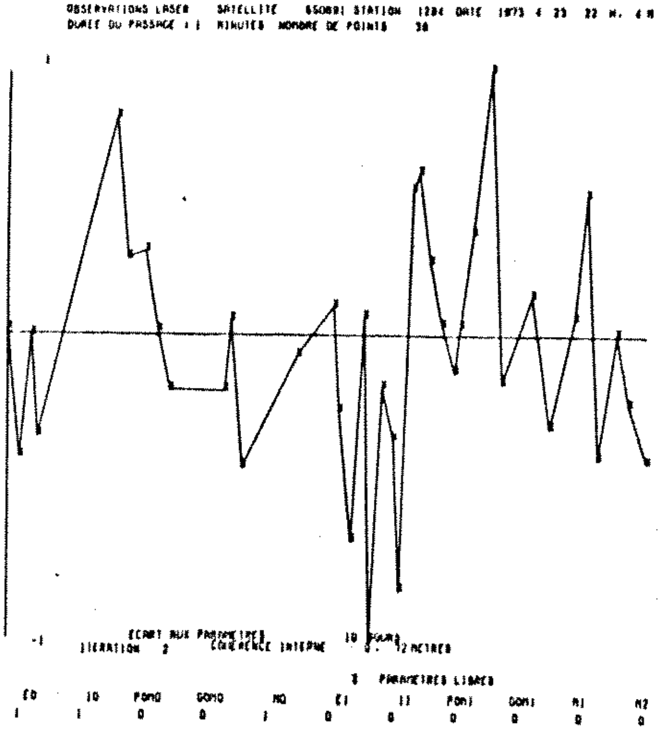
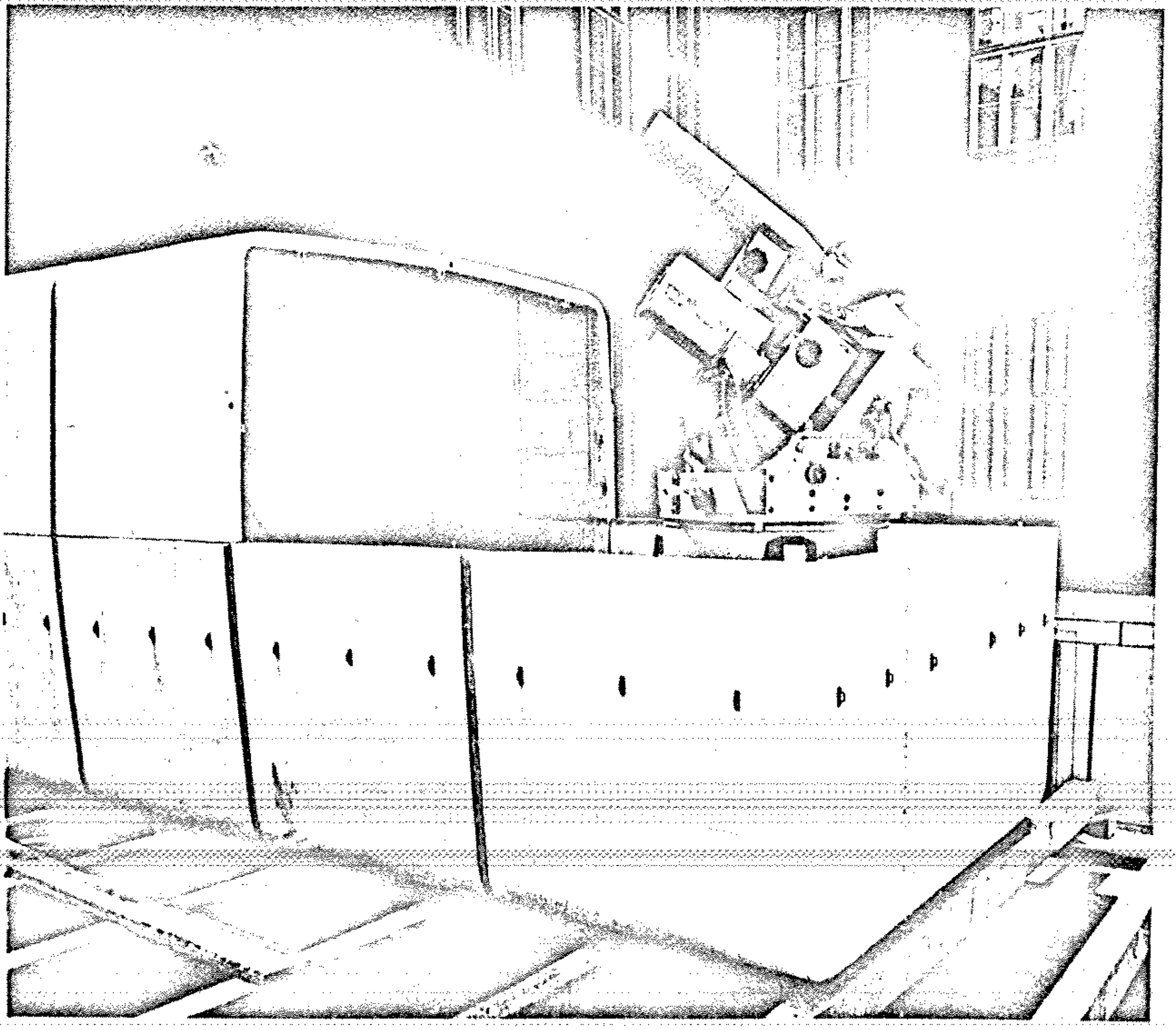


Fig. 3. CRGS CNES internal coherence computation



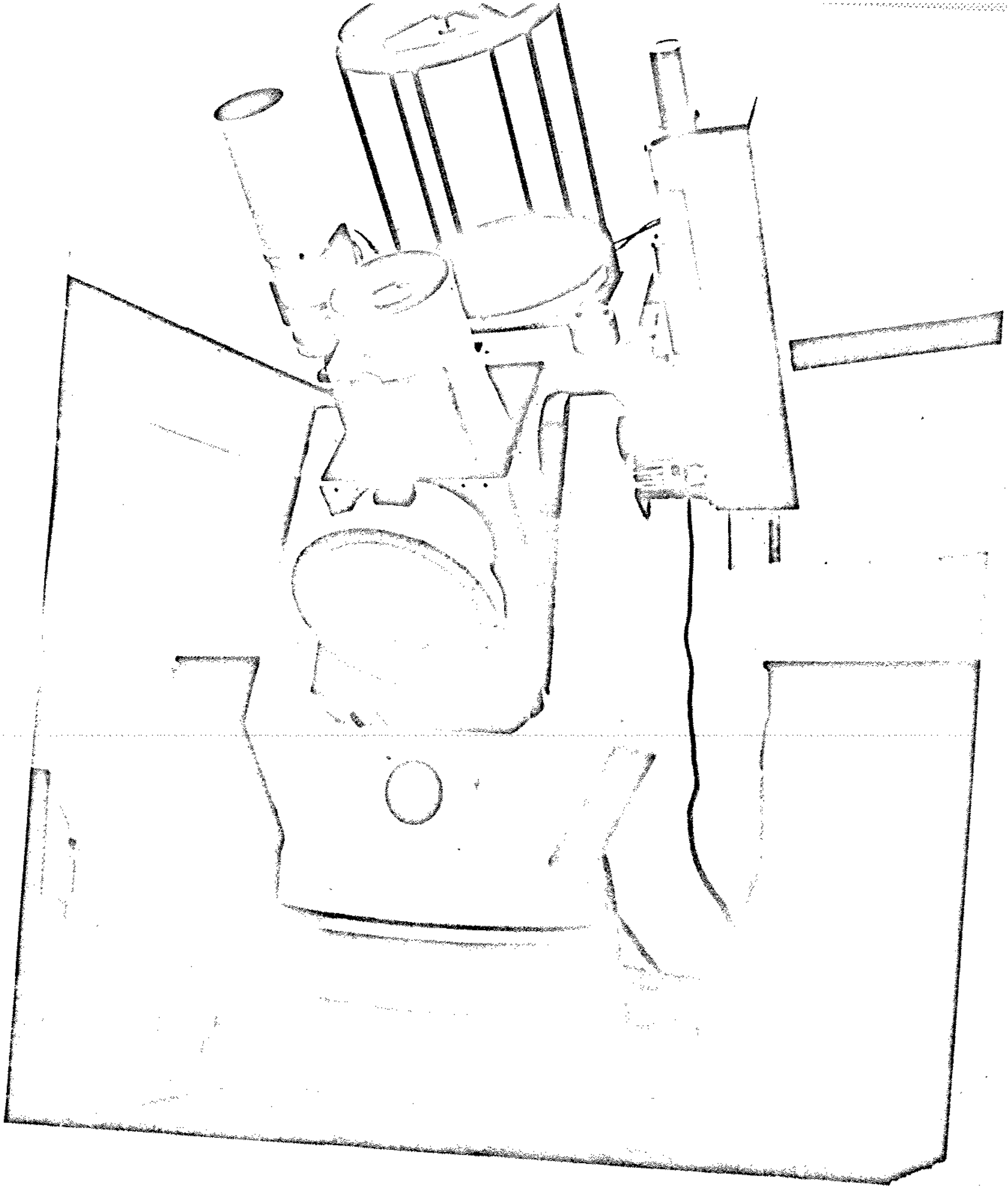


Fig. 5. Automatic 4axis mount

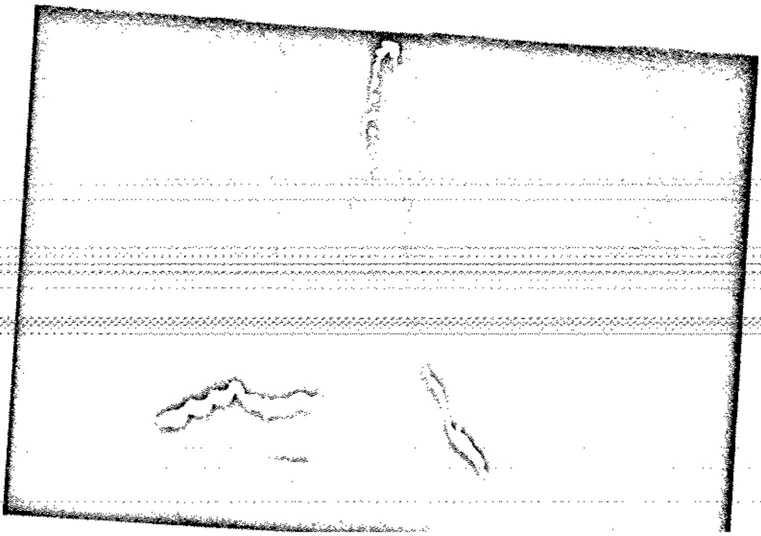


Fig. 6. Laser pulse 5 nsec/div

АВТОМАТИЗИРОВАННАЯ УСТАНОВКА ДЛЯ ЛАЗЕРНОЙ ЛОКАЦИИ ЛУНЫ.

Ю.Л.Кокурин,В.В.Курбасов,В.Ф.Лобанов,А.Н.Сухановский.

В начале 1973 года на телескопе ЗТШ-2,6 Крымской Астрофизической обсерватории была установлена автоматизированная лазерно-локационная система,позволяющая осуществлять измерения с частотой лазерных вспышек I/3 гц и имеющая ряд улучшенных параметров по сравнению с предыдущей установкой [I].На этой аппаратуре в 1973 году были начаты регулярные измерения расстояний до светоотражателей установленных на Луне.В настоящее время на Луне находится пять светоотражателей.Два отражателя французского производства установлены на советских автоматическ аппаратах "Луноход-I"и"Луноход-2",а три отражателя доставлены на Луну американскими экспедициями "Аполон-II","Аполон-I4"и " Аполон-I5".

Задачей проводимого эксперимента являются длительные, в течение многих лет,измерения расстояний до этих отражателей от заданной точки Земли.

Работа выполняется Физическим институтом им.П.Н.Лебедева АН СССР совместно с Институтом теоретической астрономии АН СССР и Крымской астрофизической обсерваторией АН СССР.

Лазерно-локационная система.

Лазерно-локационная аппаратура состоит из четырёх основных частей: лазерного передатчика,фотоприёмника,телескопа с системой наведения и приёмно-измерительного комплекса.

На рис.I изображена оптическая схема установки.В состав лазерного передатчика входят следующие элементы:-оптический квантовый генератор/ОКГ/,включающий в себя электрооптический затвор /ЭОЗ/,рубиновый стержень- /$Р_I$/ диаметром I2мм и длиной 240 мм и зеркало $З_4$;

- оптический квантовый усилитель /ОКУ/ на рубиновом стержне /$Р_2$ диаметром I5 мм и длиной 240 мм;

- вспомогательная система, состоящая из газового лазера /ЛГ/, коллиматора /Т/, призмы/$П_I$/, подвижной призмы /$П_2$/, диафрагмы/$Д_2$/, линзы /$Л_3$/ и экрана /Э/, служащая для оптической настройки всего лазерного передатчика в целом;
- вспомогательные элементы: поворотная призма /$П_3$/ клинья настройки /КН/, зеркало/$З_I$/ для переключения "приём-передача", диафрагма /$Д_3$/.

Рубиновые стержни $Р_I$ и $Р_2$ вместе с двумя импульсными лампами накачки типа ИФП-8000 иотражателями помещены в общий герметический корпус. Охлаждение лазера производится дистиллированной водой, температура которой поддерживается с точностью ±0,5°С.

Фотоприёмник имеет: диэлектрическое отражающее зеркало /$З_3$/, окуляр /$О_2$/ для визуального контроля, диафрагму /$Д_I$/, определяющую поле зрения приёмника, согласующую линзу /$Л_2$/, настраивающийся интерференционный фильтр /Ф/ и фотоумножитель ФЭУ-77.

Подвижное зеркало /$З_I$/ занимает положение "передача" только на короткое время для пропускания импульса лазера и большую часть времени остаётся положении "приём", позволяя вести измерение светового фона фотоприёмником. Уровень фона регистрируется самописцем.

Линза /$Л_I$/ и телескоп /$З_5$/, /$З_6$/ и /$З_7$/ образуют галилеевскую телескопическую систему, которая служит для коллимирования лазерного пучка.

Наведение лазерного луча на цель, находящуюся на тёмной стороне Луны, производится по опорным точкам /кратерам/ на освещённой части. Для наведения в фокальной плоскости телескопа установлена координатная площадка из двух взаимноперпендикулярных линеек, по которым перемещается местный гид /$О_I$/, /$З_2$/. Фокус лазерного передатчика и фокус гида разводятся в плоскости линеек на расстояние, соответствующее угловому расстоянию между уголковым отражателем и опорным кратером. Масштаб и ориентация координатной сетки калибруются периодически по парам звёзд.

Приёмно-измерительный комплекс осуществляет:

- детектирование, накопление и выделение отражённого сигнала на фоне шума;
- измерение времени распространения сигнала с точностью 10^{-8} сек;

- временное селектирование отражённого сигнала с помощью предвычисленного значения времени распространения /эфемерид/,с дискретностью 10^{-7} сек;
- привязку моментов измерений /запуска лазера/ к атомной шкале времени;
- обработку и выдачу информации о каждом цикле измерений.

Блок-схема приёмно-измерительной части установки изображена на рис.2. Она состоит из фотоприёмника,измерителей времени распространения,стандарта частоты и времени,блока управления и программирования и блока регистрации и обработки результатов измерений.

Информация,полученная за каждый цикл измерений /время импульса,эфемерида,показания измерителей временных интервалов/ выводится на цифропечатающую машину и через плату интерфейса поступает в процессор мини-ЭВМ 1001-ТРА-i .

Система на базе этой машины,работающей в реальном масштабе времени,предназначена для сбора,накопления и обработки информации,поступающей от измерительной части комплекса.

С целью оперативного обнаружения сигнала по ходу сеанса ЭВМ работает в режиме временного анализатора,сортируя разности между измеренным и предвычисленным временем распространения $t_o - t_c$ по 8 тысячам каналов,при ширине каждого временного канала 10 нсек. Содержимое каналов отображается в виде гистограммы на экране дисплея с разрешением по оси X - 100 точек,по оси У - 80 точек.Возможно представление на экране панорамной гистограммы - интервала длительностью 80 мксек - с ценой деления по горизонтали 800 нсек /содержимое каждых 80 каналов суммируется и образует ординату точки/.Возможно также представление на весь экран любого участка панорамной гистограммы с шириной временных каналов,определяемой длительностью выбранного участка /от 10 нсек и выше/.

На рис.3 в качестве иллюстрации приведена фотография экрана дисплея,с гистограммой полученной при локации "Лунохода-2" 22.06.73 года. Фотография иллюстрирует накопление сигнала в одном из временных каналов ,на фоне шумовых импульсов распределённых по остальным каналам.Цифровые обозначения на фотоснимке: в верхнем левом углу - начало отсчёта относительно момента открытия временных ворот, единица измерения – I0 нсек; в центре – количество импульсов лазера в иллюстрируемой серии; в верхнем правом углу – верхняя цифра – ширина временного канала, единица измерения – I нсек; в верхнем правом углу – нижняя цифра – количество сигнальных точек, накопленных в течение серии измерений.

В системе предусмотрен вывод информации на перфоленту с целью её повторного просмотра и обработки.

Параметры аппаратуры.

Длина волны лазерного передатчика $\lambda_{пер} = 6943 Å$; энергия в импульсе $W_{пер} = 2,0-2,5$ дж; длительность импульса по уровню 0,I $\tau_{имп} \approx 1,5\ 10^{-8}$ сек; частота повторения импульсов $F = I/3$ гц; диаметр светового пучка $d = I5$ мм; диаметр главного зеркала телескопа $D_т = 2,6$ м; расходимость светового пучка на выходе телескопа $\theta = 6'',0$; полоса пропускания интерференционного фильтра $\Delta\lambda_{0,5} = 5 Å$; коэффициент пропускания фильтра $к_ф = 0,45$; квантовая эффективность фотокатода ФЭУ-77 с учётом призменной насадки $к_{пр} = 8-9\%$; относительная стабильность стандарта частоты $I0^{-9}$; дискретность измерения интервалов времени $\mp 10^{-8}$ сек; длительность временных ворот $T \leq I00$ мксек; точность привязки временной шкалы к сигналам точного времени $\pm I$ мсек.

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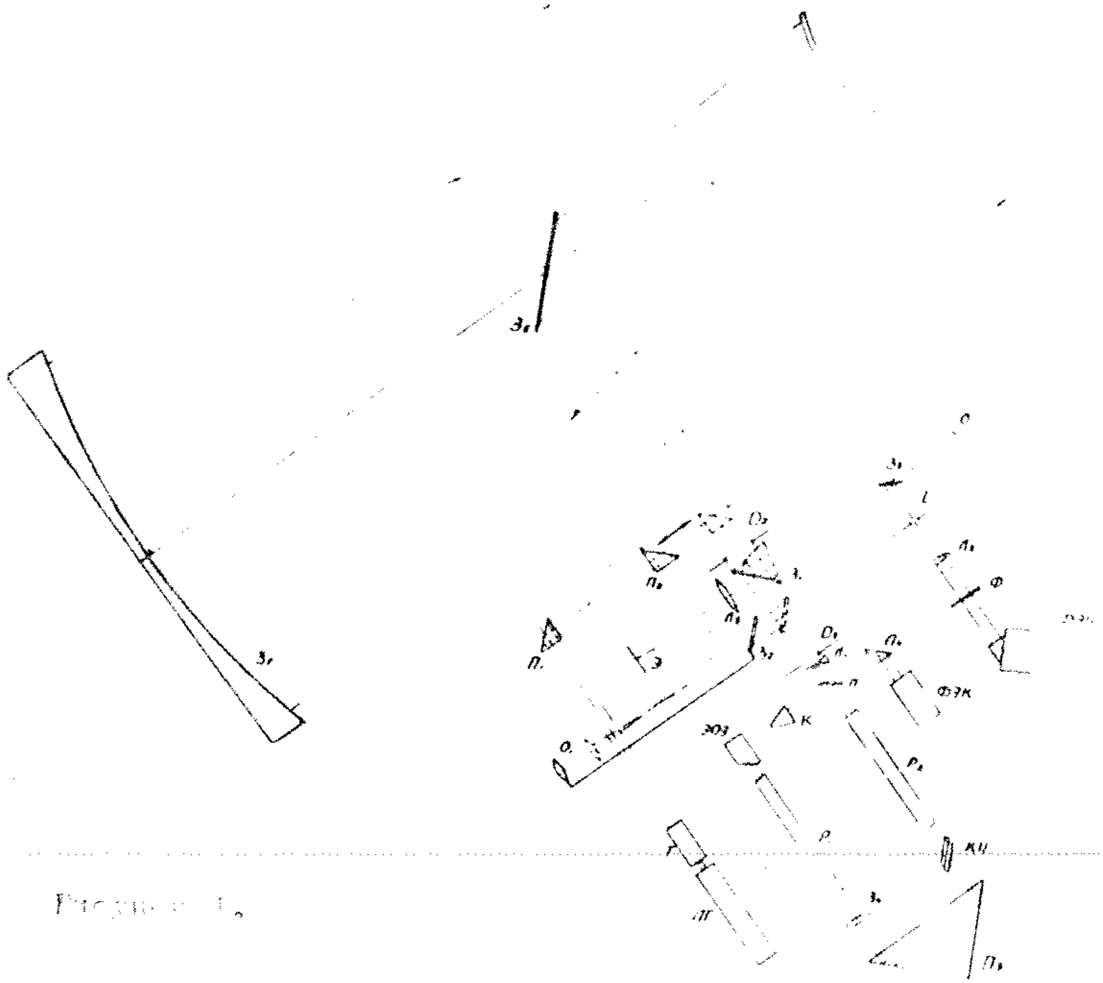


Рисунок 1.

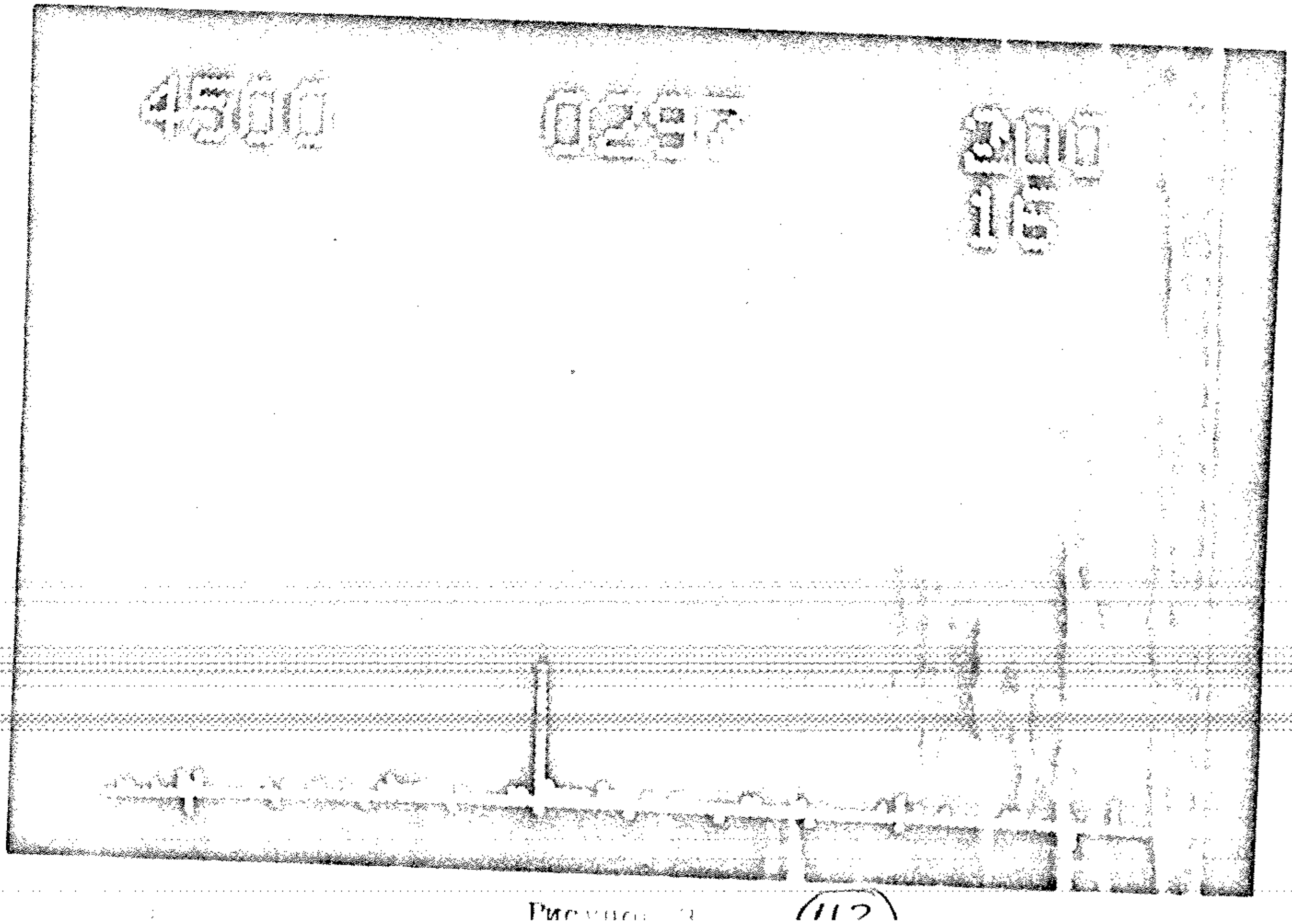


Рисунок 3

The U. S. Lunar Laser Ranging Stations

The McDonald Observatory Station

The McDonald Observatory Lunar Laser Ranging Station is located at approximately 103 deg. W and 30 deg. N in S.W. Texas. The system has been in operation since the fall of 1969 and currently has produced approx. 1800 normal points with the firing of over 700,000 laser shots. The ranging system has been described in some detail in the Journal of Applied Optics 13, p. 565, 1974. Since that description is still accurate with the exception of the timing electronics, we will only briefly summmarize each of the main areas of concern. More detailed documentation of both the equipment as well as the operations is available to any interested party by writing the author in Fort Davis, Texas.

Table I summarizes the most important parameters of the McDonald Lunar System. To give you some idea ofthe overall operating problems,I will list a few of the statistics of operation which have been accumulated over the course of the last five years.

