Preliminary work has also been carried out to shorten the pulse to 5 ns, to use a common detector for both start and stop pulses, and to use a transient digitizer and a computer as the timing processor. Also improving the telescope's pointing accuracy is under work.

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# Future Plan on the Laser Ranging Systems at the International Latitude Observatory of Mizusawa

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We are now planning to be equipped with a satellite laser ranging system in a couple of years and a lunar laser ranging system in the next couple of years at the International Latitude Observatory of Mizusawa.

Our interests are concentrated mainly on a cooperative work in a derivation of the rotation of the Earth and of a relative movement of the station referred to the other stations.

1) The system for satellites will be of the second generation and should have a capability of observing Lageos. Details of the system will be fixed in the near future but the main specifications now in our minds are as follows :

Laser : Yag, Nd, Glass
- Power : 0.2 Joule
- Pulse width : 1 nsec or less
- Wave length : 5320 Å
- Pulse rate : 0.33 pps

Optical System
- Emitter : $\phi$ $250^{mm}$
- Receiver : $\phi$ $600^{mm}$

Mounting : Alt-Az, Coudé
- Accuracy of pointing : $\pm 0\overset{\prime}{.}1$

2) The system for the Moon is under investigation.

# OPERATING SATELLITE RANGING SYSTEMS; CONCLUDING SUMMARY

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Four levels of satellite ranging can be distinguished:

- -centralized operation of station networks (NASA,Interkosmos, CNES,SAO);
- -operation of single stations (Wettzell, Kootwÿk, Potsdam, Dionysos);
- -preparation of stations for near-future operation (Cagliari, Zimmerwald,Metsähovi, Tokyo);
- -planned preparations of stations.

In all there are about 30 satellite ranging systems in operation or about to start. These are globally deployed, although far from uniformly. Their reported single shot rms precisions range from about a 100 to about 5 cm.

Three classes of satellite ranging systems are somewhat loosely defined, retaining their potential single shot rms precision as the criterion; those of:

- -first generation: not better than 50 cm;
- -second generation: better than 10 cm;
- -third generation: better than 3 cm;

There is some concern as regards the implementation of sophisticated TV-aided visual acquisition devices, in that such devices might divert the attention from the need to obtain fully automatic blind firing capabilities.

The requirements put on satellite ranging data by the scientific users are not very convincing. For lunar ranging data a rms 3 cm normal point precision has been stated as being a practical lower limit to strive for. However because of differing inherent strategies of data condensation, this limit does not necessarily apply to satellite range data. It is felt that the ultimate design goals for satellite ranging systems should be about 1 cm (rms single shot) instead, as far as precision is concerned.

Data condensation is a controversial topic. High repetition rate systems will give rise to questions of practical data handling, considering on the other hand the requirement that no signatures of geophysical or other scientific phenomena should be lost. To retain one data point per second is stated as the possibly highest demand. On the other hand one could hardly think of geophysical phenomena which require more than 30 or 50 points per pass in order that no information is lost. Unless further scientific requirements are specified, this problem is likely to be solved from a purely data-handling point of view.

Although systems precisions at the 10 to 5 cm level are attainable, the construction of satellite ranging systems with first generation characteristics could still be considered of value:

- for groups to enter the field in case such first generation systems are substantially cheaper;
- provided they will be soon, if not immediately available.

The near or mid-term prospects for all-weather satellite tracking devices are that it is very unlikely that second and third generation laser ranging systems are to fear competition. Even in the long-run, laser ranging is likely to be the only technique capable of providing data on the 3-1 cm precision level.

Although there is a tendency to develop precise satellite laser ranging systems capable of being used in a high-mobility mode, some applications (e.g. Earth rotation and polar motion studies) require fixed-site systems of the best available precision.

## NASA LASER SYSTEM PERFORMANCE SUMMARY

1. The estimated accuracy of the NASA systems is between 5 and 10 cm depending upon the characteristics of the satellite being tracked.

2. Range calibration is performed by prepass and postpass calibration to an external target. The target position is surveyed with respect to the laser station to an accuracy of 1cm using an AGA Model 76 geodimeter. During calibration the RMS jitter of the data is typically $<5$ cm and the drift in the mean values for periods of several hours are typically $<4$ cm.

3. Epoch time is maintained by using a cesium beam frequency standard as the local time standard. Synchronization is achieved by a combination of techniques depending upon the location of the station, to an accuracy of $\pm 1$ microsecond. These techniques include travelling clocks, Loran -C, Loran - D, VLF (For frequency synchronization) and finally NTS receivers.