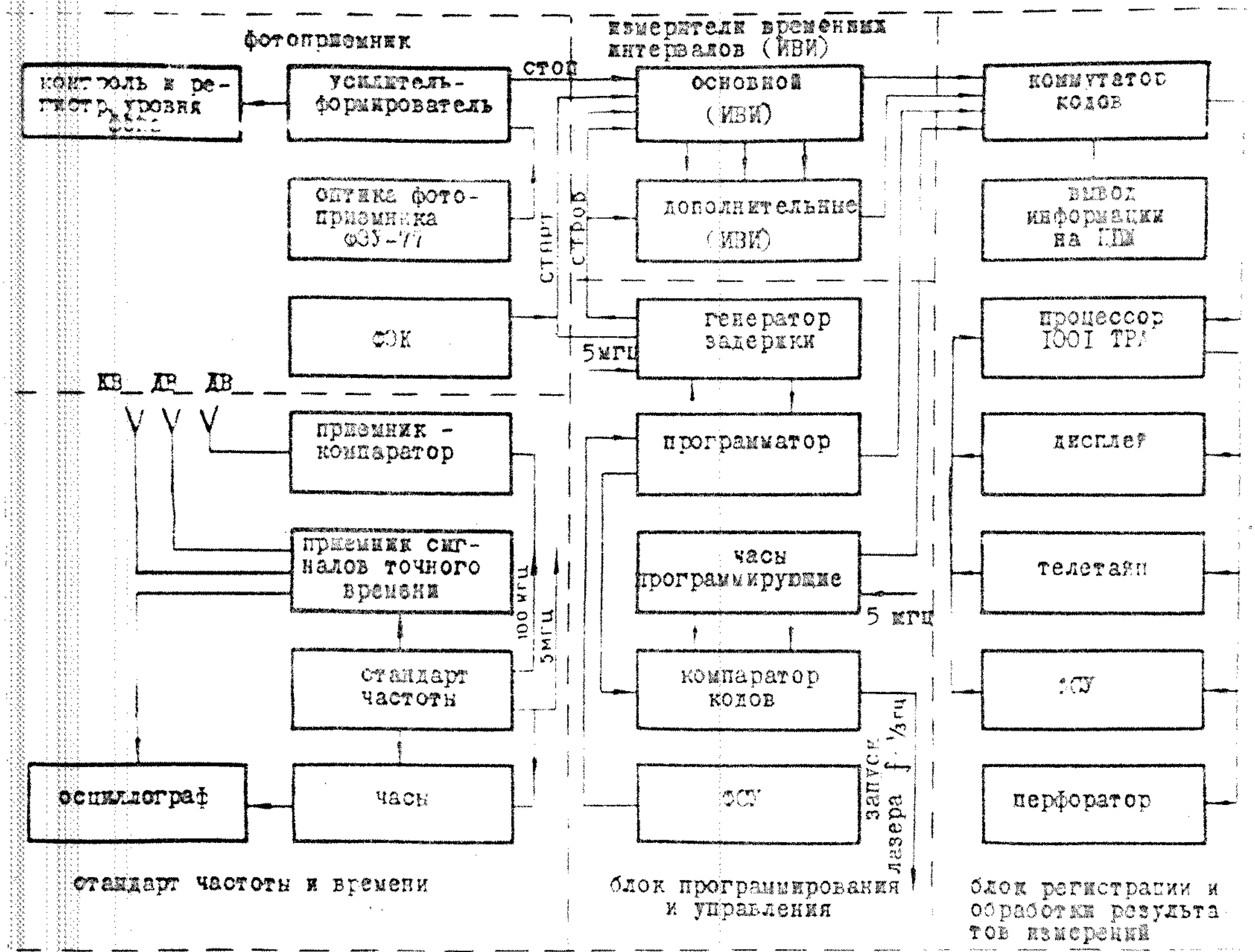
a) The average signal for the best month of operation was approximately 0.1 photoelectron for each laser shot.

b) The peak signals which have been seen at the observatory approach a level of 1 photoelectron/shot.

c) The average signal for a year of operation will average approximately 0.03 photoelectrons/shot for the Apollo 15 corner reflector.

d) The ratio of successful runs to attempted runs averages about 75% for the last three years.

e) The average accuracy of the 1800 normal points is about 10cm.



БЛОК-СХЕМА ПРИЕМНО-РЕГИСТРИРУЮЩЕЙ АППАРАТУРЫ РИС.2

Table I

Important Parameters of the McDonald Station

transmitter/receiver size	2.7m diam.
output energy per shot	1.2J @ 6943Å
spacial filter	6 arc sec
spectral filter	1.2 Å
total receiver efficiency	~0.5%
laser pulse width	3.0 FWHM
repetition rate	0.33 Hz
single shot uncertainty	~30 cm
limiting collimation	1.5 arc sec

- - - - - - - - - - - - - - - -

The Electronics: The timing electronis of the McDonald system has recently been upgraded to higher accuracy. The new system uses an EG&G Time Digitizer to measure both the epoch of firing of the laser as well as the epoch of the received pulse from the moon. The EG&G device has permitted us to contruct a lunar timing system using only commercial equipment with an RMS jitter of 125 picoseconds. The system is self calibrating and is expected to be extremely reliable. Schematic diagrams are available on request.

Calibration: The system calibration is accomplished by sending a small portion of the outgoing laser beam to the PMT each time that the laser is fired. This enables us to statistically determine the system calibration constant on each day with an accuracy of about 200-300 psec. The system does not appear to drift in excess of 50 psec per week in the absence of room temperature variations.

The Guiding: Most of the current ranging is done by directly pointing the telescope at the site using the observers knowledge of nearby features on the lunar surface. This has only become possible because of the many observing runs which the two regular observers have made (approx. 2500). During periods when the observer can not see the site in question, such as around new moon, the telescope is offset from small craters using the accurate differential encoders which are available on the 2.7 meter instrument.

The Hawaii Station

The University of Hawaii has been constructing a laser station on the summit of Mount Haleakala in Maui, Hawaii for about two years. The station is an ambitious second generation station which is designed for a normal ranging accuracy of 2-3 cm. The two major design criteria were of the following nature. a) In order to permit ranging near new moon when the contrast on the moon was low, the system should be capable of absolute pointing to the necessary accuracy. b) In order to permit ranging under a wide range of less than optimum conditions, it was decided to attempt to obtain a return signal which was about three times the average at McDonald. In order to satisfy these criteria, it was decided to use a system which had a separate transmitter and receiver. The transmitter is a 0.4 meter refracting telescope which is directed toward the moon by means of a siderostat. The receiver, which is currently being contructed at the National Bureau of Standards by J.E. Faller, is a flyseye system using 80, 30 cm objective lenses brought to a common focus. The electronics is a 2 channel, 8 stop system with 100 psec resolution designed by D. G. Currie and C. Steggerda of the University of Maryland. The basic designed specifications of the instrument are given in Table II.

Table II

Specifications of the Haleakala Lunar Laser Station

transmitter size	0.4 m refractor
receiver	~2.0 m "flyseye telescope"
spectral filter	2.2 Å
laser pulse width	~200 psec
laser energy	200 mj/shot @ 5320Å
repetition rate	3 Hz
single shot uncertainty	~7 cm
minimum collimation	~3 arc sec

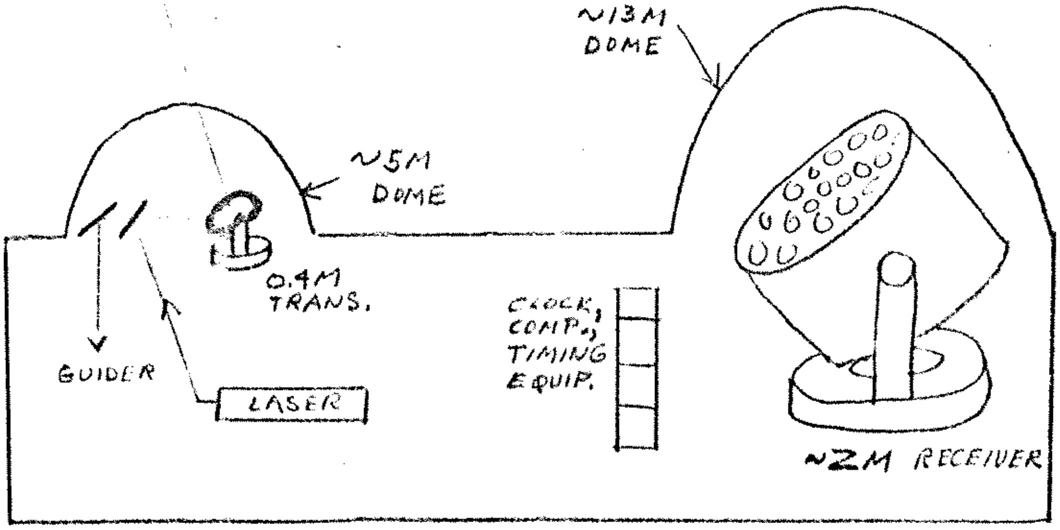


Figure I: The Haleakala Laser Station

A rough schematic drawing of the layout of the Haleakala station is shown on the last page.

At present the basic ranging system at Haleakala is complete with the exception of the receiver. In order to proceed as far as possible under these circumstances, it was decided to attempt some preliminary observations using the 0.4 m transmitter also as a receiver. This has permitted the station personnel to debug most of the equipment, particularly using ranging to a corner reflector on the Mauna Kea Observatory which is 124 Km distant. It was hoped that some lunar ranges could be obtained with this preliminary system under optimim conditions, but a number of attempts so far proved unsuccessful. Further details of this system can be obtained from the project director, Dr. William Carter, Institute for Astronomy, Box 157, Kula, Maui, Hawaii 96790 U. S. A.

E. C. Silverberg
Aug. 12, 1975

LUNAR AND SATELLITE RANGING SYSTEM AT TOKYO ASTRONOMICAL OBSERVATORY

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UNIVERSITY OF TOKYO

1. INTRODUCTION

Since 1972, we had made routine observation of satellite ranging by laser. It was, however, the first generation system with ranging accuracy of about 1 meter.

Recently, 1975, we have installed new equipment for both lunar and satellite ranging. Our system is installed at the Dodaira Observatory, Tokyo Astronomical Observatory, which is about 100 kilometers apart from down town Tokyo. The altitude is about 850 meters.

2. SYSTEM

We have two telescopes i.e. one is receiving telescope for moon and the other is transmitting telescope for moon which is also used for satellite receiving telescope.

Fig. 1 - 3 show our system. The system specifications as follows:

i/ Lunar Receiving Telescope /Fig. 1/

Diameter	3,8 meters metalic mirror
Mount	Az-El Mount
Drive	Torgue Motor /Direct drive/
Encoder	Inductosyn 1.8" /arc/ resolution
Field of view	10" - 30"

ii/ Lunar transmitting telescope /Fig. 2/

This telescope is also used for satellite receiving telescope switching the optical path.

Diameter	0.5 meters glass mirror
Mount	X-Y Mount ø Cudé optics
Drive	Torgue Motor /Direct drive/
Encoder	Inductosyn 1.8" /arc/ resolution
Lunar Laser Final Beam width	5" - 10"
Satellite Laser Final Beam width	1´ - 10´

iii/ Lunar Laser

Wave length	6943 Å /Ruby/
Constitution	oscillator + 3 stages Amplifiers
Oscillator mode	TEMOD
Oscillator output	about 100 mJ
1st stage amolifier output	0.4 - 0.5 J
2nd stage amplifier output	1.5 - 2 J
3rd /last/ stage amplifier output	4 - 6 J
Pulse width	20 - 25 ns
Repetition rate	0.2 Hz
Beam divergence	40" /arc/

iv/ Satellite Laser

Wave length	6943 Å /Ruby/
Constitution	Oscillator + slicer + amplifier
Oscillator mode	Multi Mode
Oscillator output	1 J /60 MW/
Oscillator pulse width	15 ns
Power level after slicer	40 MW /peak/
Amplifier output	150 MW /peak/
Pulse width	2.5 ns
Repetition rate	0.1 Hz
Beam divergence	5 mrad

v/ Range counter

Accuracy	1 ns
Resolution	0.1 ns

vi/ Range Gate

Accuracy	± 10 ns
Resolution	100 ns
Digits	8 Digits

vii/ Pulse distribution analyzer

A 4 bit 112 words high speed memory records the PMT output pulse number in sequence of 25 nsec of time interval. This equipment is used only for lunar observation.

viii/ Timing

Station oscillator is crystal /Salzer/. The clock is calibrated through Loran C radio signal, and also linked through VHF radio to Cs frequency standards at MITAKA Observatory. The MITAKA Observatory is our main office.

The timing accuracy is about ± 5 μs for USNO.

ix/ Computer Interface

Here, we mention only for telescope offset command /Fig. 3/. This is provided in order to offset the telescope from its computed position without computer off. By pressing appropriate buttom /corresponding to desired axis/, computer add or substract a specified value on encoder value, and controlls the driving. Hence, the telescope axis is offset from initial position.

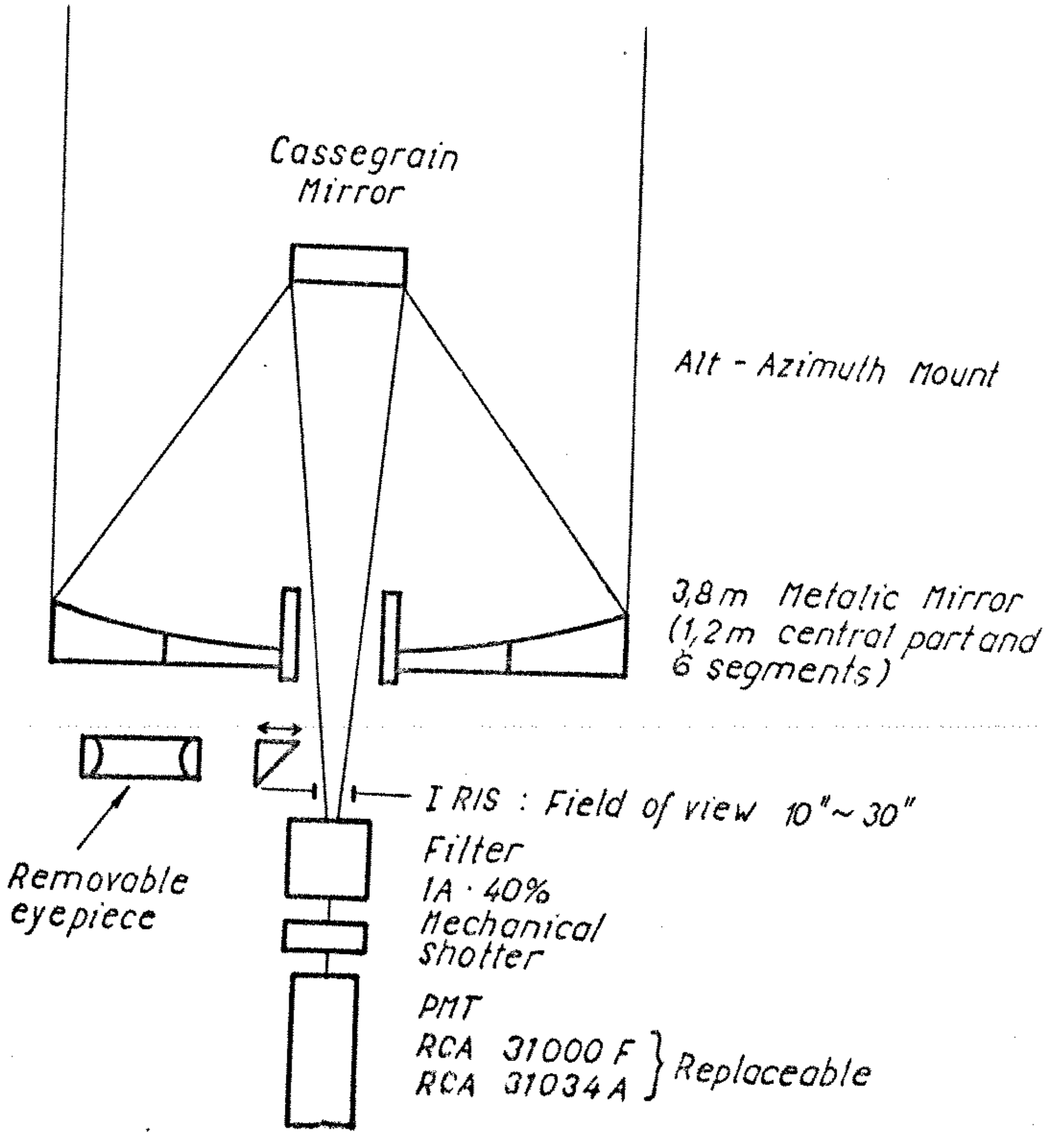


Fig. 1 Receiving telescope for Moon.

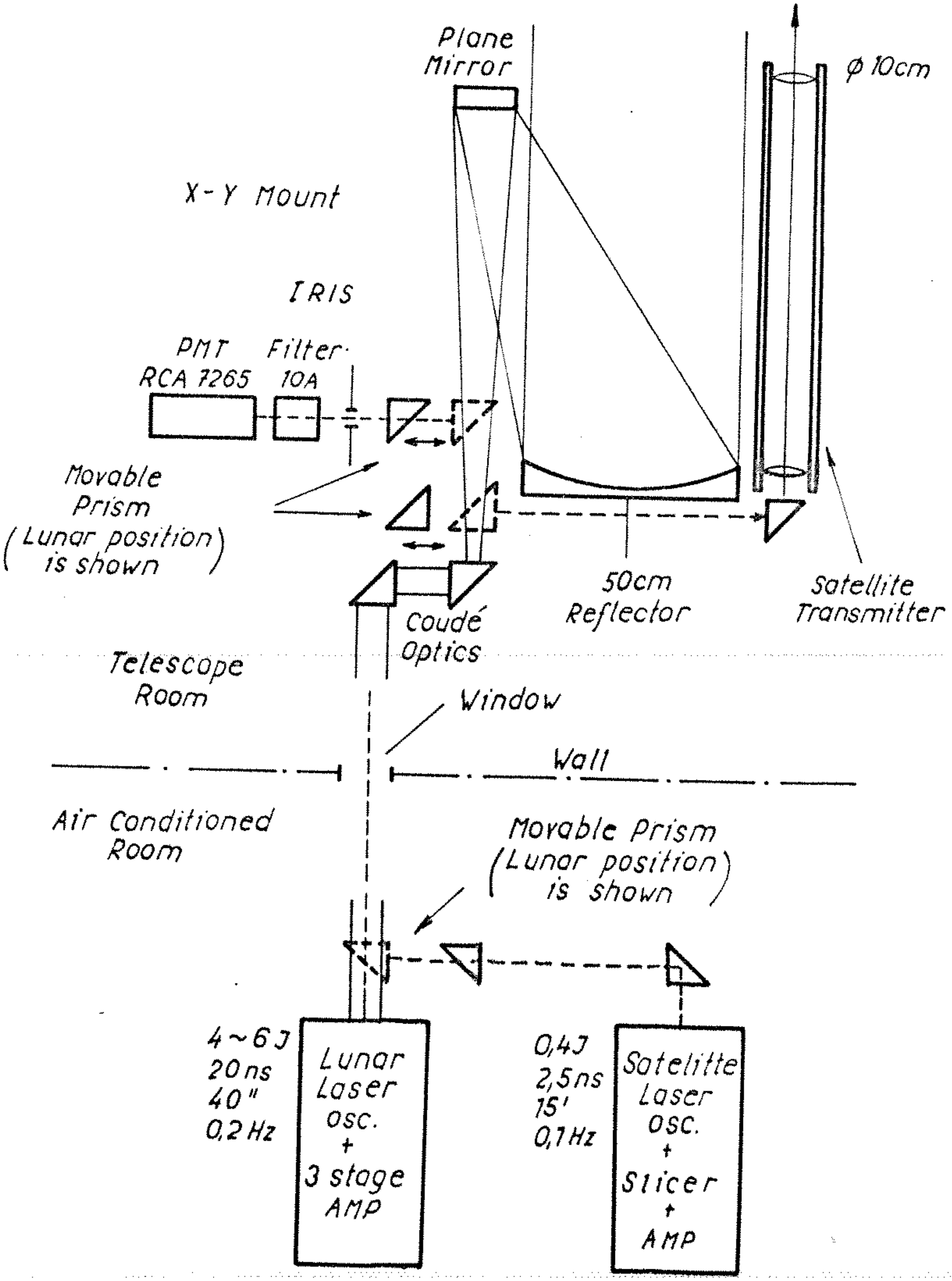
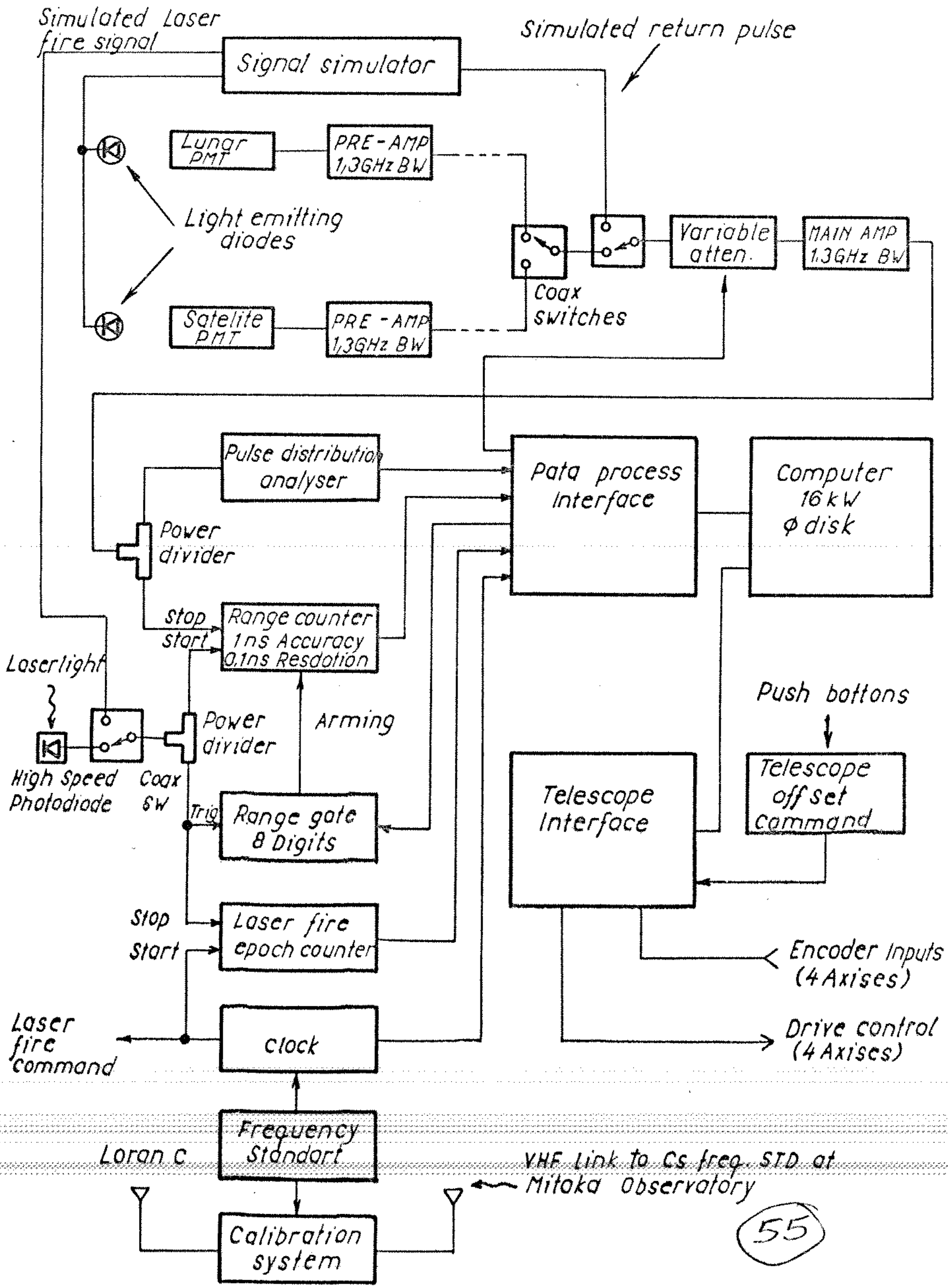


Fig. 2 Lunar Transmitter and/or Satellite Transmit - Receive Telescope.


Simulated Laser fire signal
Signal simulator
Simulated return pulse
Lunar PMT
PRE-AMP 1,3GHz BW
Light emitting diodes
Coax switches
Variable atten.
MAIN AMP 1.3GHz BW
Satelite PMT
PRE-AMP 1,3GHz BW
Pulse distribution analyser
Data process Interface
Computer 16kW Ø disk
Power divider
Stop
Start
Range counter 1ns Accuracy 0.1ns Resdotion
Laserlight
Power divider
Arming
High Speed Photodiode
Coax SW
Trig
Range gate 8 Digits
Telescope Interface
Push bottons
Telescope off set Command
Stop
Start
Laser fire epoch counter
Encoder Inputs (4 Axises)
Laser fire command
clock
Drive control (4 Axises)
Frequency Standart
Loran C
VHF Link to Cs freq. STD at Mitaka Observatory
Calibration system

UNIVERSITY OF MARYLAND LASER RANGING SYSTEM

C. O. Alley

I. Introduction

Following the design, installation and initial operation of the McDonald Observatory lunar laser ranging station, in cooperation with the University of Texas and the Goddard Space Flight Center, the University of Maryland group turned it attention to research and development for future laser ranging systems. Work has concentrated on short pulse /∼100 ps/ high repetition rate /high average power/, Nd-YAG lasers which offer high accuracy as well as a trade-off against telescope aperture which can be very effective in reducing costs. Another area of research has been the construction of improved timing electronics to work with this type of laser. A third area has been the experimental study of timing jitter in photomultiplier tubes for single photoelection detection.

II. Nd-YAG Laser /Steve Davis, John Degnan, Sherman Poultney/

This laser has been redesigned and rebuilt following initial design and construction at the Sylvania Co. /W. Fountain/ under contract to the Office of Naval Research /F. Quelle/. It consists of an acousto-optic mode-locked oscillator using continuous krypton arc lamp pumping of a 6.4 mm x 5 cm laser rod producing a pulse train of 120 ps FWHM pulses at 150 MHz. One pulse can be selected by Pockels Cell switches as often as 30 times per second for injection into a multi-pass cavity for amplification to ~ 2 millijoules and subsequent extraction by Pockels Cell switch and frequency doubling to 5321 Å by a KD*P crystal with 30% conversion efficiency. Beam divergence is maintained at the diffraction limit, about 0.4 milliradians. Amplitude stability of a few percent has been exhibited. /See Figure 1./

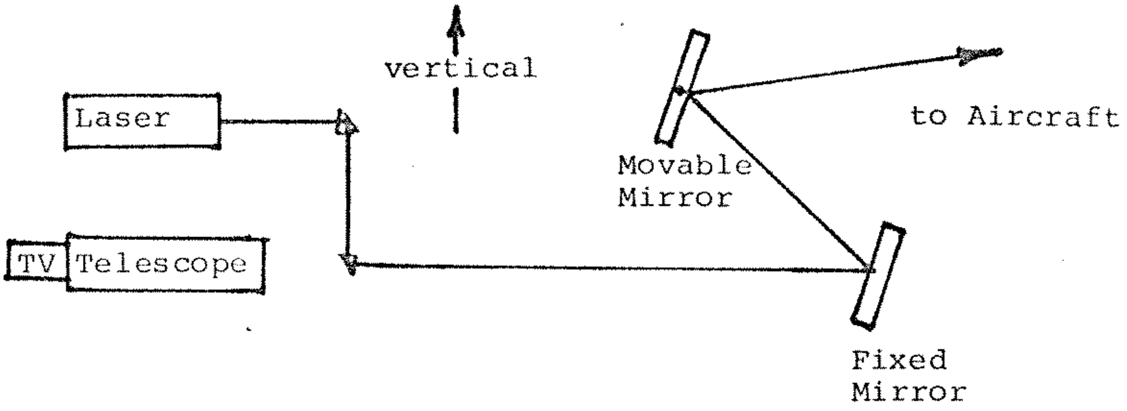
III. "Event Timer" Electronics /Douglas Currie, Charles Steggerda, John Rayner, Al Buennagel/

A new type of timing system which eliminates the need for many time-interval measuring systems has been constructed. By using synchronous counters and latch circuits along with dual slope time stretching vernier circuits it is possible to record the epoch of a pulse directly /in a time base desired from a 5 MHz signal/ with a resolution of 100 picoseconds, up to 100 pulses per second. The epoch of the event in fractions of Julian Days is recorded in the memory of a NOVA 2/10 computer. By taking time differences between incoming and outgoing laser pulses, the range time is determined by the computer. A system of this type was delivered by Maryland in 1973 and forms part of the Haleakala Lunar Laser Ranging Station.

IV. Field Operation in the Atomic Clock General Relativity and Laser Pulse Time Transfer Experiment

In order to compare the time of a set of atomic clocks in an aircraft with those of a similar set on the ground, the laser has been incorporated into a ranging system with an event timer and photomultiplier. A similar event timer and photomultiplier is on the aircraft. The photomultipliers are RCA type 31024, used with Hewlett Packard Type 8447 D and E low noise wide band amplifiers and the Ortec Type 473 constant fraction discriminator. A corner reflector of the lunar type is attached to the aircraft just outside the window behind which is located the photomultiplier detector /with neutral density light attenuators/.

The raw laser beam /$\sim$ 2 mm diameter/ is injected /with small prism/ into the center line of a stationary 20 cm refracting telescope and the beam is directed to the aircraft by a 29 cm flat mirror driven in azimuth and elevation by joy-stick controlled tachometer feed-back to motors.



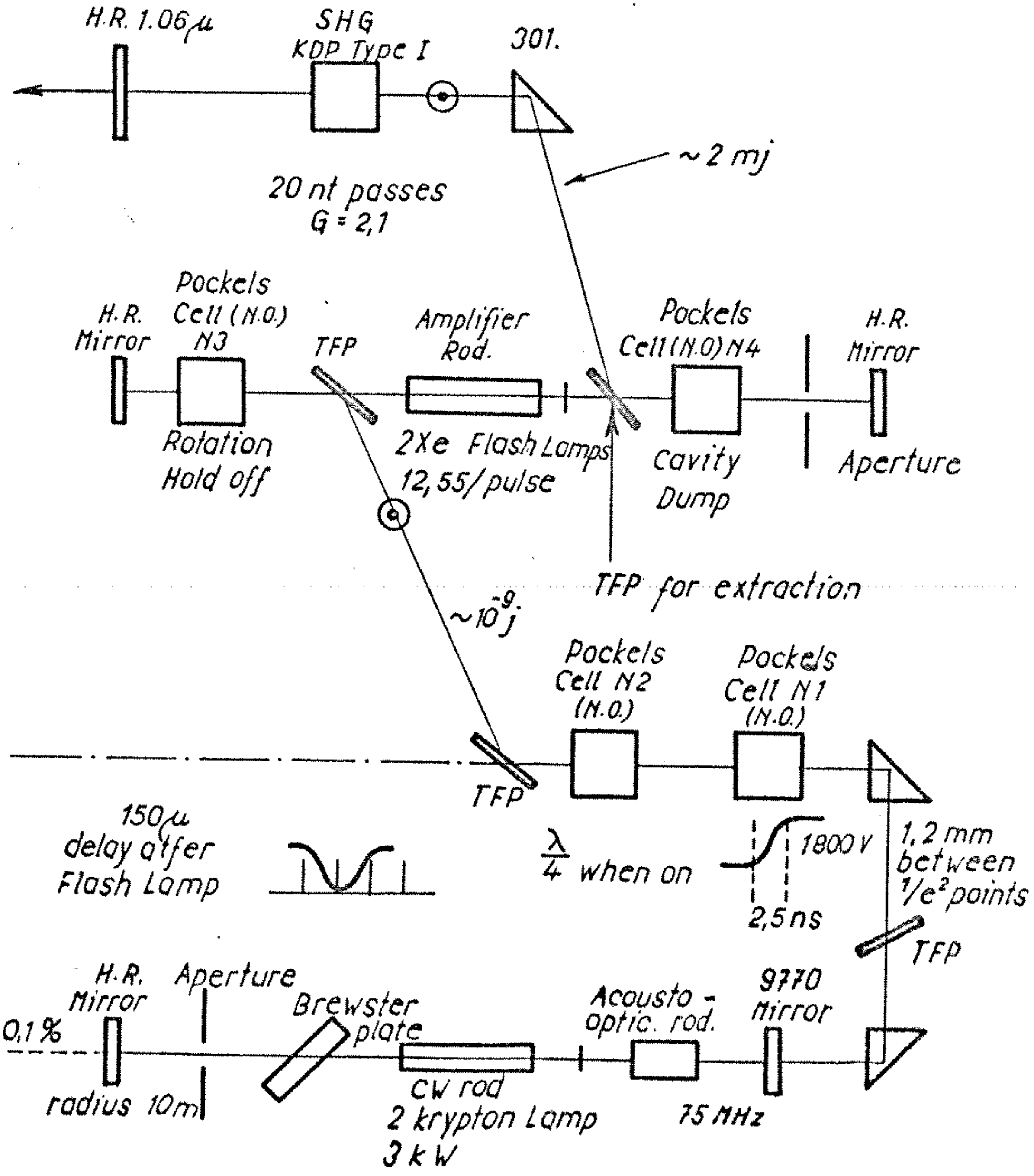
Visual tracking with closed circuit television is used. The laser ranging system performs very reliably in a bus located at the airfield. After transportation from the University in the bus /130 km/ no adjustment of the optics was necessary to achieve satistactory operation. On one occasion the system operated continuously for 12 hours with no difficulties.

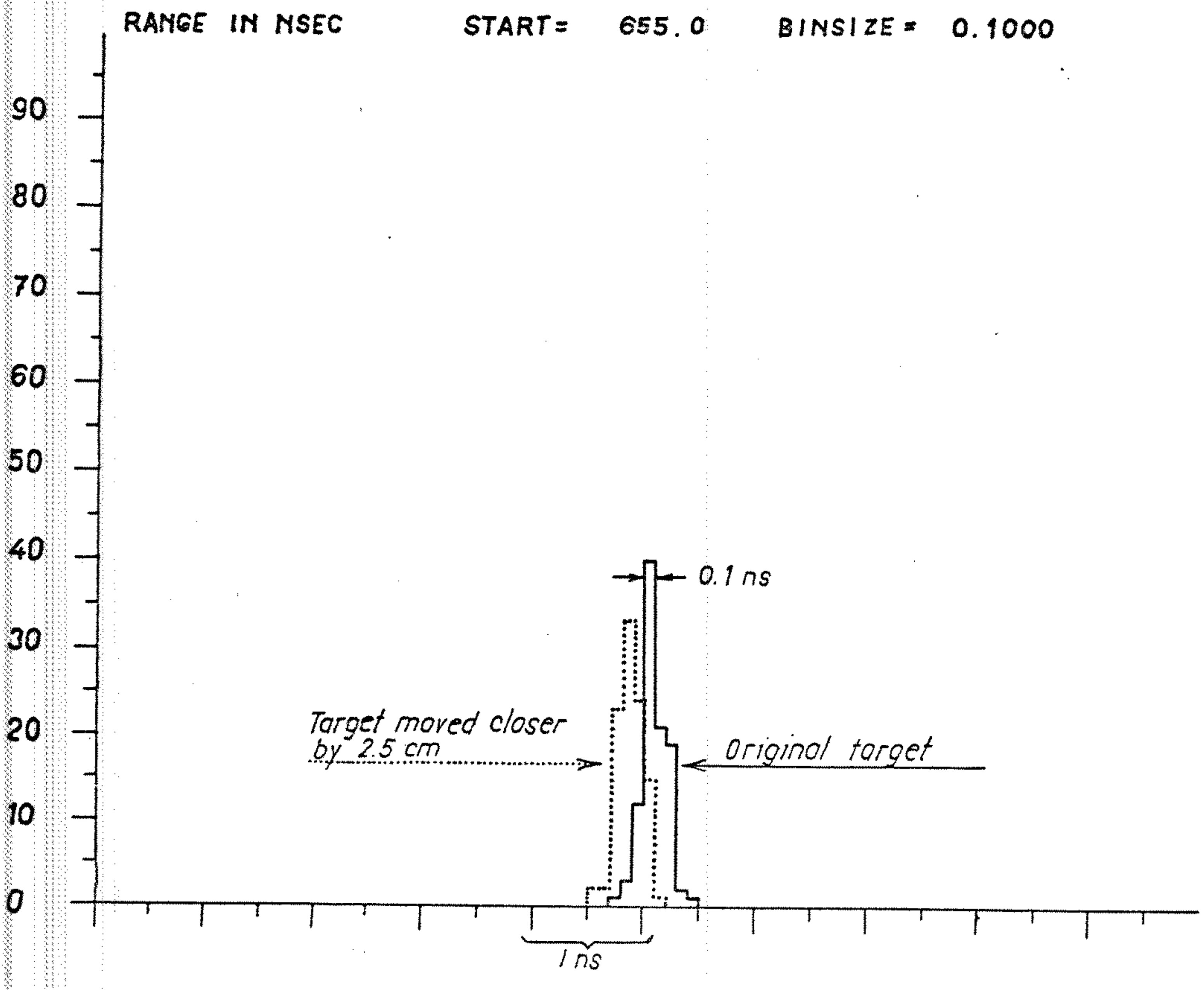
Histograms of 160 laser ranging shots to a stationary target /white diffuse flat plate/ at a distance of about 100 m are shown in Figure 2 to illustrate system performance. The solid lines are the original target position and the dashed lines are for the target moved 2.54 cm /1 inch/ closer to the transmitter.

V. Future plans

The system will be coupled to a new 1.2 m /48 inch/ telescope at the Goddard Space Flight Center and used in research on new techniques to achieve 1 cm range accuracy for spacecraft and /with amplifiers/ lunar tracking.

Steve Davis
John Deguan
Sherman Paultney




RANGE IN NSEC
START= 655.0
BINSIZE= 0.1000
90
80
70
60
50
40
30
20
10
0
0.1 ns
Target moved closer by 2.5 cm
Original target
1 ns

O.N.E.R.A. LASER TRACKING STATION

Claude VERET

The ONERA* laser tracking station is actually in operation on the GRAN CANARIA island, 28° north in latitude, near the Africa west coast.

This station includes an azimutal pedestal which is a modified BOFORS gun; laser transmitter and receiver are mounted on it.

The main features of this equipment are the following:

- Laser transmitter:
  - Ruby laser Q-switched by rotating prism.
  - Energy per pulse: 1 J
  - Half width of the pulse: 30 ns
  - Frequency of pulses: 1 per second
  - Divergence of the beam /out of the laser/: 30´
  - Afocal refractive telescope: X 10
  - Divergence /out of this telescope/: 3´
- Receiver:
  - Cassegrainian reflective telescope
  - Diameter of the primary mirror: 60 cm
  - Telescope focal length: 2.2 m
  - Spatial filter giving a field of view of: 3´
  - Spectral filters: 0.5 or 1 nm
  - Rotating density filter
  - Detector: PMT, 56 TVP RTC

Two modes of tracking can be used:

Mode 1: Visual tracking

An observer, sit on the pedestal, see the satellite in a refractive telescope /diameter 120 mm, X 23/ and track it with the aid of a joystick acting on azimutal and elevation mecanisms. During a passage, the laser is fired permanently at the recurrence frequency of one shot per second.

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*ONERA: Office National d'Etudes et de Recherches Aéro-
spatiales
92320 Chatillon /France/

Acquisition is done visually from the predictions.

Mode 2: Semi-automatic blind tracking

This second mode is mainly used for high magnitude satellites uneasy to track visually such as STARLETTE. Other satellites, such as GEOS and BEACON, can also be tracked by this mode when they are in the shadow, by night, or in crepuscule conditions.

Predictions of the satellites are computed by the CNES Centre in TOULOUSE and sent by telex to the station. These predictions are either ephemerides or orbit parameters. They are introduced in a computer, the output of which is applied on a cathodic oscilloscope, at the time predicted for the passage. On the screen of the oscilloscope appear several spots: the spot at the centre of the scope correspond to the predicted position of the satellite at the observation time; the other spots are positions earlier or later.

An other reticle appears on the screen corresponding to the optical axis direction of the pedestal; this reticle is obtained by voltage applied to the scope due to azimutal elevation encoders mounted on corresponding axis.

An observer seeing the screen, acts on a joystick to move the pedestal and the reticle with it. With a good prediction, tracking is obtained maintaining the reticle on the central spot.

If the satellite is delayed with regard to the prediction, acquisition can be done exploring with the reticle the other spots appearing on the screen. The first echo obtained by mean of this exploration, the computer receives an order to delay its program and tracking is then done as for a good prediction.

All datas are acquired by the memories of the computer. After experiment, they are extracted from it and perforated punched tape which is transmitted by telex to the CNES Centre for processing.

Calibration procedure

As for most laser tracking stations, calibration constant can be determined, illuminating a target at a known distance.

An other mode of calibration procedure can be also used.

When operating, the start signal for the counter is given by a diode detector in the laser transmitter, and the stop signal is given by the photomultiplier in the receiver.

The diode is illuminated by a small part of the laser pulse reflected by a beam splitter /glass plate without coating/.

The calibration constant includes the optical and electronic delays due to the fact there are twodifferent detectors and associted electronics for starting and stopping the counter. If a light pulse would act on the same detector /i.e. the diode/ for start and then for stop after reflexion on a target, the calibration constant would be zero, or only corresponding to a geometric distance. So, to get the calibration constant, the following procedure is possible:

The beam splitter, before the diode is rotated by 90°. So, when firing the laser to a target there is no pulse on the diode when leaving the transmitter. The pulse illuminates the target and comes back to the transmitter - - receiver. Part of this light, reflected by the beam splitter gives a pulse on the diode which starts the counter; an other part of the light reflected by the target goes through the receiver and gives a pulse on the photomultiplier which stops the counter. The recorded time is the calibration constant.

By means of suitable density filters before diode and photomultiplier, it is possible to adjust, for the calibration, light levels as in operating conditions. Adjustable density edge existing permanently before the photomultiplier allows calibration constant determination versus light pulse return level.

LASER BEAM WAVEFRONT DISTORTIONS MEASUREMENTS

H. Billiris and N. Tsolakis
National Technical University of Athens
Surveying Laboratory

ABSTRACT: Laser beam wavefront distortions affect the accuracy in range measurements, mainly in the case of satellite range measurements. In this paper we discuss a new technique foe the direct measurements of the Laser beam wavefront distortions for the Laser Ranging System of the Satellite Tracking Station, in Athens, Greece.

INTRODUCTION

During the last decade Laser Ranging Systems have provided with the most accurate Satellite range measurements. Today this accuracy is of the order of 30 - 50 cm for ranges of a few megameters. In order to achieve a better accuracy using the existing Laser systems we have to find more sophisticated algorithms for the data analysis. Lehr et al., /1973/ and Billiris /1974/, have discussed for new ways of analysing the data. Laser pulse photography, Lehr et al., /1973/, gave a new correction of the order of a few nsec and Laser beam distortions, Billiris /1974/, provided with another new correction of about the same order of magnitude. The last correction is possible if we know the laser beam wavefront corrugations as well as the position of the target in the Laser beam.

Studies of Korobkin et al., /1966/, /1967/, on Laser pulse photography with a streak camera showed the directional distribution of the radiation with differences of the order of 20 nsec. Ambarsumyan et al., /1967/ and Gibbs and Whitcher /1967/ have shown that the magnitude of the wavefront distortion is comparable to the duration of the Q-switched laser pulse.

This paper describes a new technique for the direct measurements of the laser beam wavefront distortions for the Satellite Tracking Station at Dionysos Athens, Greece.

The experiments carried out, show that the wavefront structure of this system affects the accuracy of ranging to satellite.

EXPERIMENTAL SET UP - MEASUREMENTS AND RESULTS

The laser transmitter consists of a TRG 104A ruby laser and a rotating roof prism. The output pulse is about 60 MW with a width of 25 ns. The beam divergence is 1-2 mrads and the repetition rate 2 ppm. We also used a Hewlett Packard, AH 5360A Computing Counter with a resolution of 1 ns. As photosensitive unit we used a 931A multiplier phototube at a distant of about 50 m. The laser light incidents the photosensitive surface of the tube through a 90° prism, of 4 mm diameter next, to which a 6943 Å filter was set.

Figure 1, gives the block-diagram of the used system, where we have used the START circuit of the laser system and as STOP pulse the one coming from the phototube. Using the system´s amplifier we controlled the STOP pulse to be of constant height 1 V, to avoid a correction from pulse´s centroid. The threshold of the START pulse was 2 V and of the STOP pulse - 0.6 V.

We started lasing to the tube, centered at the beam´s center, and we supposed that these counter reading corresponds to the system delay. In each experiment we measured this system delay at least three times and the standard deviation of the mean was about 0.5ns. Then we moved the laser mount according to a matrix. In order to find the wavefront structure we subtracted the counter reading of the points of the matrix from the system delay.

Figure 2, shows the results from the experiment # 3 /see Table 1/ and two sections of the beam. The matrix was 5x5 with space interval $0^{\circ}.100$ on the mount. At the end of the experiment we also measured a matrix 3x3 with space interval $0^{\circ},050$. for the same experiment. To each point we lased 10times. We fount strong wavefront structure and peaks of laser light close to the center. We run more experiments and we sow again the same peaks and, in general that the wavefront structure is reproducable. The standard deviation of the mean counter reading in each point was of the order of 1 ns.

As a conclusion we can say that this way of measurement of the beam wavefront structure can give the wavefront distortions of the laser beam. The accuracy of these measurements is very good for laser units, like the examined one, which shows a strong wavefront patern. For more accurate measurements, care will have to be taken for the cables the tube responses and maybe correction from the centroid.

The study of the wavefront distortions will give explanations on the spreading of counter reading for the case of ground targets /especially prisms/ and will improve the satellite ranging accuracy if we know the position of the satellite at the instant of laser range measurements.

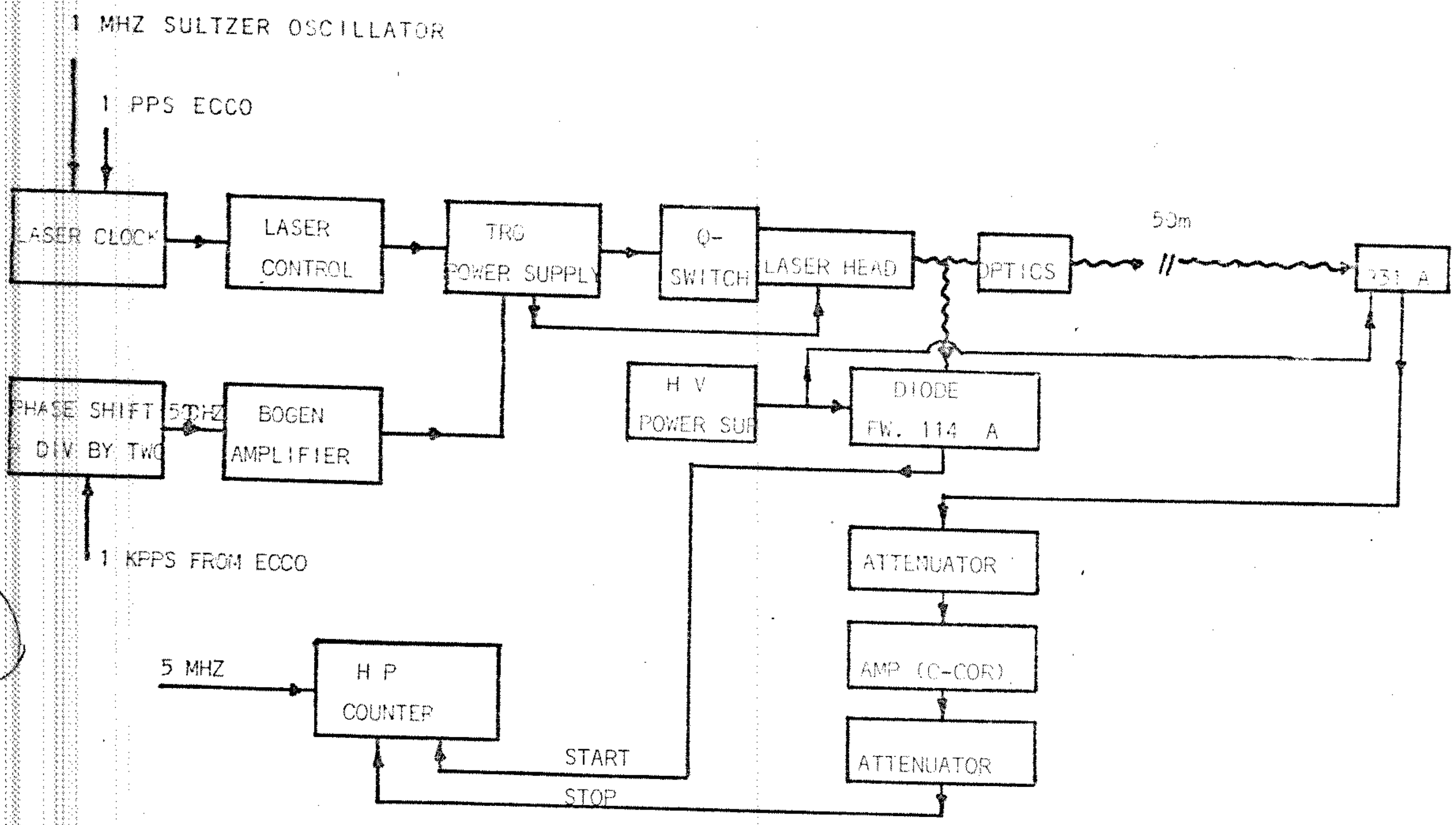

Figure 1 Block diagram of the system used in experiment # 3, # 4, # 5, # 6.

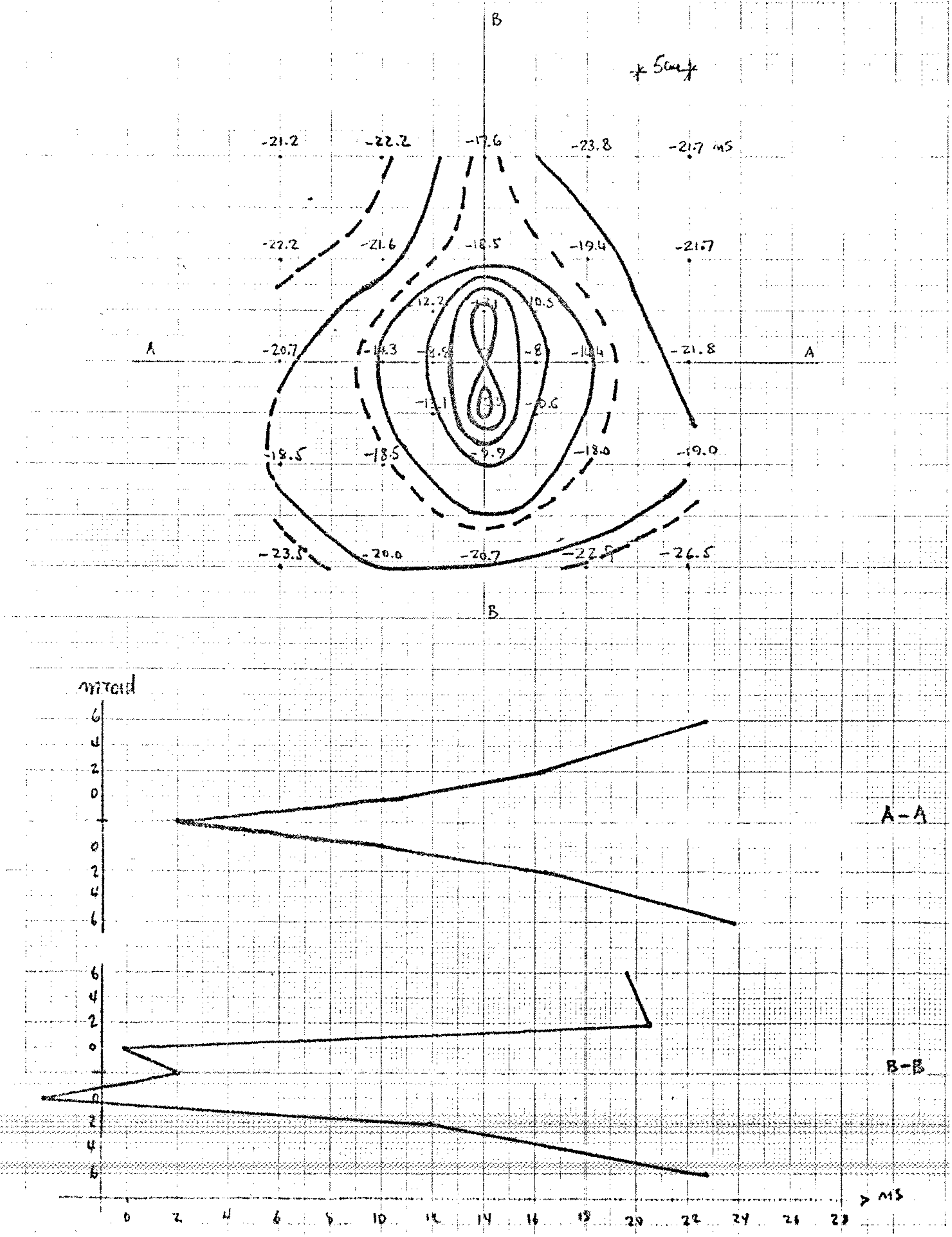

Fig. 2. Wavefront structure as of the experiment of the 22nd of

TABLE 1

RESULTS FROM THE WAVEFRONT'S STRUCTURE EXPERIMENTS

Points a/a	# 3 Space between points (0°.100)			# 4 (0°.100)			# 5 (0°.100)			# 6 * (0°.025)		
	Mean ns	σ_m ns	Gain db	Mean ns	σ_m ns	Gain db	Mean ns	σ_m ns	Gain db	Mean ns	σ_m ns	Ga d
1	-21.2	0.51	32	-21.4	0.65	31				-15.6	0.31	2
2	-22.2	0.80	30	-29.0	1.25	25				-13.4	0.41	2
3	-17.6	0.39	26	-17.7	1.29	23				-3.0	1.64	2
4	-23.8	0.48	27	-26.5	0.81	26				-14.2	0.80	2
5	-21.7	0.27	31	-26.5	0.73	30				-17.2	0.65	24
6	-21.7	0.70	30	-26.5	1.72	27				-13.2	1.50	2
7	-19.4	0.58	23	-21.8	1.46	24	-23.9	2.19	21	-9.7	1.05	21
8	-18.5	1.20	17	-15.1	1.02	19	-18.0	0.74	19	+12.6	1.05	21
9	-21.6	0.69	22	-24.7	2.12	21	-19.2	0.67	22	-14.4	0.45	20
10	-22.2	0.85	30	-30.0	1.92	27				-15.2	0.70	23
11	-20.7	0.52	26	-26.4	0.41	26				-13.3	1.97	23
12	-14.3	0.60	21	-22.0	1.23	19	-20.8	0.22	19	-13.5	0.75	18
13	0	0.41	8	0	0.46	8	0	0.95	10	0	0.70	10
14	-14.4	0.70	21	-23.3	1.40	19	-18.4	0.49	19	- .3	1.58	23
15	-21.8	0.94	26	-28.1	2.04	26				-13.5	0.70	24
16	-19.0	0.76	30	-30.7	1.04	27				-13.6	0.61	24
17	-18.0	1.06	23	-21.4	0.90	22	-23.7	1.27	22	-10.3	0.99	23
18	- 9.9	0.62	14	-11.2	0.86	19	-11.3	1.42	19	+ 6.4	1.08	21
19	-18.5	0.63	22	-22.6	0.89	22	-22.5	1.10	22	- 9.5	0.95	22
20	-18.5	0.83	30	-27.4	1.19	27				-15.5	0.45	23
21	-23.5	1.19	32	-25.2	0.86	32				-17.0	0.63	23
22	-20.0	1.13	30	-28.2	0.57	29				-13.6	0.34	22
23	-20.7	0.77	26	-27.2	1.08	26				- 4.6	1.51	22
24	-22.9	0.80	29	-27.8	2.08	30				-10.7	0.72	23
25	-26.5	0.98	34	-33.9	1.74	35				-18.6	1.13	24
26	-12.2	0.54	19	-15.8	1.10	19						
27	+ 2.1	0.82	18	- 1.0	0.13	17						
28	-10.5	0.58	20	-14.4	0.55	20						
29	- 8.0	0.77	20	- 9.5	1.47	20						
30	- 8.8	0.54	19	-13.8	0.58	19						
31	-13.1	0.69	20	-14.6	0.70	20						
32	+ 5.3	0.69	18	+ 4.1	0.59	19						
33	-10.6	0.56	20	-11.8	1.55	20						
	10 meas.per point			4 meas.per point			4 meas.per point			4 meas.per point		

* There is no correlation in numbering of the points in exp. #6. But we could correlate the values of the same point number for the experiments #3, #4, and #5.

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A LASER RANGE TRACKING STATION FOR GEODINAMIC SATELLITES

by L. CUGUSI*, F. MESSINA**, E. PROVERBIO*

In this paper the authors describe the final plans for the realization of a Laser telemetry station, which is now in an initial stage of construction.

The Optical-Mechanical System

- Mount: modified CONTRAVES EOTS-B Cinetheodolite, 15" pointing accuracy; maximum velocity 30°/s, minimum velocity $0^\circ.02$/s, maximum acceleration $60^\circ/s^2$
- Tracking: manual by joy-stick, monitoring the satellite by a closed circuit television camera (Magneti Marelli CT S/1)
- Transmitter optic: 12 cm Ø Galilean telescope, 8x
- Transmitter beamwidth: $4\times10^{-4} \div 3\times10^{-3}$ rad.
- Receiver optic: 50 cm Ø Cassegrain telescope, 1:2.5 parabolic primary mirror (Duran 50 SCHOTT glass type), 4x hyperbolic secondary, e.f.l. 500 cm
- Receiver beamwidth: $3\times10^{-4} \div 6\times10^{-3}$ rad. by variable field diaphragm
- Tracking telescope: 20 cm Ø Maksutov-Newtonian telescope, 1:3 primary mirror, giving a visual angle of 2.5 on 1 inch vidicon
- Interference filter: 7 to 10 Å bandwith, 50 to 55% peak transmission (ORIEL or BALZERS), working in parallel light

The Laser

- Ruby KORAD LASERS:
- multimode oscillator stage K15QPTM (Pulse Transmission Mode) which can supply pulses of 250 mJ in 4 ns with, 60 ppm
- amplifier stage capable of raising the pulse energy to 750 mJ, 60 ppm, thus giving an instantaneous power of about 150-200 MW at 3 mrad. FAHE

The Electronics (see the block-diagram)

- Photomultiplier: RCA C31034A or VARIAN VPM-163, 15% of QE at $\lambda = 6943$ Å
- Peltirr effect cooling chamber (TE 102 PRODUCTS for RESEARCH Inc.)
- Time-counter: ELDORADO 796, 1 ns resolution
- Time base Atomic Cs Master Clock (OSCILLOQUARZ B 5000)

- -Constant fraction discriminator
- -Printer: H.P. model 5055 or SODECO model PS
- -Visualization of the angular position of the telemeter on two counters of the up-down type with solid state display controlled by two incremental encoders of the optical-electronic type, giving 4,000 pulses per revolution (C.O.M.P. Company of Milan)
- -Oscilloscope: TEKTRONIX 7000 Serie

With this set-up and with a precise calibration of the statio on targets as a function of echo height, we should expect a standard deviation of less than 20 cm for an "average" passage of a "typical" satellite.

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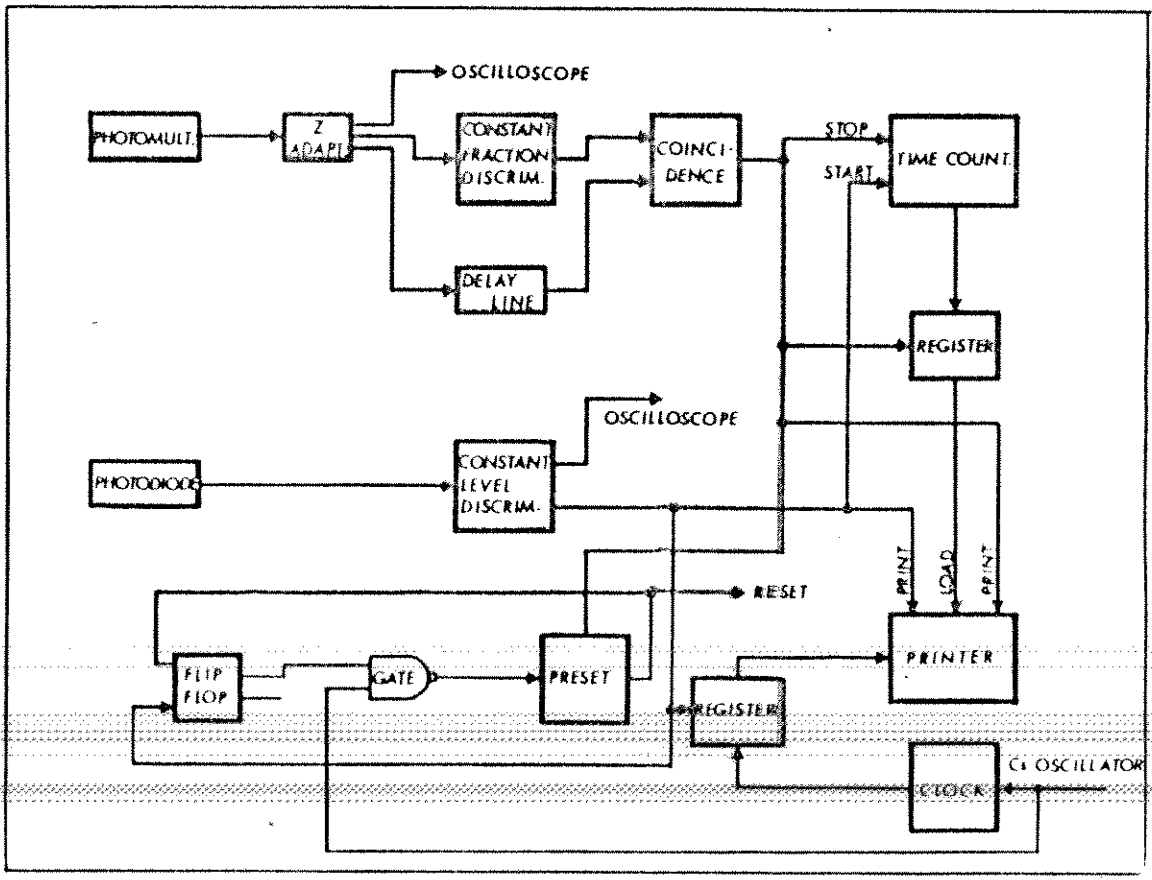
** Stazione Astronomica Internazionale di Latitudine, Cagliari-Carloforte, ITALY



Block diagram for pulse detection

Performance of the Potsdam laser rangefinder

H. Fischer, R. Neubert, H. Pauscher, Ch. Selke, R. Stecher
Central Earth Physics Institute, GDR

Workshop on Laser Tracking Instrumentation
11. - 15. August 1975
Prague

73

The Instrument

The development carried out at the Central Earth Physics Institute in Potsdam had the aim of extending the already available satellite camera SBG made by VEB Carl Zeiss Jena in such a way that besides the determination of angular positions, satellite ranges can also be found with the aid of a laser attachment. For this, the SBG was equipped with an additional hinged mirror which is swung into the ray path during ranging. Thereby it is possible to have a rapid changeover between the two types of observation, so that in the course of a single passage both photographic and laser observations can be carried out.

The technical parameters of the instrument are typical for first-generation systems. Details of the instrument are published elsewhere /1/.

Transmitter

Output	1 to 2 J
Pulse duration	15 to 25 ns
Repetition-frequency	max. 0.1 Hz
Angular aperture	1 to 3′

Receiver

Effective aperture	320 mm dia.
Field of view	1 to 10′
Filter	$\Delta\lambda$ = 1 nm, T = 50 %
Photomultiplier RCA C 31000 A	S-20, 2 ns
Counter resolution	10 ns

Oper[illegible] of [illegible]

[illegible] first successful satellite echos [illegible]
March 1974 [illegible]
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the laser satellites are very faintly visible with our guiding telescope. This and unsufficient training of the observers have led to a low number of observations so far. Ranges from 20 satellite passages were obtained, with up to 32 echos per passage. The largest measured range of GEOS A was 2,8 Mm.

The used photomultiplier generates a relative large rate of dark pulses with higher amplitudes. So the threshold of the discriminator has to be set to 15 electron equivalents for a gate time of 5 ms. To increase the effectivity of the system, we want to replace the multiplier and to improve the guiding system.

Ranging error

Analysis of the first range measurements by the short arc method led to standard deviations between 0,8 and 1,2 m /2/. It is assumed that this random errors are primarily due to variations in signal amplitude and shape and to counter resolution. Simple statistical analysis showed that the mean standard deviation produced by the limited counter resolution is $\tau/\sqrt{6}$, where τ is the counter resolution. Therefore one would expect for 10 ns resolution a standard deviation of 4 ns corresponding to 0,6 m, if other sources of error are absent. Using the well known relation for the resulting standard deviation $\sigma_{res} = \left(\frac{\tau^2}{6} + \sigma^2 \right)^{1/2}$, which is applicable with some restrictions, it is seen that in our case the contribution of the other error sources ranges from 0,5 m to 1,1 m.

To study the influence of the signal amplitude we made range measurements to a small retroreflector prism 2 km away. The signal amplitude was varied by glass filters in front of the receiver. Since we used a simple leading edge discriminator, the measured range shift is nearly proportional to the logarithm of the signal amplitude. This corresponds to the exponential rising of the laser pulse, at levels far below the pulse maximum. It was found that a tenfold signal increase shortens the travel time by 7 ns corresponding to 1 m. This value may depend on the laser adjustment and the concentration of the Q-switch-solution. If it is assumed, that the mean signal amplitude from the satellite is different from the calibration level by two orders of magnitude, an additional systematic error of 2 m would result.

Recently we replaced the simple trigger by constant fraction detector developed in our laboratory. This circuit reduced the shift to less than 3 ns within the dynamic range of 20 dB. For very high signal amplitudes a positive shift up to 10 ns per 10 dB has been observed, which is presumedly due to overload.

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H. 2, S. 53-56

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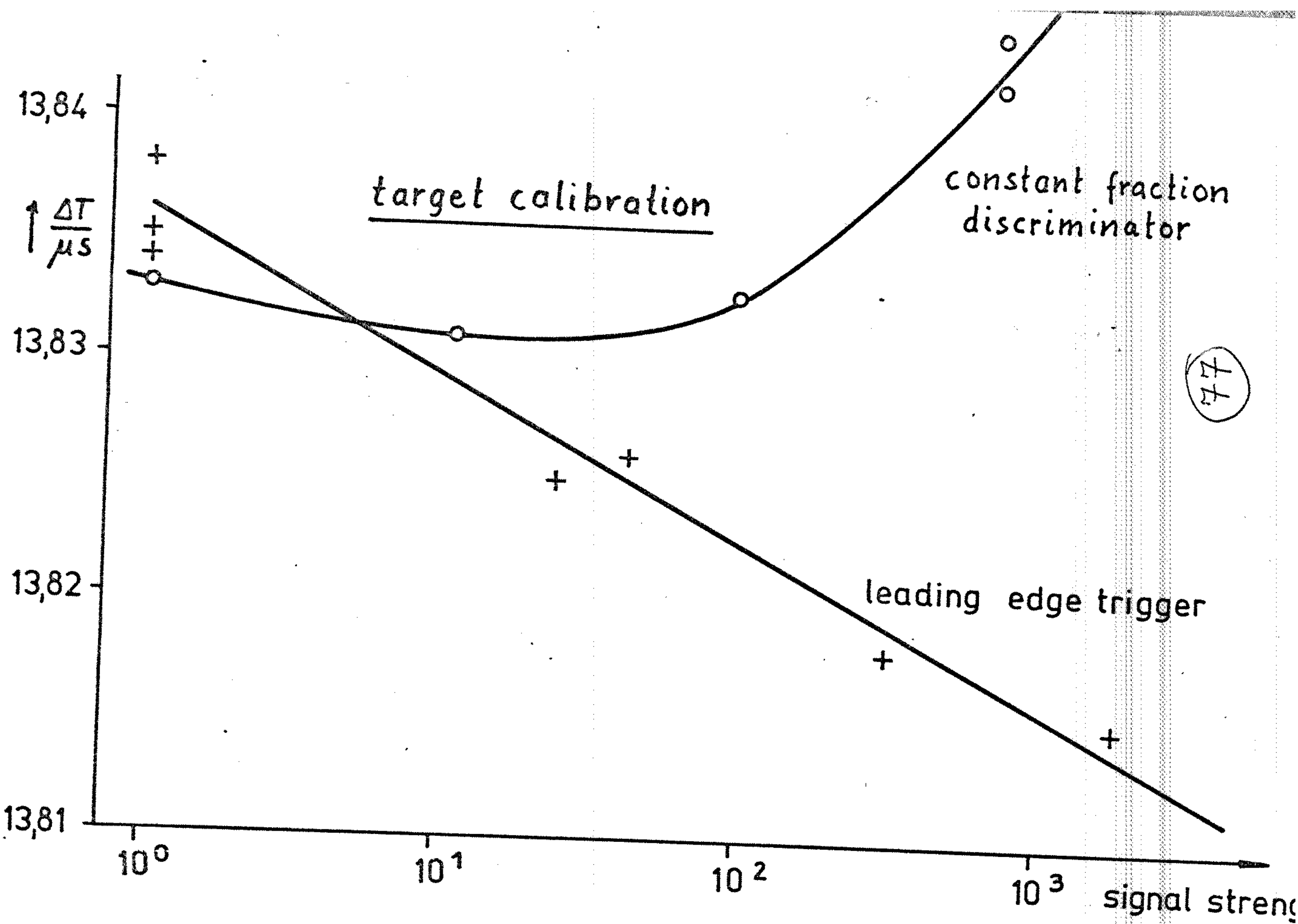
Vermessungstechnik <u>23</u> (1975)
H. 2, S. 60-63


target calibration
constant fraction discriminator
leading edge trigger
$\uparrow \frac{\Delta T}{\mu s}$
13,84
13,83
13,82
13,81
10^0
10^1
10^2
10^3
signal streng

(77)

COMPUTER SIMULATION OF PULSE CENTROID CORRECTION PROCEDURE

K. Hamal, M. Vrbová

We attempted to find the theoretical limit of time interval measurement accuracy when pulse centroid correction procedure is done. The computer was used to simulate some realizations of photomultiplier current and to fulfil the analog centroid correction procedure /1/.

It is possible to find to every function $I(t) \geq 0$, representing a detected pulse signal, the monotone functions $A_1(\tau)$, $A_2(\tau)$, $F(\tau)$

$$A_1(\tau) = \int_{-\infty}^{\tau} I(t)\, dt \; ,$$

$$A_2(\tau) = \int_{\tau}^{\infty} I(t)\, dt \; ,$$

$$F(\tau) = \frac{A_1(\tau) - A_2(\tau)}{A_1(\tau) + A_2(\tau)} \quad \varepsilon \quad \langle -1, +1 \rangle \; .$$

Fig. 1 shows us three random realizations $I_r(t)$ of photocurrent $I(t)$ for three different signal levels. N is number of photoelectrons detected. I_o is the ensemble average $\langle I_r(t) \rangle$ and it is proportional to instantaneous light intensity. $F_r(\tau)$, $F_o(\tau)$ denote the functions F appropriate to $I_r(t)$, $I_o(t)$ respectively. The center of light pulse is defined by equation $F_o(\tau_o) = 0$.

In the case when pulse center τ_r is numerically obtained the equality $F_r(\tau_r) = 0$ is satisfied. The random value $(\tau_r - \tau_o)$ representing of the error of this correction is the distance of the points where functions $F_r(\tau)$ and $F_o(\tau)$ intersect the τ axis.

The analog pulse centroid correction needs the stop time τ_s and the value $F_r(\tau_s)$ to be measured. $F_o(\tau)$ is assumed to be known from callibrations or from pulse shape measurements. The equality $F_o(\tau_1) = F_r(\tau_s)$ enables us to obtain the correction τ_1. The error $\Delta\tau$ of this measurement is equal to the horizontal distance between $F_r(\tau)$ and $F_o(\tau)$ for $F = F_r(\tau_s)$.

The simulation procedure was repeated and the statistic ensemble of results was discussed. Results are summarized in Table 1.

Table 1. Theoretical limit of accuracy

Number of photo-electrons per shot	10^3	10^2	10
Accuracy of adaptive threshold correction /nsec/	± 1.3	± 3.3	± 7
Accuracy of analog centroid correction /nsec/	± 0.4	± 1.5	± 7

The laser pulse length 15 nsec and PMT resolution time 1 nsec were supposed. The success of pulse centroid correction procedure depends on the signal level and the theoretical accuracies of numerical and analog centroid corrections are the same as far as the measured value $|F_r(\tau_s)| \leq 0.8$.

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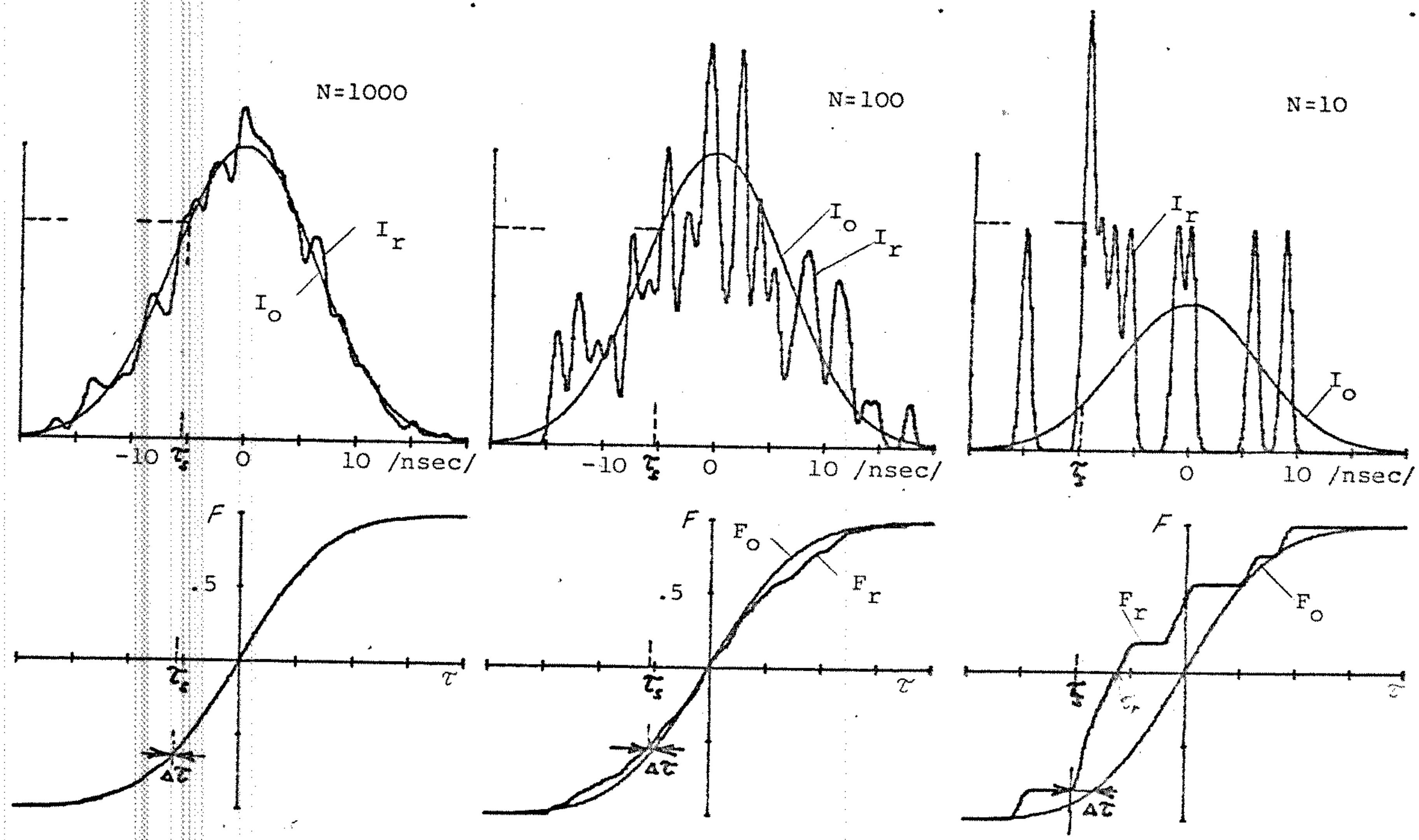

Fig. 1. Stochastic signal realizations and functional characteristics

The Satellite Ranging Station at Kootwijk (Holland)

William H. Havens } Institute of Applied Physics
Huibert Visser } Delft

Adriaan Backer } Delft University of Technology
Franklin W. Zeeman } Working group for Satellite geodesy

1 MEASURING SYSTEM SET-UP

- Detection PMT : RCA model 8852 (ERMA III photocathode)
- Optical filters: bandwidths: 3 Å , 10 Å , 100 Å , 500 Å
- Programmable attenuator: 0 - 63 dB, attenuation predicted on paper-tape. Manual correction has been provided.
- Amplifier: amplification 30 dB, risetime 0.8 ns.
- Range gate generator and Epoch clock: SAO design.
- Time interval counter: Hewlett-Packard model 5360 A with time interval plug-in H 01-5379 A.
- Laser control unit: produces CHARGE and FIRE trigger signals for the laser system. The laser can be fired at any predicted time on full seconds. Manual correction of the firing epoch with -3.999 to +3.999 seconds has been provided.
- Station clock: Hewlett-packard 5065A Rubidium time standard. Continuous frequency monitoring by means of VLF phase comparison against MSF, Rugby, 60 kHz (receiver TRACOR model 890A). Time comparison against Netherlands national time standard (VSL, The Hague) using TV sync. pulse technique. Timing accuracy: within 5 µs of UTC.

2 TRANSMITTING AND RECEIVING TELESCOPE

A sketch of the integrated receiving and transmitting telescope and the mount itself is shown in figure 1. The transmitting telescope is of a refracting coudé design and the receiving telescope is a partial coudé design (optical path passes through the elevation axis) with a catadioptric (lens-mirror) optical train. The transmitting telescope is located where the second reflector is usually positioned in the more conventional cassegrain reflecting telescope. Notice that by folding the receiving telescope back on itself and placing the transmitting telescope concentric to the receiving telescope, the size of the complete optical system has been significantly reduced. The transmitted laser beam will have a beam diameter of 200 mm and the divergence will be adjustable from 1 to 20 arc minutes.. The aperture of the receiving telescope will be 500 mm and the field of view will be adjustable from 0.5 to 20 arc minutes. The mount angular position will be read out using absolute optical shaft encoders. The mount control unit compares the actual position with the desired position given by the paper tape reader. The error signal generated will then be used to drive the DC servo motor. An absolute pointing error of less than 20 arc seconds is expected.
The reflection of the laser beam on the second prism will be directed via a secondary optical path to the photomultiplier. In this way it is possible to perform an internal calibration for every shot using a second time interval counter.
A possibility for visual tracking has been provided by directing the light with wavelengths < 600 nm to an eyepiece.

3 LASER SYSTEM (Apollo, USA)

Specifications

Optical Train

Oscillator Rod	3/8" x 6" AR coated ruby
Amplifier 1	1/2" x 6" AR coated ruby
Amplifier 2	5/8" x 6" AR coated ruby
Output Mirror	3/4" x 1/8" 0° sapphire etalon
Q-Switch	0,45" clear aperture, KD*P Pockels cell, fluid immersed
Q-Switch Polarizers	Two Brewster plate stacks, five plates per stack
Rear Mirrors	100% dielectric-coated, 1" diameter
Cavity Configuration	Flat-flat, 26" mirror separation, pulse-on switching
Electro-optical Shutter	0,45" aperture, KD*P Pockels cell with dielectric polarizer. Transverse laser-triggered spark gap switch with coaxial transmission line pulse forming network.
Output Polarization	Plane of polarization perpendicular to mounting plane of optical train
Oscillator Power Monitor	ITT F4000 biplanar photodiode, S-1 surface
Amplifier 1 Energy Monitor	10 mm PIN silicon photodiode, UDT Type PIN10D
Amplifier 2 Power Monitor	Same as oscillator monitor

Performance Characteristics

Wavelength	6943 Å
Linewidth	0,3 Å fwhm
Output Energy:	
4 ns shuttered mode	3 joules
20 ns Q-switched mode	10 joules
Long pulse mode	15 joules
Beam Divergence	3 mrad between half energy points 5/8" maximum diameter
Output Stability	± 20% within one minute ± 10% within five minutes
Repetition Rate	15 per minute, maximum

4. AIRCRAFT DETECTION SYSTEM

One of the safety problems that arises when operating a laser ranging station is the possibility of eye damage to airplane passengers. To reduce this danger an aircraft detection system is being developed which will automatically disable the laser if an aircraft approaches the laser firing angle. The optical aircraft detection system shown in figure 5 will be used to perform this function. During the day a small field of view (5 arc minutes diameter) is scanned around the axis of the laser beam (1 degree off axis from the laser beam). If the constant signal level from the homogeneous background of the blue sky is interrupted by an airplane, the AC coupled photomultiplier signal can then be used to disable the laser.

During the night the system will detect the running lights of the airplane itself (red and green lights at the wing tips and at the tail a white light).

In the focal plane of the objective, the off axis pinhole is replaced by a pattern of transparent rings with a width of about one minute of arc.
When an airplane light passes a ring the AC coupled photomultiplier will give an electrical pulse. The field of view of the system that corresponds to the total area of the rings is so small that an acceptable false alarm rate caused by the star background is anticipated.

The aircraft detection system is under test now. The first results especially of the daylight system are promising. Testing of the night system is difficult during the summer, due to the lack of airplanes during the few hours of darkness.

5 CONCLUSION

The two major requirements for this system were first that the station be a second generation system capable of making single ranging measurements with an accuracy of better than 0.15 m and second that in the interest of design economy the station would be patterned after the operating SAO stations.
The complete system will be ready for test-operation by the end of 1975.

Besides this the system should also be able to illuminate satellites in order to perform alternatively range and direction measurements in conjunction with the existing camera equipement.

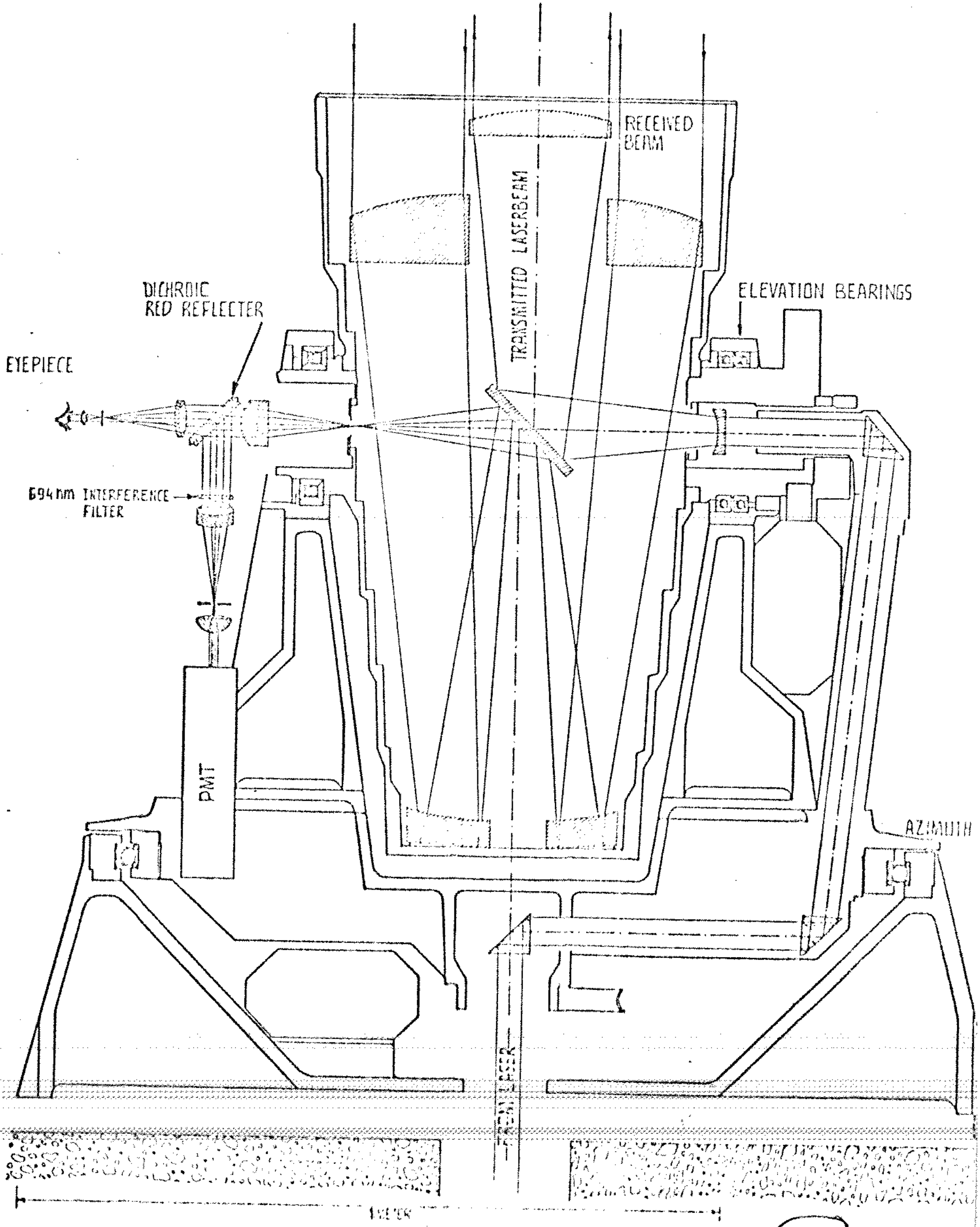
RECEIVED BEAM
TRANSMITTED LASERBEAM
DICHROIC RED REFLECTER
ELEVATION BEARINGS
EYEPIECE
694nm INTERFERENCE FILTER
PMT
AZIMUTH
FROM LASER

figure 1

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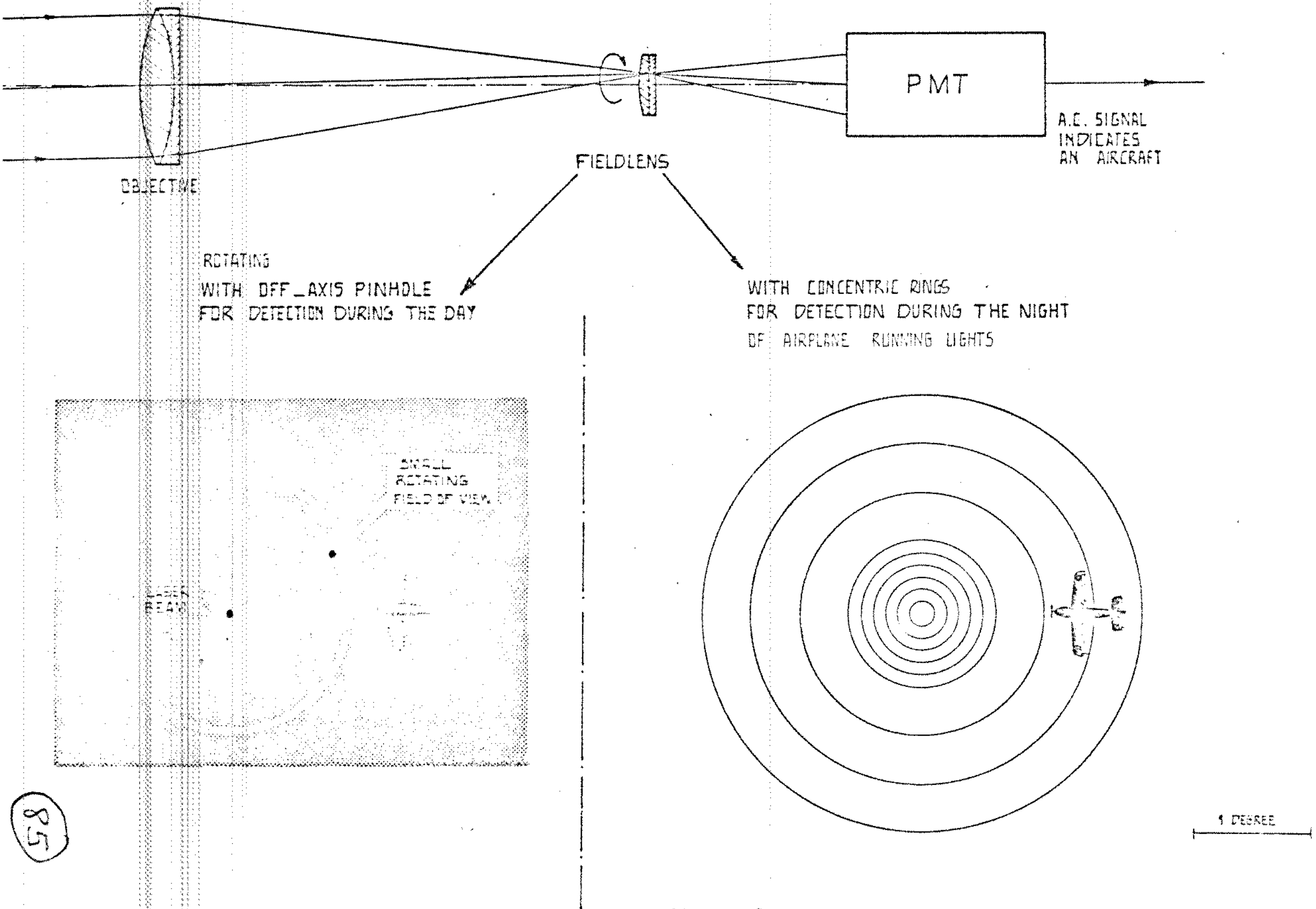

OBJECTIVE
FIELDLENS
PMT
A.C. SIGNAL
INDICATES
AN AIRCRAFT
ROTATING
WITH OFF_AXIS PINHOLE
FOR DETECTION DURING THE DAY
WITH CONCENTRIC RINGS
FOR DETECTION DURING THE NIGHT
OF AIRPLANE RUNNING LIGHTS
SMALL
ROTATING
FIELD OF VIEW
LASER
BEAM
1 DEGREE

figure 2

LONG DISTANCES MEASUREMENT ELECTRONIC SYSTEM

P. Hiršl, Vl. Krajíček, M. Pfeifer

Faculty of Nuclear Science and Physical Engineering

Prague, Czechoslovakia

If distances up to 5.10^5 km are to be measured with accuracy better then 15 cm there is necessary to use a clock with short term stability better then 3.10^{-10}. This claim could be satisfied by a good crystal oscillator.

Our electronic device allows the bind to the absolute time /UTC/ better then 1 μs, the accuracy of measured time intervals <1 ns with resolution ± 0,3 ns.

Measured data represent the instants of start - stop pulses; start pulse from the laser and stop pulses from returns. Measured data are fed in a computer, or other installed hardware, to compute the time intervals.

The 5 MHz signal from the crystal oscillator is translated to 10 MHz square wave and counted by a synchronous counter. Data from the counter are fed in a shift register at the moments of start and stop pulses. After coming the stated series of pulses, one start pulse and three stop pulses, the data from the register, including the data from time expanders, are fed in the computer. Because at least two out of three stop pulses are supposed to be noise pulses the computer program must be able to recognize the right returns.

The transcription of measured data from the register is controled by a device programable from a keybord, computer or punched paper tape/Fig.6./. The data trascription can be made to an individual hardware device /magnetic tape recorder, paper tape puncher, printer or computer/ or to some of them simultaneously. Numerical display used for optical checking of applied program or of measured data makes the part of this device.

The basic period of the clock pulses is 200 ns. This interval is divided by time expanders up to 0,1 ns.

The expander is stretching the intervals between start or stop pulses and the next in time clock pulses/Fig.1./ As to diminish difficulties with mechanical construction there is used special system of automatic calibration. This is very useful because there is no need in using thermal stabilization of expanders, which is used for examle in the counter Hewlett - Packard 5360 A .

As for delays in the unit there are used common signal paths for all start and stop pulses as maximum as possible. Common path is used for all stop pulses and partially for start pulse too. As the next there is used double cycle operation of expanders. In the first cycle of operation one from the expanders is started by a start /or stop/ pulse and stopped by the second next in time clock pulse. The achieved value stretched in the expander is counted up by an up - down counter. In the second cycle of operation instead of start / or stop/ pulse there is fed in a clock pulse through the start / stop / signal path and the expander is started and stopped by two neighbour clock pulses. The interval measured must be 200 ns and its stretched value is counted down by the sama up - down counter. Because all signals are going through the same signal path the resultant preccision is quite high. The operation of an expander is shown on Fig.2.

The expander is started at the moment t and stopped by the second next clock pulse at the moment

$$t_H + d$$

where d is delay of the stop pulse coming through different way. The stretched interval in the first cycle of operation is then $k\ (t_H - t + d) = N_1\ T_o$

where N_1 is the number of clock pulses inside the stretched interval
T_o is the period of clock pulses.
The interval $t_H - t + d$ is chosen greater than T_o.

The second cycle is started after the end of interval $N_1\ T_o$. This time the expander is started by a clock pulse at the moment

$$t_H + N\ T_o$$

and stopped at the moment

$$t_H + d + (N + 1)\ T_o$$

where $N > N_1$.
This second interval is stretched by the same way as in the first cycle of operation.

By the assumption the interval between both cycles is short enough to hold the same conditions for expander function that means

$$k = \text{const}, \quad d = \text{const},$$

the stretched interval in the second cycle of operation is

$$k\ \big(t_H + (N + 1)\ T_o + d - (t_H + N\ T_o)\big) = k\ (T_o + d) = N_2\ T_o.$$

The difference of both stretched intervals is

$$(N_1 - N_2)\ T_o = k\ \big((t_H - t + d) - (T_o + d)\big) = k\ (t_H - t - T_o).$$

That means that mode of operation eliminates the influence of delays. The difference $N_1 - N_2$ is read on the up - down counter.

In this mode of operation there is necessary to control only one of parameters, the parameter k, by means of a special feedback circuit. The number of expanders is chosen for one greater than needed in both groups of pulses and all the time one of each group is calibrated alternatively. In the time the expander is calibrated it is started by a clock pulse in the first cycle of operation too as in the second cycle. Then it is stopped after two periods of clock pulses by means of the path with delay d. The stretched interval will have the length

$$N_1' T_0 = k \left(2 T_0 + d \right).$$

The second cycle of operation is the same as above. Its stretched length will be

$$N_2 T_0 = k \left(T_0 + d \right).$$

The difference of both expessions

$$(N_1' - N_2)\ T_0 = k\ T_0$$

that means $N_1' - N_2$ is the actual value of the parameter k.

If there is no agreement between the actual value and required value of k the feedback calibration is led in action and some of parametrs of the expander are changed to get

$$N_1' - N_2 = k\ .$$

The block diagram of the whole device is on Fig.3. The block diagrams of start and stop pulses are on Fig.4. resp. Fig.5. The selected value of the parameter **k** is

$$k = 1000\ .$$

The time interval resolution of the system is 0,1 ns, with jitter of expanders ± 0,3 ns and accuracy of time interval < 1 ns.

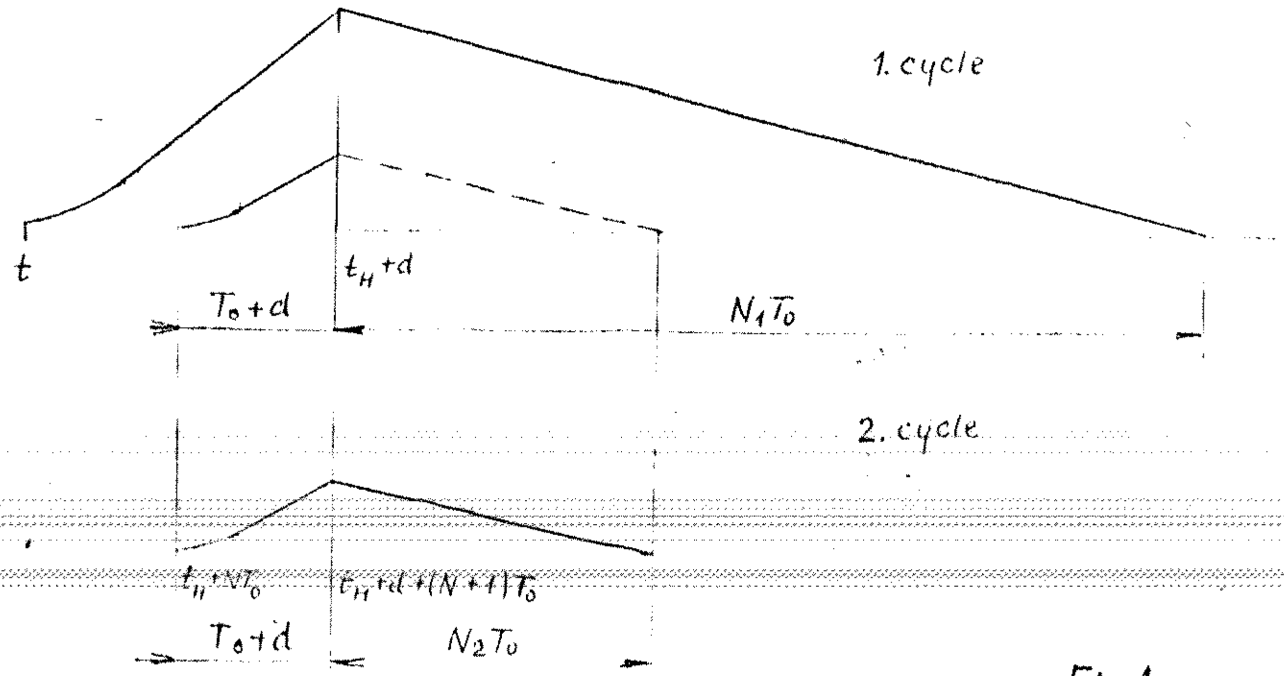
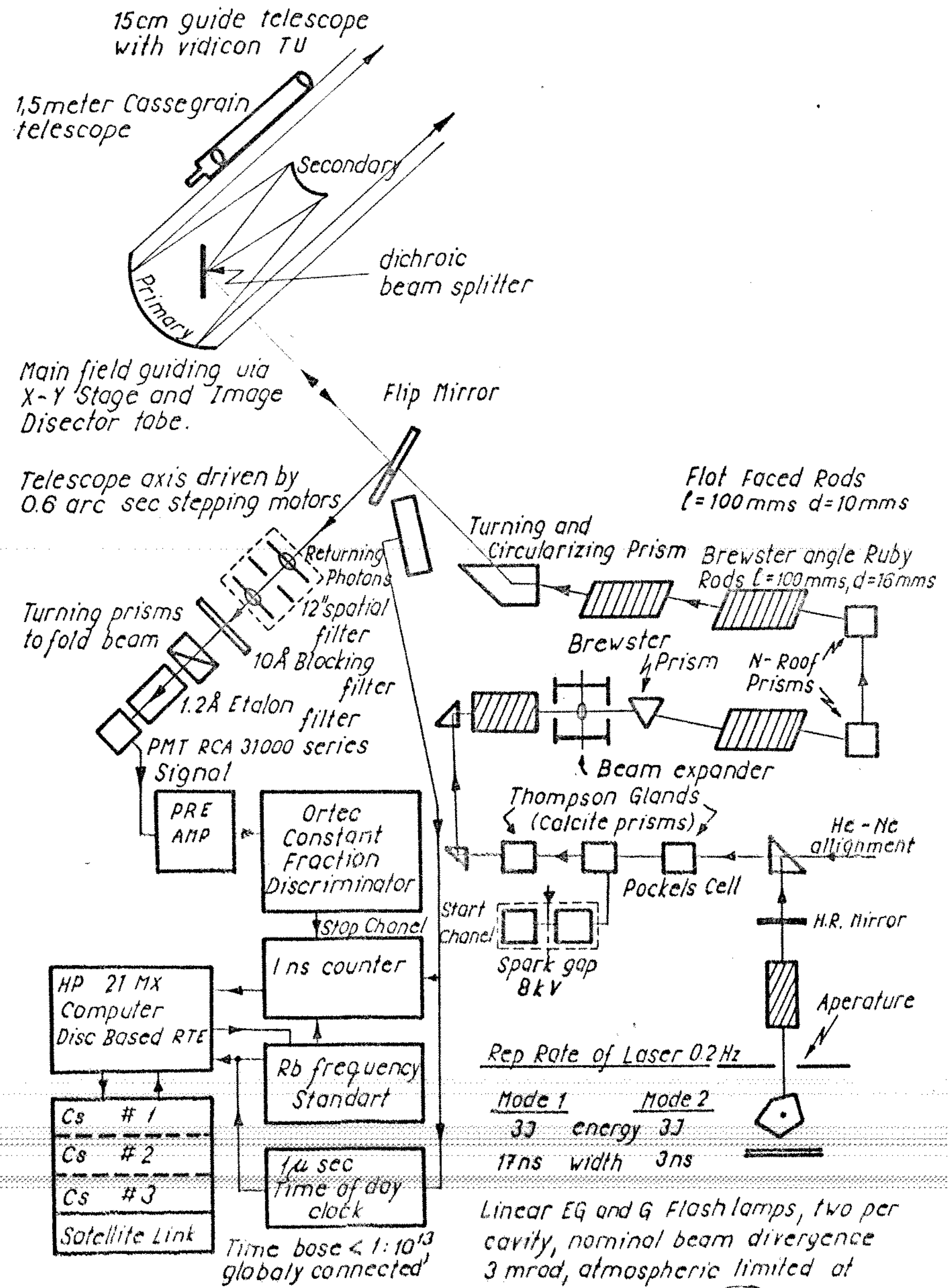


Fig. 1.

A Schematic of the Australian Lunar Ranger

P. Morgan



Rep Rate of Laser 0.2 Hz

Mode 1		Mode 2
3J	energy	3J
17ns	width	3ns

Linear EG and G Flash lamps, two per cavity, nominal beam divergence 3 mrad, atmospheric limited at transmission.

INTERKOSMOS SATELLITE FOR LASER RANGING.

Pavel NAVARA +/.

ABSTRACT:

The basic data of the INTERKOSMOS satellite AUOS-Z, that as the first IK satellite enables laser ranging, are presented. The satellite orbital data, the description of the corner cubes panel, the brief explanation of the technical solution as well as the preliminary satellite technical parameters are summarized. The parameters depending on the final technical realization /like the transfer function/ are omitted and will be supplied in the report that is prepared for COSPAR Plenary Meeting 1976.

+/

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Astronomical Institute
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251 65 ONDREJOV,

Ondrejov Observatory,

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THE SATELLITE LASER RADAR WITH IMPROVED PARAMETERS.

P. NAVARA, Astronomical Inst. Czech. Ac. of Sciences.

SHORT PRELIMINARY INFORMATION:

The satellite laser radar with the improved technical parameters /compared with Interkosmos laser radars in the action now/ will be complected on Ondrejov Observatory at the end of this year. We suppose the following technical parameters / the cross marks the realized instruments till now/.

TRANSMITTER+ /one stage ruby laser/: Faculty of Nuc. Phys. Prod.

Output power	~ 100 MW
Pulse length	< 15 nsec
Repetition rate	60 ppsec
Output beam divergence	0.5 ÷ 1 mrad /first version/ + 0.1 mrad /second version/

RECEIVER /Cassegrain - Manging/+: Astronom. Inst. Prod.

Diameter	630 mm
Filter	HBW = 1 Å T ~ 20%
PMT	RCA C 31 000 /ERMA/.
Field of view	0.1 mrad /according to tests/

MOUNT /two axes/ : Škoda Plzeň Prod.

Pointing accuracy	5 arc sec
Axes step	10 arc sec
Stepping motor	1.5 deg/step, step accuracy 0.5 deg. +
Tracking	punched tape /first step/ + minicomputer /second step/

ELECTRONICS:

Time base	5 µsec +
Universal counter	1 nsec /aut. addaptive thr. level/ +
Absolute time	0.1 usec /TV comparision with OMA osc./ +
Range gate	programmable

We wish to reach the accuracy better then 0.5 m and the action radius during the second step realisation 10 ÷ 20 Mm.

A NOVEL CENTIMETER ACCURACY, SUBNANOSECOND DOUBLE-PULSE SATELLITE LASER RANGING METHOD

Matti V. Paunonen

All current laser ranging systems are using single pulses. In this case discrimination against noise pulses is not very effective, and therefore for reliable detection a considerable number of return photoelectrons are needed. The use of multiple laser pulses to discriminate against background /1/ or to get greater accuracy or efficiency /2/ is known, but perhaps for technical reasons not used.

The proposed ranging method is based on the use of a precise double-pulse. In the detection process two signal pulses are needed, single or multiple photoelectrons, with known spacing, fig. 1 .

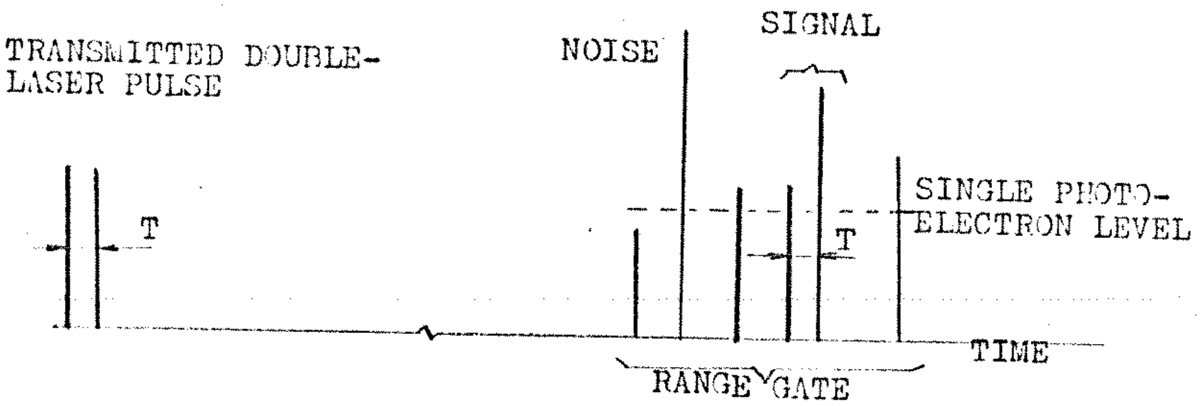

Fig.1. Double-pulse ranging method

The advantages of this system are: a) Automatic discrimination of background to a high degree. It is rare that during night time there appears two noise pulses with short spacing, say 5 ns, b) Effective received energy is increased without having to increase the transmitter power. The basic time resolution is better with two pulses than with only one. c) Detection is extended to a single photoelectron level.

The accurate double-pulse generation can be accomplished by slicing a Q-switched pulse or isolating two adjacent mode-locked pulses.In this proposal slicing is preferred for the following reasons: a) Both Q-switching and slicing methods are well proved b) Pulse length is easily adjustable, c) Relatively easy to accomplish d) Pulse quality is good. e) Well-suited for the double-pulse method. f) The same system can be used normally Q-switched or sliced at will. The shortening of the diffraction limited Q-switched pulse can be accomplished by a fast 50 ohm Pockels cell electro-optical shutter. driven by a laser triggered spark gap. A short pulse can be obtained by pulsing the Pockels cell with a short Vλ/2-pulse, whereas the double pulse formation needs two times Vλ/2-voltage. There are also three possible operating modes with this system, fig.2. The Q-switched pulse may be useful in preliminary seek of the satellite before precision measurements. With some commercially available Pockels cells and LTSGs one can obtain at least 0,5 ... 1 ns pulse widths.

The receiving method is straightforward and simple. Two photomultiplier pulses,comprising single or multiple photoelectrons,

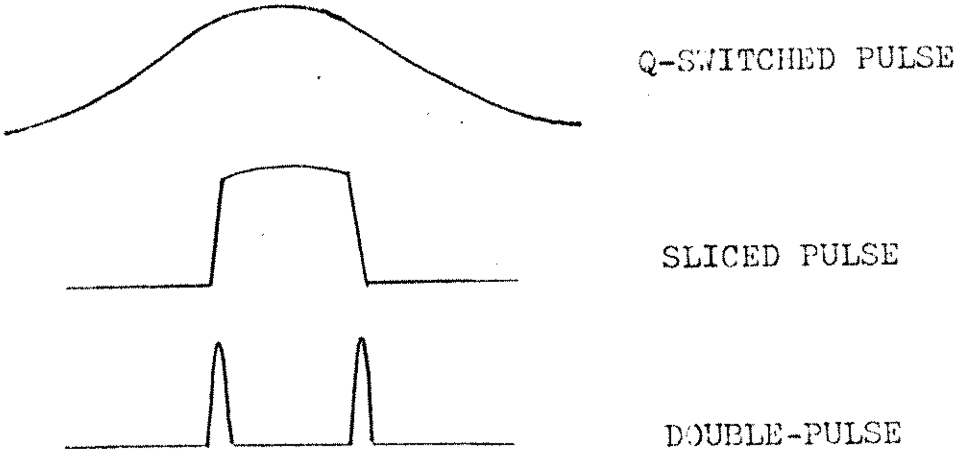

Fig.2. Operational modes of the system

separated in time by T, are needed for detection. The pulse sequence is detected, and using a simple delay line both the pulses are linearly multiplexed and processed e.g. in a CFD-discriminator to take care of pulse height variations. Modern PMT's have single-electron transit time spread about 300 ps or less. Possible electronic resolution seems to be some tens of picoseconds in a dynamic range of 1:200. Also modern interpolating range counters give a resolution of better than 100 ps. The total receiving resolution is near 300 ps (FWHM) in this case.

If a 1 ns bell-shaped pulse is supposed, the standard deviation of the the double-pulse system might be 5 cm in a single measurement even at minimal conditions, i.e. one photoelectron in both the sub-pulses.

Also the use of closely rectangular pulses, say 5 ns long , is interesting. It has been shown/3/ that the minimum-square-error with rectangular pulses decreases quadratically as the photoelectron number. Also the timing method is worth noticing: the optimum estimate for time measurement is the mean value of the first and last photoelectron pulse.

References:

/1/ S.Ackerman, T.S.Morrison, and R.L.Iliff: A programmed multi-pulse range measurement system. Appl.Opt. 6(1967)353.

/2/ I.Bar-David: Communication under the Poisson regime. IEEE T. Inf. Theory IT-15(1969)31.

/3/ I.Bar-David: Minimum-mean-square error estimation of photon pulse delay. IEEE T. Inf. Theory IT-21(1975)326.

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Radio Laboratory
SF-02150 ESPOO 15, Finland

RELIABILITY AND LASER HAZARDS

Michael Pearlman

This session concentrated on the issue of aircraft safety. The general concensus of the attendees was that most attention should be devoted to our interaction with local authorities, since current laser exposure standards for the eye are extremely conservative and, in general, authorities appear to be overreacting to the situation.

Representatives from each group currently operating or planning to operate laser ranging systems were asked to discuss their programs for aircraft safety.

Many of the groups have agreements with local agencies for restricted air space based on location and schedule. Most of the groups reporting use spotters, either direct visual or with T.V. Several groups had performed analyses to show the extreme remoteness of an aircraft being struck by a laser beam.

Dr. F. Zeeman from the Netherlands described an optical scanning system that his group is building to detect aircraft in the vanicity of the laser beam during both daytime and nighttime conditions. Dr. P. Morgan from Australia discussed a precursor pulsing system using a small laser to check the beam direction before his lunar ranging system is fired.

The attendees agreed that we should make literature on eye safety readily available. Each member was requested to send pertinent material or biographies to Dr. M. Pearlman of the Smithsonian Astrophysical Observatory who will distribute copies to requesting individuals.

THE NEW TELESCOPE OF THE LASER STATION AT ZIMMERWALD

M. Schürer, W. Lüthy

Astronomical Institute, University of Berne

A new telescope system for laser satellite telemetry, placed on a biaxial horizontal mounting, has been constructed for the Zimmerwald astronomical observatory. The system is charakterized by using the main mirror simultaneously in the receiver and the sighting telescope. The sighting telescope is equipped with a TV system designed to allow observation of objects of a magnitude up to 9.5 .

In the domain of satellite telemetry by means of laser radar systems optical components are used for transmitting and receiving the laser pulses. These optical components have to be mounted in a way to permit the tracking of a satellite. Up to now such possibilities have not been available at Zimmerwald. Therefore, a new laser telescope has been designed for this laser station. The instrument has been constructed at the Astronomical Institute of the University of Berne. The mechanical components have been completed and the optical components, the main mirror and several lenses, are presently under construction.

The laser telescope is mounted horizontally, the two axes being horizontal and vertical respectively. The two axes are driven by a stepping motor each permitting an angular resolution of 2.7 seconds of arc in elevation and 5.4 seconds of arc in azimuth. The stepping frequency of the motors is controlled manually with the aid of two potentiometers while observing the satellite in the sighting telescope.

The mounting carries the optical and electronical components of the sighting telescope, the receiver of the laser telemeter and the transmitter optics. The laser output is guided to the transmitter optics (1:5 beam expander) by means of a Coudé optical system. The mechanical construction of the receiver and sighting part of the telescope is made up of glued aluminium tubing and sheet metal for good stability and light weight. A schematic view of the whole instrument is given in Figure 1 .

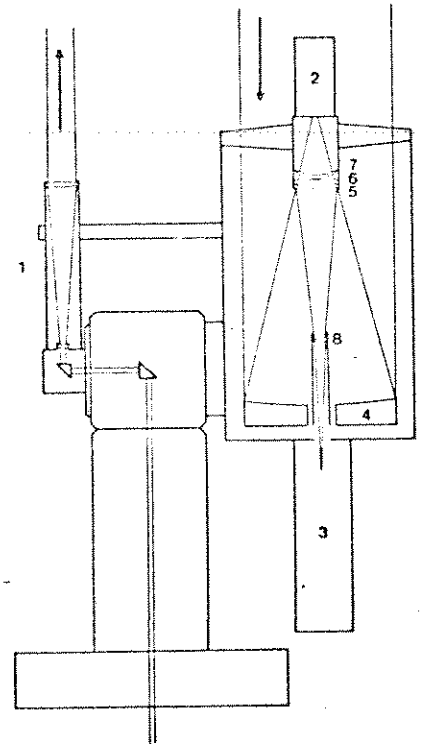


Fig. 1. The Zimmerwald laser tracking telescope.
1: beam expander
2: TV camera
3: photomultiplier
4: main mirror
5-8: lenses

The telescope for receiving the retroreflected laser light is a modified Cassegrain-type instrument. The spherical main mirror (4) has a diameter of 52.5 centimeters and a focal length of one meter. The second mirror used in usual telescopes is replaced by a system of three lenses (5-7). The front of the lense (5) facing the main mirror has a dielectric coating for optimum reflectance at the laser wavelength

The resulting focal length of the system at this wavelength is 3 meters. This focal length is enlarged up to 4.5 meters with a Barlow lense (8). Subsequently, the laser light passes a mechanical shutter, interference filter and Fabry lense after which it is detected by an RCA 7265 photomultiplier (3).

The sighting telescope views the sky in the light transmitted through the dielectrical mirror (5). Three correcting lenses (5-7) assure good image quality on the cathode of the TV camera (2). The most important advantage of the optical system described above is the large entrance diameter of the sighting telescope. It makes it possible to use a TV camera of relatively low sensitivity and therefore low cost.

A Grundig FA 42 S camera is used in the sighting telescope. The field of view covers an area of 33 x 44 minutes of arc with a focal length of one meter. The resolution is 3.2×10^5 points in the picture plane corresponding to a bandwith of 8 megacycles. The TV system is designed for observation of objects up to a magnitude of 9.5 if the object does not move in the picture plane. The visibility of objects passing the field of view in a time interval of one second is reduced to magnitudes of about 8.

We would like to thank Messrs S. Röthlisberger and W. Schaerer for their expert help in the construction and design of the instrument.
We further acknowledge the financial support of the Swiss National Foundation.

FUTURE PLANS: A MOBILE LUNAR LASER STATION

The University of Texas has been involved for some time in the design of a transportable lunar laser ranging station. It is hoped to start construction on this system in the near future so that it may be used for validation tests in late 1977. Table 1 presents the basic specifications for this system as they are currently envisioned. Figures 1, 2 and 3 are largely self-explanatory and we present them without further comment.

E. C. Silverberg
Fort Davis, Texas
July 21, 1975

Table I

Basic Specifications of the University of Texas Mobile Lunar Laser Station

I. Telescope
  A. Aperture: 0.8 single transmitting, receiving, and guiding aperature
  B. Configuration: alt-alt, symmetric yoke or cradle mount with fixed laser coude focus
  C. Field of view: 30 arc minutes at the folded Cassegrain guide focus and 14 arc seconds at the Coude focus

II. Laser
  A. Type: frequency doubled, mode-locked neodymium system
  B. Energy per pulse: 150 millijoules
  C. Pulse width: approximately 200 picoseconds
  D. Repetition rate: 10 hertz
  E. Beam divergence: less than 10 times diffraction limit

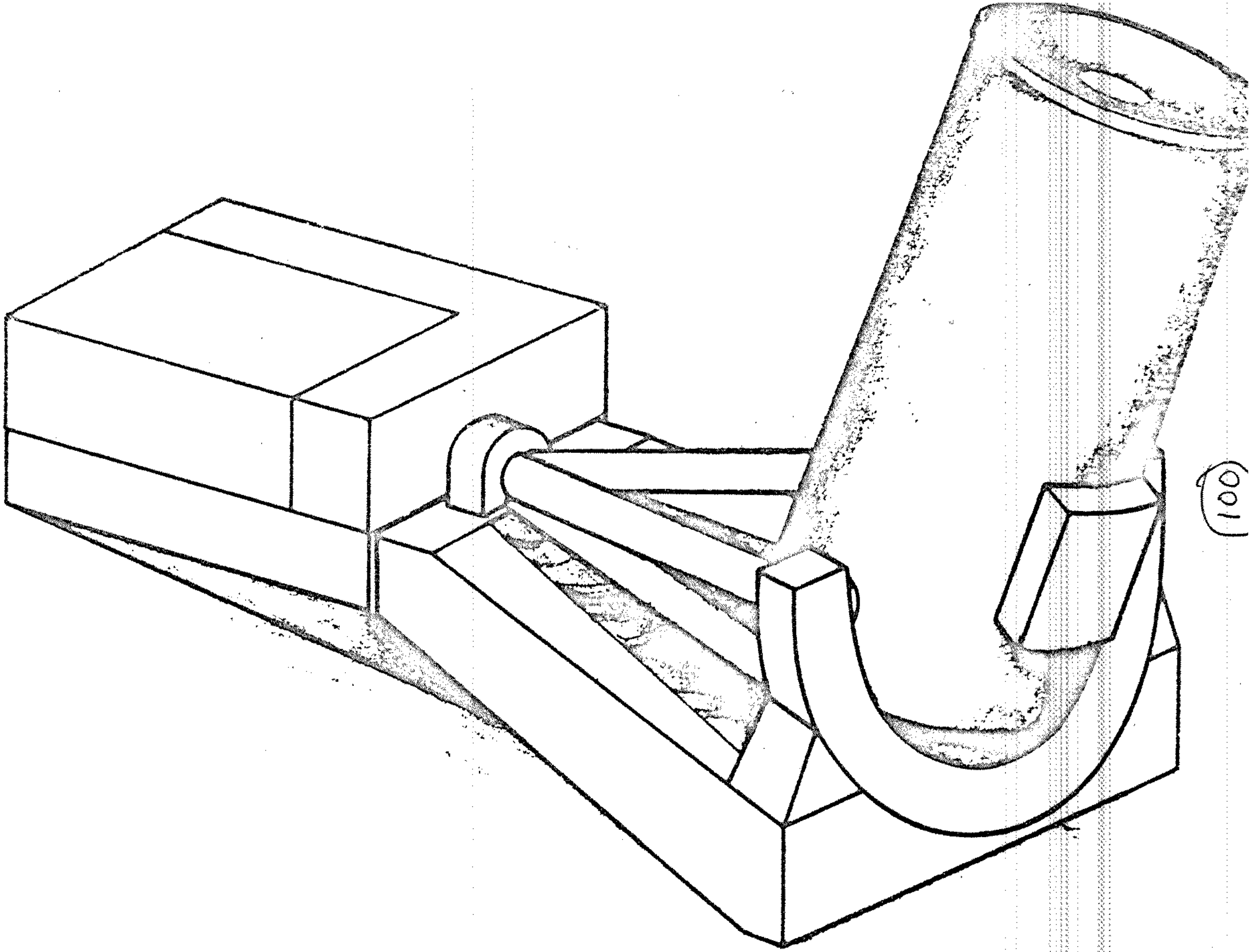
III. Guiding: Computer biasing the telescope track rate via a T. V. sensor which is offset to the edge of the moon. Observer correction using the visual display of the image is also available.

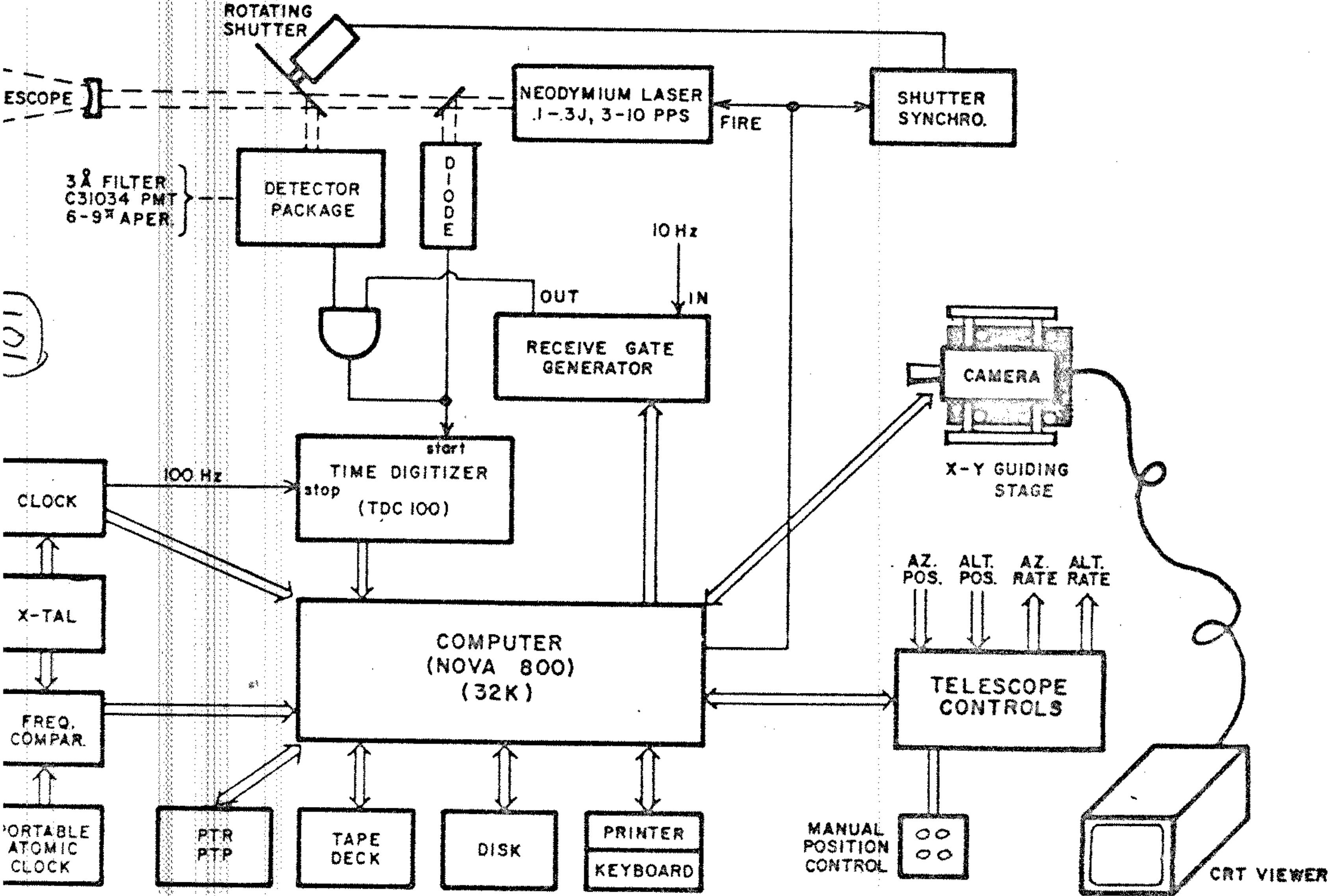
IV. Detector
  A. PMT: Ga-As photomultiplier
  B. Spacial filter: approximately 6 arc seconds
  C. Spectral filter: 3 angstrom, conventional interference filter

VI. Single shot uncertainty: approximately 0.7 nanoseconds

VII. Calibration accuracy: better than 100 picoseconds

VIII. Accuracy: 3 centimeter ranging accuracy on the Apollo 15 corner reflector with less than 10 minutes of firing in 5 arc second seeing conditions.




ROTATING SHUTTER
ESCOPE
NEODYMIUM LASER
.1-.3J, 3-10 PPS
FIRE
SHUTTER SYNCHRO.
3Å FILTER
C31034 PMT
6-9" APER.
DETECTOR PACKAGE
DIODE
10 Hz
IN
OUT
RECEIVE GATE GENERATOR
CAMERA
X-Y GUIDING STAGE
CLOCK
100 Hz
start
stop
TIME DIGITIZER
(TDC 100)
X-TAL
FREQ. COMPAR.
COMPUTER
(NOVA 800)
(32K)
AZ. POS.
ALT. POS.
AZ. RATE
ALT. RATE
TELESCOPE CONTROLS
PORTABLE ATOMIC CLOCK
PTR
PTP
TAPE DECK
DISK
PRINTER
KEYBOARD
MANUAL POSITION CONTROL
CRT VIEWER

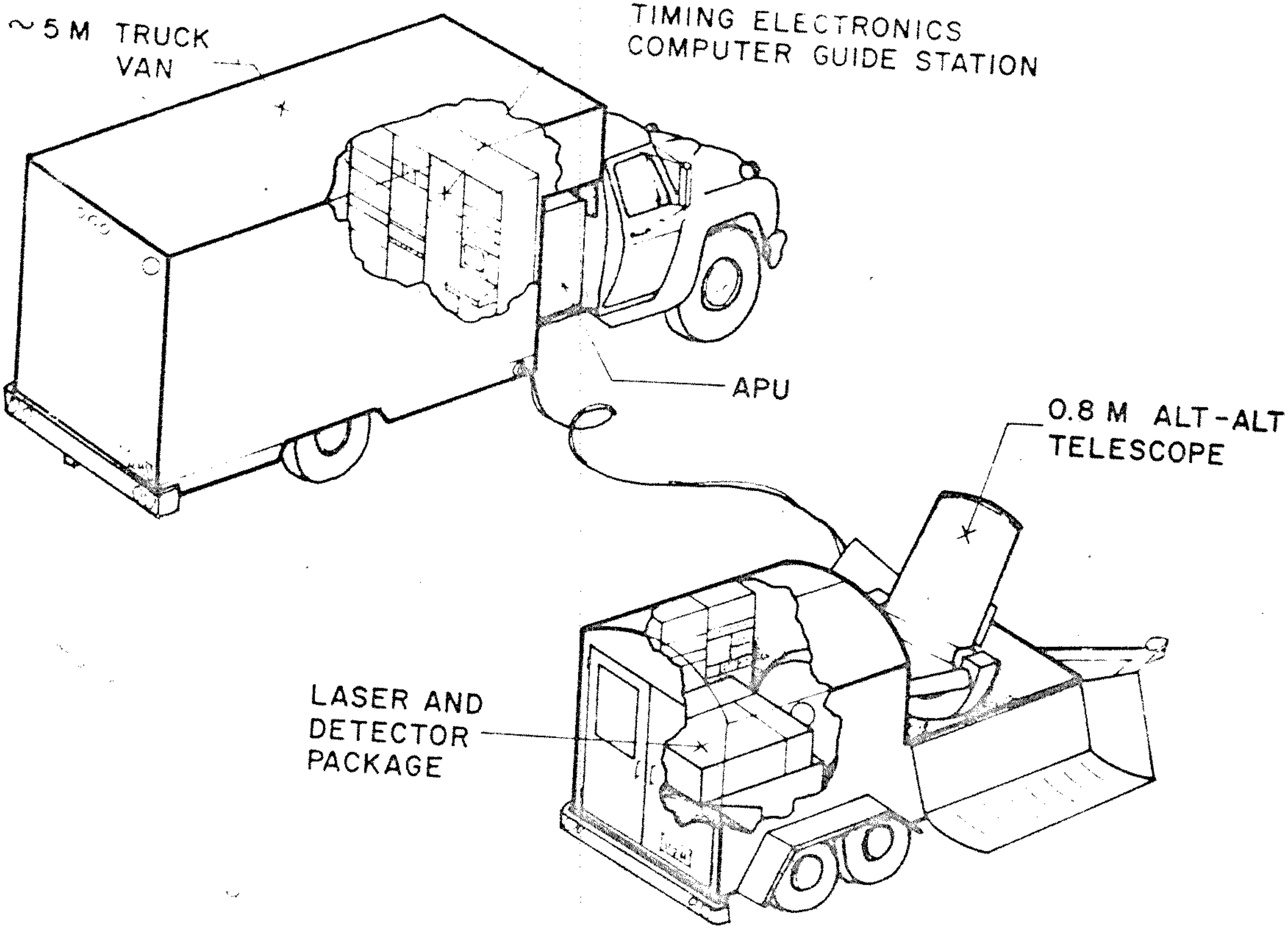


FIGURE 3 : ARTIST'S VIEW OF THE MOBILE LUNAR

ENCOURAGING THE DUAL PURPOSE STATION: AUTOMATED LUNAR GUIDING

by

E. C. Silverberg
McDonald Observatory
Fort Davis, Texas 79734

The Lageos satellite which is to be placed in orbit in 1976 will require the use of techniques which more nearly approach lunar laser ranging than those used for the earlier low altitude satellites. It is our contention that many of the ground stations designed for Lageos can, with minor modification, be also capable of a program of lunar laser ranging. This note is to encourage the development of dual purpose capability wherever possible.

A lunar laser ranging system will have a sufficient signal to noise ratio, even at full moon, if the transmitted energy exceeds approximately 50 millijoules per pulse. Since most satellite systems exceed this criterion very easily we shall continue. Our experience at McDonald Observatory indicates that the return from the Apollo 15 corner reflector averages approximately 6 photons per meter^2 per joule transmitted, under moderately good seeing conditions. Using this empirical criteria we can deduce that a system will have sufficient size to acquire the Apollo 15 corner reflector if the product of its (aperture) x (average power transmitted) x (receiver efficiency) exceeds a certain minimum value. Including the beam divergence (Θ), we get the following formula as an indication of the minimum size laser ranging station which can successfully range the Apollo 15 lunar corner reflector.

$$\frac{A(\mathrm{m}^2)\cdot P(\mathrm{watts})\cdot e(\%)}{\Theta^2\ (\mathrm{arc\ sec})} \geq .03\ \mathrm{m}^2\cdot\mathrm{watts}\cdot\%/(\mathrm{arc\ sec})^2$$

In other words, a 0.6 meter receiver with a 2% overall efficiency, operating in conjunction with a one watt (average power) transmitter, will just qualify as a potential lunar ranging system, if the transmitted beam divergence is approximately 4 arc sec. Many future satellite ranging systems may qualify as potential lunar ranging systems under these criteria. The one major remaining question is whether or not the proper guiding techniques can be developed to hold the narrow divergence beams on the lunar target for a high percentage of the time. The rest of this short note is to present a mode of automatic guiding which can make lunar ranging operationally similar to satellite ranging and, we hope, encourage the consideration of a number of dual purpose ranging installations.

The techniques for guiding differ more than in any other technical area between the lunar and satellite systems. To date, almost all the lunar ranging has been done with manual pointing, relying strictly on an observer's ability to recognize the proper place at which to point the telescope. The satellite guiding, on the other hand, is primarily automatic using precalculated positions. From an operational standpoint it is highly desirable if the lunar guiding could be automated to the extent that extensive personnel training is not required to locate a corner reflector on the lunar surface. The ideal solution would be to be able to rely on absolute pointing. One or two arc second absolute pointing, however, is a very difficult engineering problem which has not (to this investigator's knowledge) become routine on any instrument of 0.5 meter size or larger. It is hoped that a simpler system can be found which uses a closed loop optical feedback from some portion of the lunar image. McDonald Observatory is currently attempting to develop such a mode of operation both for the Fort Davis installation as well as a proposed transportable station.

The lunar surface is an exceedingly difficult object for which to design any automatic guiding system. Since the characteristics of any particular site change considerably from day to day and from night to daylight ranging conditions, it is hard to envision any but the most sophisticated systems using image recognition on the surface itself. The lunar edge, on the other hand, does have sufficient contrast to be discernable, even a few days from new moon, and benefits further from the fact that its simple shape can be recognized by a minimal computer program.

The geometry which we propose for an automatic guider is shown in Figure 1. An area detector is aligned to some zero location relative to the outgoing laser beam and then offset the approximate distance from the corner reflector site from the edge of the moon. The detector beam only covers about one square arc minute of surface area such that arc sec quality resolution can be obtained without necessitating a great deal of information storage. At the edge of the moon the detector is automatically positioned so that the limb bisects its area. The image is now read into a small computer which uses a least squares algorithm to calculate the angle of the limb relative to the orientation of the array (Θ). Knowing this angle, the geometry of your instrument and the lunar attitude at that time you can then deduce the surface coordinates (Xi_E, Eta_E) for the point at which the tangent line is parallel to the edge. Given the surface coordinates of that point on the limb and Xi and Eta of the target, it is then a simple matter to calculate the relative offsets (Δx and Δy) which are required to place the center of field at a corner reflector site.

While the hardware requirements for the scheme are relatively simple, the calculation does require considerable software, particularly for a small computer. We have used a 32 x 32 array of silicon diodes to create a computer-readable image at the edge of the moon. In order to simplify the software calculations we will align the columns of the diode array to true North/South and rotate the camera and X-Y stage at lunar rate. To date we have completed the software for calculating Δx and Δy as a function of x_{iT}, Eta_T and Θ, but have not yet checked out the accuracy of the algorithms for measuring Θ. The angle Θ must be found to about 5 arc minutes to calculate coordinates for that point on the edge which have arc second precision. We hope that such a system will permit us to make a completely automated laser run within about two years, in time to lead to a truly operationally acceptable system for lunar laser ranging.

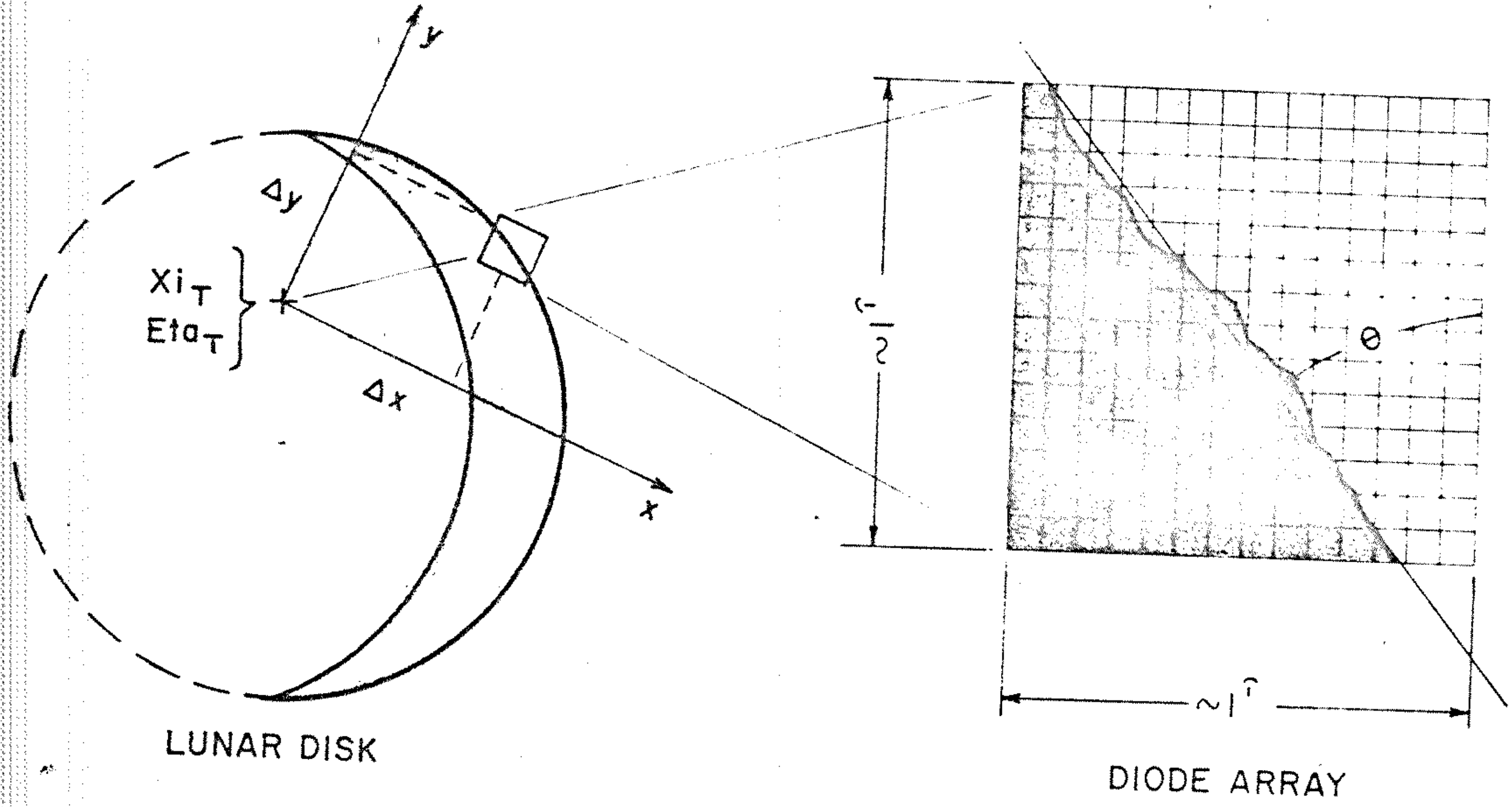


FIGURE 1: GEOMETRY OF THE PROPOSED AUTOMATIC GUIDING SCHEME

Preliminary Plan of the Earth Satellite Tracking Station at the Mizusawa Latitude Observatory

Sigetugu Takagi
The International Latitude Observatory of
Mizusawa

1. In consideration of the recent development of new techniques of observation in the field of geodynamics, the Mizusawa Latitude Observatory decided to make a plan to establish a satellite tracking station at or near the Observatory.

Our works based on this tracking station will be chiefly to promote investigations of the pole motion obtained from results of observation independent of the astronometric method.

2. Doppler Satellite Station.

We have started a test program of pole coordinate determination based on the Doppler satellite observation since February 1974. We are making studies on the pole motion by means of results obtained from the Doppler satellite observations. We have two kinds of data , that is, pole coordinates and the latitude and longitude at the Doppler station.

A merit of Doppler satellite observations is in the point that we can obtain results of observation with accuracy of ± 50 cm in all weather. A new Doppler station are now under investigation sponsored by the Defense Mapping Agency of U. S. A. We have an intention to settle an up-to-date s station to make studies on the pole motion at our Observatory in the near future.

3. Laser Ranging Station.

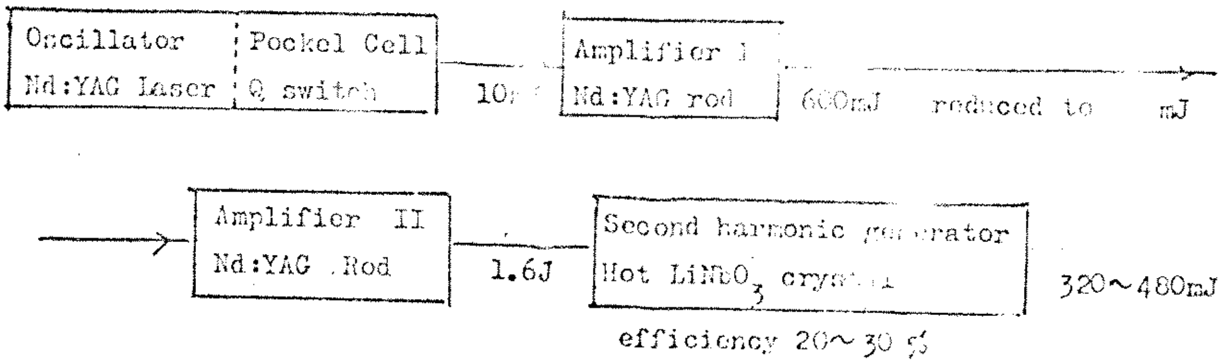
In Japan, several Institutes and Laboratories have [illegible]led the Laser Ranging system for scientific and geodetic purpose.
The accuracy of Laser ranging is expected to be improved to about ± 10 cm in the near future. After we attain this goal, we will be able to develop our studies on the pole motion with more accurate data based on the satellite observation. It will be desireable for us to establish a Laser ranging station near the Mizusawa Observatory simultaneously with the Doppler satellite and astronomical observations. We have many advices and informations on the Laser techniques from the Tokyo Astronomical Observatory. We have a future plan of a Laser ranging station. The Laser tracking system will be almost the same with those of the Tokyo Astronomical Observatory, but we have an idea to replace Ruby laser in the emitter by a Nd:YAG laser.

4. Block Diagram of the emitter.

Data for Nd.Yag laser:

Wave length	0.53 micron (second harmonics of 1.06 micron)
Output energy	more than 200 mJ (TEMoo mode)
Pulse duration	5 ns
Repeating frequency	10 pps
Beam divergency	0.5 mrad.

Block Diagram



We compared the returned signal from GEOS-C for emitters with Ruby-Laser and Nd:YAG Laser by the foumulae given in H.H.Plotkin's paper.

$$S_0 = \frac{P_T G_T G_R \lambda^2 \sigma L_S}{(4\pi)^3 R^4}$$

		Ruby Laser		Nd:YAG Laser	
		DB	Value	DB	Value
P_T	Power Transmitted	0.	1J	- 5.2	0.3J
G_T	Transmitt er Gain	81.1	$\theta_r = 5 \times 10^{-4}$		
G_R	Receiver Gain	127.1	$D_R = 0.5$m		
λ^2		-123.2	$\lambda = .6943$	-130.7	$\lambda = .53$
σ	Radar Cross Section				
	$\sigma = N \frac{4}{36} \frac{A^2}{2}$	82.5	$D_C = 3.5$ cm $N = 270$		
$(1/4\pi)^3$		-33.0			
$1/R^4$	Range	-238.7	$R = 9.27 \times 10^5$ m		
L_S	System Losses	-11.1	$\rho = 7.8$ %		
S_0	Received Signal	-115.3	2.95×10^{-12} J	-122.8	5.25×10^{-13} J

$$N_S = \eta \frac{S_0}{h\nu}$$

η	Quantum Efficiency	- 17.0	0.02	- 10.0	0.10
$(h\nu)^{-1}$	Photon Energy	185.4			
N_S	Received Photonelectrons	53.1	2×10^5	52.8	1.9×10^5
N'_S	G EOS-C Array = 0.05 N_S		10^4 p.c.		9.5×10^3 p.e.

The above data are taken from the paper "Plotkin, H.H. ; Laser Technology for High PRECISION Satellite Tracking. Proc. Symposium on Earth's Gravitational

LASER-RANGING AT THE SATELLITE OBSERVATION STATION IN WETTZELL /BRD/

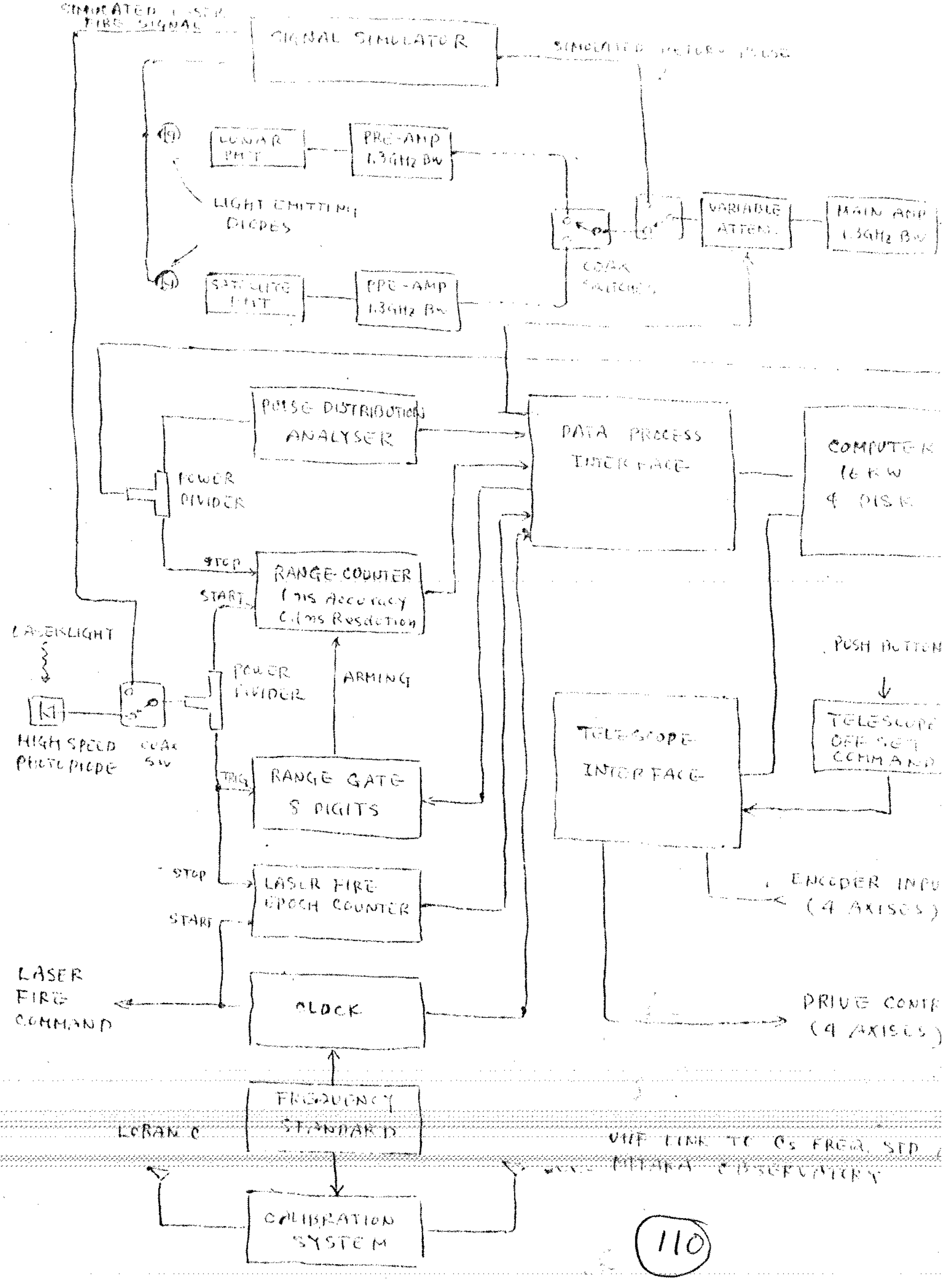
Peter Wilson, Hermann Seeger, Klemens Nottarp

1. The current system

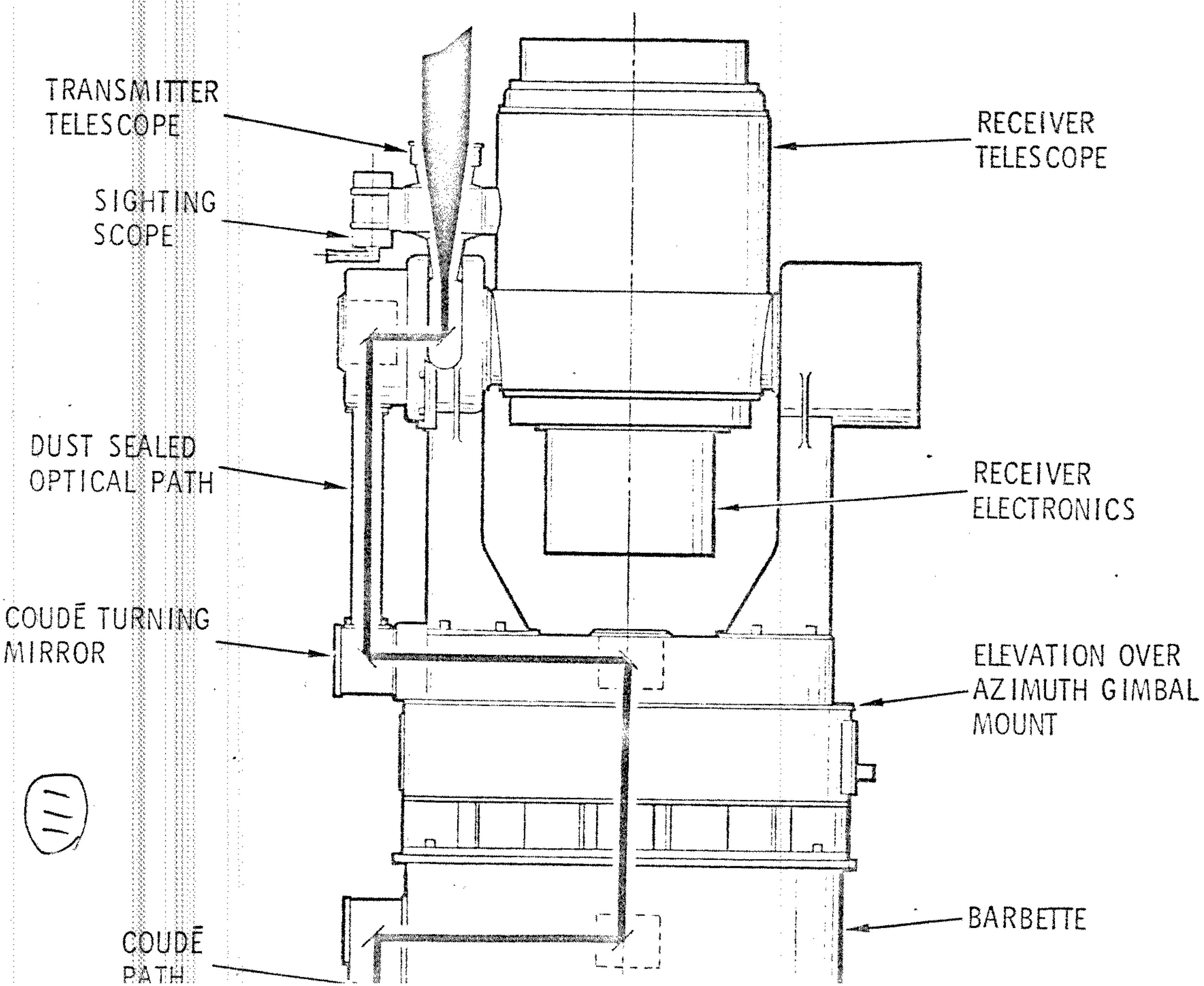
The unit currently operating in Wettzell /fig. 1/ was developed originally by the "Institut für Flugführung" at the "Deutsche Forschungs- und Versuchsanstalt für Luft- und Raumfahrt" in Braunschweig. It incorporates certain components, such as the interface to the station timing system and the device for switching between giant pulse and relaxed mode operation, which were designed, built and supplied by the IfAG. First trials of the system occurred in the autumn of 1972 and first returns were obtained in April 1973. Since September 1972 the equipment has undergone major modification. The laser has been largely reconstructed, the power unit improved and new Galileian transmitting optics have been substituted for the original Cassegrain system. Furthermore, the telescope provided to perform the manual tracking has been replaced by a more effective combination comprising a larger field scan-telescope and a high-power small-field tracking unit. The cooling-system of the laser has been redesigned.

The main characteristics of the equipment as it is now in use have been summarized in the following table:

Laser energy /maximal/	7 J
Half-energy impulse width	30 nsec
Impulse power /maximal/	240 MW
Repetition rate	0,14 Hz
Natural divergence of beam	5 mrad
Effective divergence of beam	1 mrad
Receiver objective	320 mm
Counter resolution	1 nsec
Mount	2-axes
Tracking telescope field, resolution	3
Gating	≤ 1 msec
PMT	Philips 56 TVP


SIMULATED LASER FIRE SIGNAL
SIGNAL SIMULATOR
SIMULATED RETURN PULSE
LUNAR PMT
PRE-AMP 1.3GHz BW
LIGHT EMITTING DIODES
SATELLITE PMT
PRE-AMP 1.3GHz BW
COAX SWITCHES
VARIABLE ATTEN.
MAIN AMP 1.3GHz BW
PULSE DISTRIBUTION ANALYSER
POWER DIVIDER
DATA PROCESS INTERFACE
COMPUTER 16KW 4 DISK
STOP
START
RANGE COUNTER (1ns Accuracy 0.1ns Resolution)
LASERLIGHT
HIGH SPEED PHOTODIODE
COAX SW
POWER DIVIDER
ARMING
PUSH BUTTON
TRIG
RANGE GATE 8 DIGITS
TELESCOPE INTERFACE
TELESCOPE OFFSET COMMAND
STOP
START
LASER FIRE EPOCH COUNTER
ENCODER INPU
(4 AXISES)
LASER FIRE COMMAND
CLOCK
DRIVE CONTR
(4 AXISES)
FREQUENCY STANDARD
LORAN C
VHF LINK TO Cs FREQ. STD
MITAKA OBSERVATORY
CALIBRATION SYSTEM

MOUNT GROUP


TRANSMITTER TELESCOPE
SIGHTING SCOPE
DUST SEALED OPTICAL PATH
COUDĒ TURNING MIRROR
COUDĒ PATH
RECEIVER TELESCOPE
RECEIVER ELECTRONICS
ELEVATION OVER AZIMUTH GIMBAL MOUNT
BARBETTE

ADP & CONTROL/DATA PROCESSING

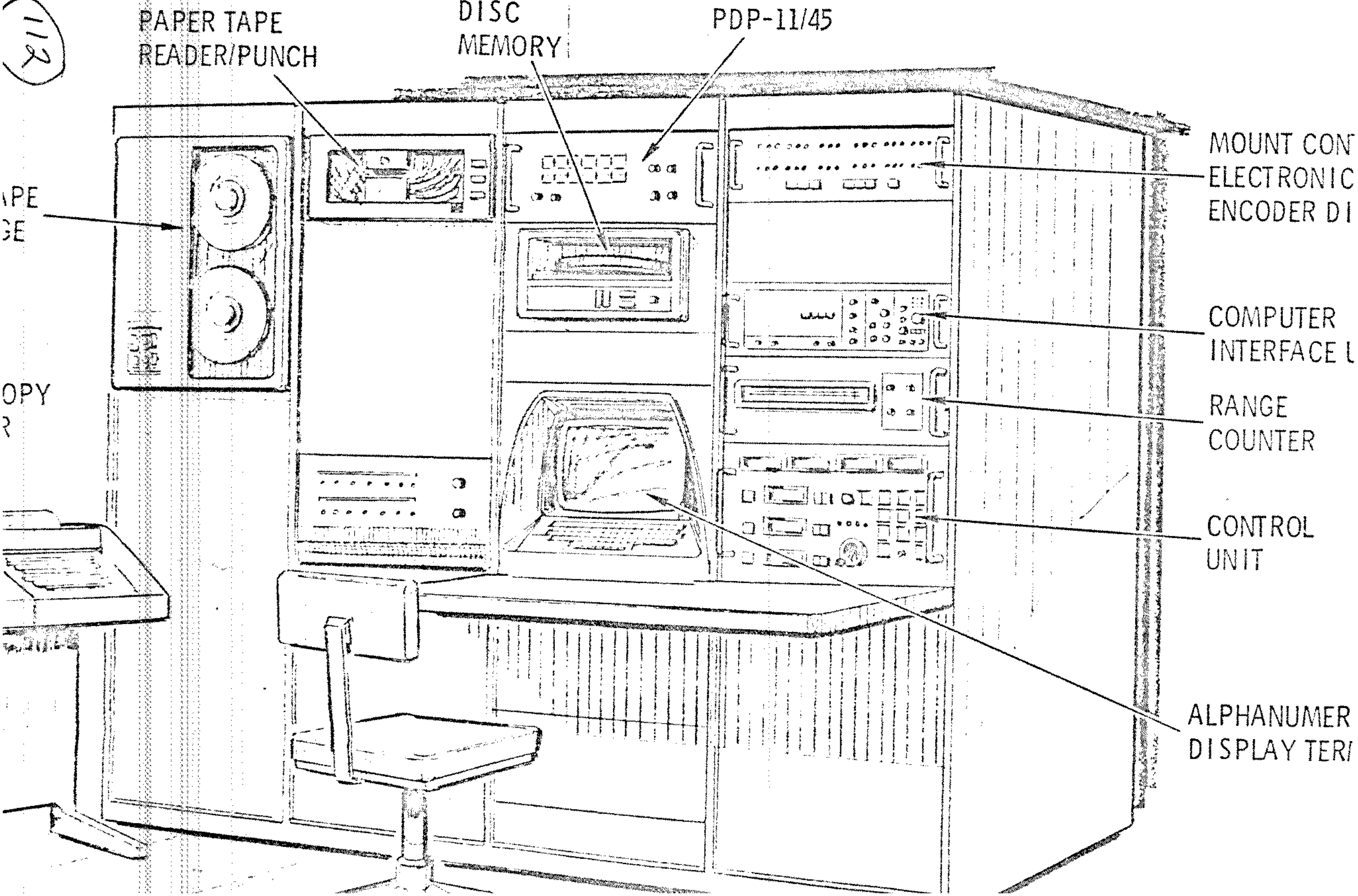


Table 2. The System to be installed in 1976

Peak Power Output.	1.25×10^9 watts at approximately 0.53 μm or 3.0×10^9 watts at approximately 1.064 μm
Energy Output:	0.25 joules per pulse at approximately 0.53 μm or 0.5 joule per pulse at approximately 1.064 μm
Output Stability:	±5%
Pulsewidth:	Less than 0.2 nanoseconds
Repetition Rate:	Up to 3 pulses per second external or internal command, and at least 1 pulse per second by manual control
Beam Divergence: (Full width containing > 90% of the energy)	Not greater than 10 times the diffraction limit from the final amplifier assembly.
Spectral Linewidth:	Less than 0.2 Å
Spectral Line Stability:	Better than 1Å
Spectral Line Position:	Repeatable to better than 1Å from one operational cycle to another
Physical Characteristics:	The following nominal dimensions apply: 1. Laser Transmitter – 1.23 meters long x 63 cm wide x 30 cm high 2. Power Supply – Self-contained cabinet 1.6 meters high x 60 cm wide x 80 cm deep 3. Cooling System – Cabinet mounted 1.6 meters high x 60 cm wide x 80 cm deep
Operational Parameters:	1. Operational Cycle Time – No intrinsic limit 2. Operational Life Time – Greater than 2×10^5 pulses for all components
Equipment Operation Mode:	1. Remote or local operation 2. Cooler located up to 7.5 meters from laser and power supply 3. Control Console – Control console has six switched functions including: power on/off, start (standby) charge, auto/manual fire control, manual fire, and emergency stop. In addition, provisions are made for mode-locked frequency adjustment, high-voltage adjustment, and trigger voltage adjustment 4. Electromagnetic interference control requirements, as per principles outlined in U.S. Government Standards
Environmental Conditions:	1. Operating: Altitude – 0-4.2 km Humidity – 0-49% relative Temperature – -40° to +125°F 2. Storage and Shipment: Altitude – 0-12.2 km Humidity – 99% relative Temperature – -30° to + 150°F
Primary Power:	Less than 8 kVa, 240/380V, 50 Hz, 4 pole, 5 wire, wye connected

(113)

SYSTEM/SUBSYSTEM SPECIFICATIONS

The following is a summary of SLRS system and subsystem performance specifications. General specifications relate to system performance, operating environments, and facility requirements. The other specifications refer to specific subsystems.

General

Range Limit – 350 Km to 36,000 Km
Range Accuracy – Better than 10 cm
Range Resolution – Better than 2 cm
Data Rate – 0.5 to 5.0 PPS
Operational Time – 24 hours per day except during inclement weather
Environment
  Temperature – +18°C to +23°C
    Mount -40°C to +50°C
  Humidity – 0 to 49% RH
    Mount 0 to 100%
  Altitude – 0 - 14,000 ft.

Operating Staff – 2 operators
Input Power – Either 220V 60 Hz or 380V 50 Hz 3ϕ, 16 kW Max.

Absolute Pointing Accuracy – ± 3 arc seconds
Pointing and Tracking – Computer Controlled
Site Facilities Required – Concrete pad for mount/laser support
  – Pre-surveyed terrestrial targets for range offset calibration and mount level correction.

Mount Subsystem

Configuration - Elevation over azimuth
Transmitter System - Laser stationary - two axes Coudé, dust-free path of transmitter
Range of Travel - ±270° in azimuth; ±100° about zenith in elevation
Tracking - Continuous, under computer control, from elevation angles of 10 degrees to within 2 degrees of zenith
Tracking Rates (in plane of orbit) - From sidereal to 1° per second
Orthogonality - ±1 arc second
Wobble - ±1 arc second
Angular Accuracy - Optical encoders with 18 bit (24 microradians) absolute accuracy and 20 bit (6 microradians) resolution

Transmitting Optics

Location - Elevation Axis
Type - Galilean
Effective Beam Divergence - 50 microradians to 1 milliradian normal
Divergence Control - Motor driven, computer controlled, to correspond to desired divergence
Diameter of Exit Beam - 160 mm
Magnification - 10X
Alignment - Within 5 microradians of reference line of sight
Alignment Stability - Less than 10% of divergence
Optical Damage Criteria - 2 GW/cm^2 max at input
Optical Coating - .10% per surface maximum loss

Receiving Optics

Type - Cassegrain
Diameter - 0.6 meter (24 inches)
Effective Focal Length - 440 cm
Focus - Fixed, temperature compensated over -40°C to +50°C
Field-of-View - Continuously variable, computer controlled, from 100 microradians to 1.1 milliradian

Receiving Optics (continued)

Sun Protection Shutter	-	Mechanical shutter protects PMT photocathode when sun within 2 degrees of optical axes
Alignment	-	Within 15 microradian of transmitter line of sight
Spectral Filter Bandpass	-	Available bandpass between 10Å and 25Å, temperature stabilized
Attenuation Control	-	Optical attenuation of received signal; continuously variable from 0 to 40 dB; computer controlled.

Laser

Type	-	Nd:YAG - Frequency Doubled, single transverse mode
Operation	-	Mode Locked/Cavity Dumped
Energy	-	0.25 Joule
Half-Energy-Pulse-Width	-	200 picosecond nominal
Pulse Repetition Rate	-	0.5 to 5.0 PPS
Spectral Output	-	0.532 μ meter
Wavelength Stabilization	-	Not required
Dust and Humidity Protection	-	Closed compartment around laser pressurized with filtered, dehumidified air or inert gas.

Receiving Electronics

Detector

Type	-	Static Crossed Field Photomultiplier
Quantum Efficiency	-	10% @ 0.532 μ meter
Rise Time	-	140 picoseconds
Photosurface	-	S-20
Refrigeration	-	Not required
Range Gate	-	Computer controlled gate width and gate centering about return pulse
Start Pulse Detector	-	Common with receiver detector; fiber optics pick off transmitted pulse; leading edge threshold detection
Epoch Signal	-	Coincident with start signal
Threshold Detection	-	Leading edge detection; threshold level computer controlled
Tolerable Pulse-to-Pulse amplitude variation	-	± 10 dB (optical)

Guidance and Data Processing

Time Interval Counter Resolution - 100 psec

Time Standard (Station Clock) - Rubidium frequency standard

Resolution - Timing - ±10 μsec

Stability of Clock - 1.5×10^{-10}/10 msec (5 MHz Ref. Frequency)

Data Flow Rate - Max. - 5 measurements/second (epoch, travel time, range)

Information Storage Medium - Magnetic Tape - Permanent Storage

- Magnetic Disc - Temporary Storage

Output - Alphanumeric Terminal

Computer Memory - 16 K words

Mangetic Tape Type - 9-channel IBM standard

Paper Tape Reader - 5-channel - for program loading

Programming Language - Fortran

System Control - Operator control three system control unit and alphanumeric terminal

Computer Interface - Through computer interface unit and alphanumeric terminal.

System Control Unit

The controls, meters, and indicators of the System Control Unit are listed below. Refer to Figure 10.

Controls (Manual or Computer Control Selectable from Front Panel)

	Computer	Manual
Attenuation, Receiver Optical	INC/DEC	INC/DEC
Field-of-View	INC/DEC	INC/DEC
Divergence	INC/DEC	INC/DEC
Start Threshold Level	INC/DEC	INC/DEC
Stop Threshold Level	INC/DEC	INC/DEC
Time Slew (Acquisition)	No	Yes
Open/Close Sun Shutter	No	Yes
Track Mode Controls	No	Yes
Laser Mode Controls	No	Yes
System Mode Controls	No	Yes

Panel Meters

Divergence, milliradians
Field-of-View, milliradians
Attenuation, dB
Transmitted Power, GW
Received Power, dB
Start Threshold, mV
Stop Threshold, mV

Indicators

Start Pulse Light
Stop Pulse Light
False Alarm Light
Sun Presence Light
High Background Light

Joystick

Manual Mount Position/Velocity Control

Computer Interface Unit (Refer to Figure 10)

- Handles all interfaces between system control, encoders, interval counter, computer, peripherals, and time (frequency) standard
- Controls data flow
- Displays encoder angles in binary
- Controls display of Alphanumeric Terminal (see Figure 11).

Software Control

Initialization Mode
- Calculation of Ephemerics
- Optical Controls
  - Field of View
  - Divergence
  - Start/Stop Thresholds
  - Attenuation Control
- Initial Mount Positioning

Software Control (continued)

- Site Calibration - Leveling, Star Tracking
- Initialization Displays

Execute Mode

- Initiation of Tracking
- Epoch Pointing
- Epoch Data Collection
- Epoch Data Recording
- Non-Epoch Mount Control
- General Laser Control and Firing
- Dynamic CRT Display
- Timing Control

Processing Mode

- Tape Handling Routines
- Data Location on Tapes
- Data Analysis
- Data Display

Playback Mode

- Mission Data Playback

Utility Programs

- Encoder Test
- Loop Checks
- Optical Gain System Tests
- Pseudo Pointing

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Workshop on Laser Tracking Instrumentation, Prague, August 1975

THE FINNISH-SWEDISH LASER PROJECT

S. Johansson, M. Paunonen, A. Sharma

The Finnish Geodetic Institute and Helsinki University of Technology have since 1971 collaborated on the project to construct a satellite laser rangefinder. In 1973 the Swedish Geographical Survey Office joined the project. The satellite laser is expected to be operational in 1975 and will be used alternately in Finland and Sweden.

Design parameters of the system are:

- Ruby laser, wavelength 694,3 nm
- Pulse energy 1...2 J
- Pulse length 5 ns, nearly rectangular
- Pulse repetition rate at least 6 per minute
- Transmitter beamwidth 0,5 ... 5 mrad
- Receiving telescope 0,6 m parabolic mirror, f.l. 1,73 m
- Filter bandwidth 2 nm
- Pointing accuracy 0,3 mrad
- Output data in digital form, displayed and recorded

The transmitter is based on a Pockels cell Q-switched ruby laser configuration followed by pulse slicing and amplifier stages. The oscillator ruby is 100 x 10 mm, select quality, flat/flat cut, AR-coated and cooled by deionized water. The helical flash lamp is energised by a maximum of 5 kJ. The oscillator yields a 20 ns pulse of at least 0,7 J when Q-switched and is expected to yield 0,2 J when clipped to 5 ns. Slicing circuit and amplifier are under construction.

The receiver consists of an astronomical telescope with a parabolic mirror and an RCA 31034 photomultiplier installed at the prime focus. The mirror has been made in the Institute for Astronomical Research of Turku University and it was coated with aluminium layer in the Uppsala University. The mount of the telescop is an equatorial one equipped with semi-automatic pointing faciliti

The optical input to the PMT is shuttered to improve average anode current capability, as well as eliminate backscatter. The shutter has a minimum opening delay of 1,5 ms and openin rise time of less than 30 pF introduced by a MOSFET amplifier and the PMT itself, and an introduced leakage resistance of about 1 Mohm. The amplifier thus behaves as an integrator and using a half-max time interval counter, centroid detection is essentially achieved. This method provides a larger signal voltage, and relative design simplicity.

Timing is based on a Hewlett-Packard quartz clock system synchronised to the Universal Time Scale (UTC) using a LORAN phase-locked frequency comparison receiver. The pulse propagation time will be measured using a 0,1 ns accuracy counter (NANOFAST,Inc, model 536 B),equipped with M/2 half-max detection unit.

Control logic and the data processing system has been construct and tested. Pointing of the telescope is by means of two stepper motors. Calibration of the direction is by means of pointing the telescope towards a known star and programming the coordinates of the star into the logic. Steps of each motor are then counted and thus, because of the equatorial mount, the actual direction is always known. The motors are stopped, when this direction is equal to the required direction set automatically or by thumb wheels. Air temperature,air pressure and relative humidity are measured sim taneously with the fire pulse. The weather data, firing time, pulse propagation time and direction coordinates are punched on a paper tape for further treatment. The outgoing and return laser pulses will be digitized by a Tektronix transient digitizer type R 7912, and the matrix information will be recorded on a cassette recorder for further processing.

The satellite laser rangefinder described will be situated in Finland at the Kirkkonummi Observatory of the Finnish Geodetic Institute. Field test measurements will be initiated there next September.

Session 2: System Errors

12 August AM

Chairman : C.O.Alley

Summary

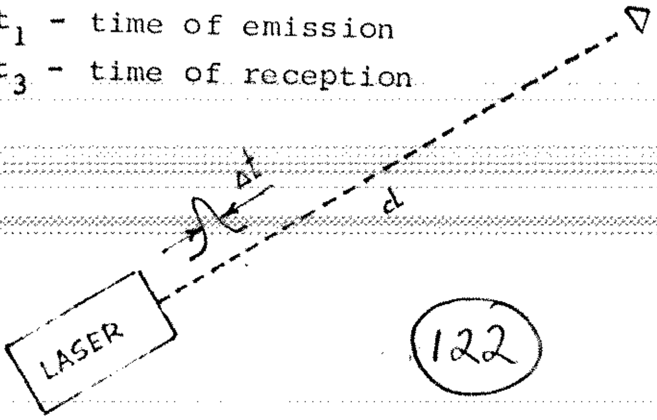
I. Introduction

The interest in laser ranging is based on the wide bandwidth of laser amplifiers which allows a very short pulse of radiation whose round trip time to a target can be measured with high precission and accuracy. Another product of quantum electronics research, the atomic clock, provides a time base for world wide distribution of epoch of sufficient accuracy (1us to 5 μs) for the most demanding geophysical application-ranging to artificial earth satellites. In contrast, ranging to the moon requires less accurate knowledge of epoch since the velocity of the moon is less. However, the time base needed for the range time interval measurement needs a better fractional stability for moon than for the artificial satellite, since the 2.5 sec range time is much longer. For both, the stability of a good crystal oscillator is sufficient. For 0,1 ns timing $\Delta f/f = \Delta\tau/\tau \sim 4 \times 10^{-11}$ over 2.5 sec is needed for the moon .

A schematic diagram of a ranging system is shown below:

t_1 - time of emission

t_3 - time of reception



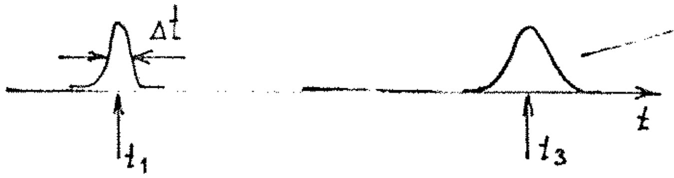
$t_2 = \frac{t_1 + t_3}{2}$ time of reflection

$$d = c\,\frac{(t_3 - t_1)}{2} = c\,\frac{\tau}{2}$$

$$\Delta d = c\,\frac{\Delta\tau}{2}$$

$c \approx 30$ cm/ns in free space

The basic problem is to derive as accurately as possible the time of the laser pulses in the given time base



degraded and spread by target and detector

This requires a light detector with fast response and low jitter, a method of deriving a time signal from some characteristic of the pulse-eg. leading edge amplitude discriminator, zero crossing discriminator, constant fraction discriminator or centroid determination or swept tube. The difference between the derived signal for the times t_1 and t_3 must be related to the time base by a counter, augumented in the most accurate systems by a vernier to go beyond the 1 ns limit of present counter resolution, perhaps time to pulse height conversion or a dual slope integrator. The entire system must be carefully calibrated and the calibration monitored for changes in delays and otherparameters with temperature and other environmental conditions.

The velocity of light in affected by the atmosphere, but it seems likely that the delay can be determined to <1 cm equivalent range by monitoring local barometric pressure and using an algorithm of Helen Hopfield. This needs to be verified by two-color range measurements which are different due to the dispersion of the atmosphere. For an absolute measurement good to 100 ps, the range time diference between 5321 Å and 3500 Å light must be determined to ~ 5 ps, which can be done with a streak tube.

The following table may be useful in summarizing system errors.

II. Specific Questions

A. Multimode Lasers

Pearlman (SAO) discussed timing problems associated with multimode lasers. The radiation is emitted into different ang at different times. See SAO report.

Ramsden (Hull) pointed out the ease of generating single mode radiation.

B. Atmospheric Delay Corrections

Weiffenbach (SAO) discussed the atmospheric delay correction of Hopfield using local barometric pressure. It seems to work well but needs two-color verification. Problems are associated with winds and horizontal gradients in weather conditions when laser ranging stations do not normally operate.

C. Distribution of Epoch

Morgan (Australia) discussed problems of epoch distribution. The Timation III satellite will allow distribution in the future to 20 ns. Now a $14,000 receiver allows 1 microsecond accuracy from the transit satellites. LORAN-C is maintained to 0.5 microsecond with respect to the U.S. Naval Observatory clocks. VLF reception plus occasoinal clock trips will allow epoch to be maintained to 5 microseconds. The Omega system is good to 5 microseconds.

D. Calibration of Systems

1. Pearlman discussed the procedure of SAO. See SAO report.

2. Silverberg described the procedure used for lunar ranging with short (2 m) path on each shot with attenuation to give the same signal as a lunar return. Statistics give the outgoing pulse shape. The calibration is extended to lunar range times with a diode light pulser.

3. Veret (ONERA) discussed a method of rotating the beam splitter 90 degrees to allow calibration of start and stop detectors with the same strength pulses, and without measuring the distance to the target.

4. Gegnebet (CERGA) discussed the timing correction needed as a function of the intensity of returned pulses as measured for his system.

5. The calibration pricedure for the Goddard Space Flight Center stations can be found in the paper by McGunigal, et. al., in these proceedings.

	First Generation ~100 cm	Second Generation ~10 cm	Third Generation ~1 cm
Laser Pulse Duration	10 - 30 ns (Q-switched)	2 - 5 ns (PTM Pulse slicing)	0.1 - 0.3 ns (Mode locking)
Time Base Epoch	Atomic Clock e.g. Loran C →	→	→
Time Base Interval	Crystal Oscillator →	→	→
Detector	Photomultiplier →	→ Single p.e. → Crossed Field →	→ → →
Discriminator	Leading Edge	Zero Crossing Constant Fraction Centroid →	→ → Streak tube
Atmospheric delay Correction	—	Local Barometric Pressure Monitor	→ Two-color
Target Structure	—	Modeling of C.M. → Lunar Reflectors →	→ → LAGEOS Starlette Shiny Ball

Summary of Session 4: Pulse Detection and Processing

Detectors: An ideal detection system employing the qualities of good efficiency, low timing jitter, high gain and capable of a high count rate is difficult to realise. Some of the new photomultipliers are good in many categories but fail in others. The RCA 31034, for instance, has excellent efficiency but requires care in operation due to stringent limitations on the average current. Crossed field tubes are available which have excellent timing characteristics but are quite costly. Future work can be expected in the areas of channel plate photomultipliers and streak tube systems.

Pulse Processing: The length of many current laser pulses favors some degree of pulse processing over simple edge detection or constant fraction discriminators. Pulse digitizing techniques used at SAO and NASA have proved quite successful. Analog techniques have been modeled in CSSR to evaluate their usefulness. Processing techniques to handle the wide dynamic range and variable shape of the return pulse appear, at present, to be limited by wave front distortions from the laser transmitter.

Timing: A number of timing systems, both for satellite and lunar work, are in operation or under construction employing the time-domain streaching technique. Single and multiple stop devices have been developed with accuracy capability well below 1 nanosecond.

Major Contributors to Session 4:

D. G. Currie	- Description of the streak-camera timing system and description of a multistop epoch timing system
Suchanovskij	- Discussion of the Soviet experience with photomultiplier quantum enhancement techniques
J. Gaignebet	- Description of the CNES system for reducing the effects of sky background
M. Pearlman	- Discussion of the U.S. experience with pulse digitizing systems
M. Vrbova	- Computer simulation of analog pulse centroid correction procedures
Veret	- Description of the channel plate photomultiplier tube
Billiris	- Discussion of the measurements of laser wave front distortion
Hirsl	- Interkosmos timing system using the time expanding technique

submitted 13 Aug.
E. C. Silverberg

SESSION 6. SATELLITES IN ORBIT - PREDICTIONS

F. Nouel

I. Satellites

Among the satellites in orbit or planned, we found:

1 - the old satellites

BEACON B and C; GEOS A and B; D1 C and D; PEOLE

2 - the new generation, for which sophisticated design were made in order to

i/ get better response from the satellite through all the pass

ii/ minimize non gravitationnal forces acting on the sat. and make them as constant as possible

D5B - STARLETTE - GEOS C - TIMATION III

3 - The "near future" satellites

LAGEOS - AUOS-Z - TIMATION IV

4 - The "others"

- SHINY BALL with no Laser corner cubes
- Laser Reflectors on the moon.

SOME CHARACTERISTICS - which were pointed out during the session

GEOS III

Tracking down to 15° due to sloped mounting of the reflectors -

$e = 0$

$i = 115^{\circ}$

altitude 850 km

It has a CO_2 corner cube

STARLETTE

- purpose of gravity studies
- Very small Area/Mass ratio
- 60 corners cubes - At least 6 of them are visible in any configuration

perigée - apogée 800 km - 1100 km

inclination 52°

magnitude 11

LAGEOS

- Altitude 5900 km
- inclination 110°
- weight 400 kg
- sphere of 60 cm diameter
- 440 corner cubes of 3.8 cm aperture
  one CO_2 corner cube

Launch planned for March 74 and magnitude will be 12.

AUOS-Z

Launch: end of 76

13 corners cubes.

They are put on a satellite which is part of the Interkosmos project and the primary mission of which is cosmic ray studies.

altitude 500 km on a circular orbit

inclination 83°.

TIMATION III

altitude 14000 km on a circular orbit

inclination 115°

Magnitude is going from 11 to 14 depending on altitude.

GSFC had successful laser echos on it.

D5B Satellite equipped with a micro-accelerometer to study atmosphere density

$i = 30^{\circ}$

perigée 200 km

apogée 1100 km

LUNAR REFLECTORS

Appolo 11-14-15 caracterised by $\frac{d\Omega}{d\omega} = 50\ km^2/strd$.

Lunarod was mentioned.

SHINY BALL

It has no corner cube but expected returns of 5 photos using 1 J laser and 1 meter telescope.

Sphere of 1 m^2 radar cross section

magnitude 6

Polar circular orbit at 500 nautical miles.

II. Predictions

1/ SAO made a report on how predictions are computed. They provide currently ephemeris on GEOS A - B - C - - BEC and STARLETTE.
It was interesting to hear that for STARLETTE, predictions over a period of one or even two months could be possible. This suggests that the earth model is known enough, but non gravitational forces limited computations so far. The same remark applies to the Drag free satellite TRIAD.

2/ Lunar predictions are sent to the station on a daily basis on a polynomial form. JPL can provide them.

FUTURE SYSTEMS

Douglas Currie

During this session we wish to consider an overall view of the future possibilities of the tracking of satellites by lasers. We now wish to gather data to determine the future capabilities and to evaluate questions of future. Thus we wish to provide a framework to permit a detailed comparative discussion.

Detailed discussion and value judgements should be reserved for the programmatic and the open discussion period. This later discussion may then provide data for future planning of the various groups. A large amount of the information on future systems has already been discussed.

Four areas which we shall consider are:

- I FUTURE TECHNIQUES
- II FUTURE STATIONS
- III SATELLITES, CURRENT AND FUTURE
- IV NETWORKS, CURRENT AND FUTURE

I. FUTURE TECHNIQUES

In this section we shall receive those technical areas which shall be of critical importance over the next few years. We hope to concentrate on the parameters and techniques which are most important in meeting the basic program goals and leave for another time those techniques which are important in order to reduce cost, increase convenience, or increase reliability.

A. RANGE ACCURACY

There are several sub-systems which are most critical in order to improve range accuracy. These are:

1. The Laser System

   To improve the laser performance as related to in the range accuracy, the important points are:

   a. Studies of multimode structure

   b. Improvement in centroid determination of long pulses

c. Develop methods to obtain short pulses from the laser system by:
   i. active mode locking
   ii. pulse slicing or chopping
   iii. passive mode locking

2. The Photodetection System

The various procedure to improve the detection timing are:

a. Photomultipliers
   i. conventional multipliers may be used in a better fashion to obtain their full capability of a r.m.s. jitter of 0.1 to 0.25 nanoseconds.
   ii. Channeltrons and channel plate tubes appear to have a performance which may be better than the conventional photomultiplier.

b. Crossed-field photomultiplier

These devices, when combined with a wideband width, low-noise preamplifier may yield time resolution at the 0.1 nanosecond level.

c. Streak tube

These detectors, which are currently used in laser fusion work, will give a time resolution, for single photo electrons or for a many photoelectron pulse of 0.001 to 0.01 nanosecond. This accuracy seems of interest only for two color systems which require a range accuracy better than two centimeters.

3. Interval Timing Electronics

Equipment to perform interval timing with an r.m.s. width of 0.04 nanosecond has already been described in the literature and has been used in field operations so will not be considered further.

4. Epoch Determination

   Equipment /1/ necessary to perform this function is available and has been described in the literature.

B. IMPROVED DETECTION THRESHOLD

1. Laser system

   Improvements in the laser system will be of interest in the area of:

   a. higher average power
   b. continuous-wave laser systems

2. Receiver Apertures

   In addition to normal receiving apertures, there are several new techniques which may provide significantly larger receiving apertures.

   a. Multi-aperture receivers

      These are currently being built in France and USA

   b. Large metal mirrors

      These are currently being built in Japan.

3. Reduced Beam Divergence

   a. Orbit predetection

      Better orbit predetections are required but seems to be available

   b. Tracking

      i. improved mounts
      ii. auto tracking techniques on sunlit satellite or on laser returns
      iii. absolute providing capability at the arc second level.

II. FUTURE STATIONS

Discussion of new stations by various workers has been given. The details of these discussions appear in other sections of this workshop. The new stations discussed were:

A. Mt. Haleakala Station /USA/

   by Eric Silverberg

B. Orrora Valley Station /Australia/
by Peter Morgan

C. Dodaria Station /Japan/
by T. Atsushi

D. Crimea Station /USSR/
by A.M. Suchanovskij

E. Greenbelt Station /USA/
by C.O.Alley

F. Netherlands Station
by F.W. Zeeman

G. Cagliari Station /Italy/
by L. Cugusi

H. LURE Mobile Station /USA/
by E.C. Silverberg

I. French Station
by Claude Veret

J. German Station
by Peter Wilson

III. SATELLITES CURRENT AND FUTURE

Some of the current and future satellites are discussed. The parameters define the problems with satellites on which stations are expected to range in the near future.

The relative return is the relative signal level when the laser energy and beam divergence of the stations are held fixed.

IV. NETWORKS, CURRENT AND FUTURE

In this section, we consider the networks of laser tracking stations.

In total, there are now 11 orbital satellite tracking stations which enter data in the SAO prediction program, and by 1977-80, there are expected to be 22. Including the Intercosmos stations and the Lunar stations, there are expected to be 35 stations by 1980 which shall need good intercomparisons of epoch.

Satellite Name	Relative Return	Visual Magnitude	Tracking Rate	Orbit Stability
High Return				
BE-B	2.9	Bright	Fast	Fair
BE-C	4.6	Bright	Fast	Fair
GEOS - A,C	4.0	Bright	Fast	Fair
GEOS B	18.0	Bright	Fast	Fair
AUOS-Z	1300.0	Bright	Fast	Fair
Medium Return				
STARLETTE	$800x10^{-3}$	11	Fast	Fair
LAGEOS	$9x10^{-3}$	12	Medium	Good
TIMATION	$3x10^{-3}$	11-14	Medium	Good
Low Return				
A 11	$2.4x10^{-8}$	-	Slow	Excellent
A 14	$2.4x10^{-8}$	-	Slow	Excellent
A 15	$5x10^{-8}$	-	Slow	Excellent
L 1	$6x10^{-8}$	-	Slow	Excellent
L 2	$6x10^{-8}$	-	Slow	Excellent
SHINY BALL	$100x10^{-8}$	-	Fast	Fair

	Current Number of Stations	Expected Number of Stations by 1977-80	Capability of all Satellites brighter than	Capability by 1977-80	Planned Colocation Experiments	Pointing and Tracking
Inter cosmos	4	8	BE-B	LAGEOS	Yes	visual
SAO	4	4	LAGEOS	LAGEOS	/tri- lateration/	absolute
GSFC	3	7	LAGEOS	TIMATION	Yes	absolute
CNES	1 - 2	3	STARLETTE	STARLETTE	Yes	absolute
ONERA	1	1	STARLETTE	STARLETTE	Yes	absolute
LUNAR	1 - 2	8	all lunar arrays	all lunar arrays	Yes	visual and for some absolute
	16	31				

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