4. Internal safety at the laser sites to protect against accidents with either high voltages or by exposure to high energy laser beams are documented in detail in a laser system safety manual. They include safety interlocks, warning signs, use of approved safety goggles, etc. External safety to avoid illumination of overflying aircraft depends upon the use of a safety observer for close - in aircraft and a high powered acquisition radar to detect the approach of aircraft beyond visible ranges.

## SAO LASER RANGING SYSTEMS

1. SYSTEM ACCURACY (25NSEC PULSE)

   SYSTEM NOISE LEVEL:

   LOW ORBITING SATELLITES: 15-30CM

   HIGH ORBITING SATELLITES: 1-1.5M

   SYSTEM STABILITY: 7-10CM(UPPERBOUND)

   SYSTEMATIC ERRORS:

   LOW ORBITING SATELLITES: 20-30CM

   HIGH ORBITING SATELLITES: 1-1.5M

   SUBSTANTIAL IMPROVEMENT ON LOW ORBITING SATELLITES ANTICIPATED WITH CHOPPER(6NSEC PULSE)

2. RANGE CALIBRATION

   METHOD:

   SURVEYED LAND TARGET

   EXTENDED CALIBRATIONS FOR SYSTEM RESPONSE

   PRE- AND POST-PASS CALIBRATIONS

   STANDARD DEVIATION AT 100 P.E.: ~±1NSEC

   SHORT TERM DRIFT(PASS): .5-.7NSEC

3. EPOCH TIMING

   CLOCK SYSTEM: EECO CLOCK (VLF/OMEGA FREQ REF)

   OSCILLATORS: RUBIDIUM STANDARDS

   EPOCH REFERENCE: NTS RECEIVERS(1978)

   EPOCH SET: PORTABLE CLOCK

4. SAFETY

   INTERNAL SAFETY: SIGNS; VISUAL ALARMS; NORMAL ELECTRICAL SAFETY PRECAUTIONS; ROUTINE EYE EXAMINATIONS

   EXTERNAL SAFETY: VISUAL SPOTTERS AND DIRECT CONTACT WITH AVIATION AUTHORITIES (AUSTRALIA) FOR AIRCRAFT SAFETY

## LASER RANGING SYSTEM WETTZELL, FED. REP. OF GERMANY

1. The estimated ranging accuracy of the system is ± 5 cm or better.

2. The range calibration is performed by firing at a fixed terrestrial target 1,2 km distant. During ranging all variable parameters influencing the measured range are varied through their entire range. An average of about 40 ranges are taken with each setting. The characteristic results are summarised by

   typical spread ............ ± 2 cm
   standard error of ranges ... ± 1 cm
   drift over period of 1 pass not observed.

3. Epoch timing is performed on-line by system clock (rubidium frequency standard). This clock is controlled by daily time comparisons with a cesium standard, two Loran-C chains and periodic clock-transfers between Braunschweig (PTB) and Wettzell. Additional comparisons are made with other rubidium standards at the station.

4. The station is occupied 24 hours/day, 7 days/week. Maintenance and internal tuning adjustments on the electronics and laser may only be performed under the supervision of one of the electronic engineers at the station, with a minimum of two people present. The station is located in an Air Defence Identification zone, but there is a local sport flying club in the vicinity. No civil air traffic is permitted to fly within 18 km of the station. A special telephone connection is available for contact with the NATO Air Force Command Centre. A communication link between the local sport traffic airfield and the station is also available. Operation times at the station are posted to the Air Traffic Controllers well ahead of time.

## SUMMARY OF LASER RANGING SYSTEM CHARACTERISTICS

Observatory for Satellite Geodesy, Kootwijk (The Netherlands)

Ranging accuracy: At present an accuracy level of 15 - 30 cm has been achieved in range measurements to GEOS - 1, GEOS - 3, Starlette and LAGEOS.

Calibration: Calibration of the system is based on prepass and postpass range measurements along a short internal light path. The standard deviation of these measurements is 5 cm or better.
The stability of the system calibration during a satellite pass is in the same order of magnitude.

Epoch timing: Standard frequency and timescale is derived from a rubidium standard. The station timescale is related directly to the Netherlands national time standard (one of the standards contributing to the definition of UTC), using TV sync pulse comparison. Accuracy of timescale synchronisation: 0.5 microsecond UTC.

Laser safety: The following safety measures have been taken:
- all legally dictated general safety measures (goggles, warning signs, shielding, etc.)
- attenuation of the laser beam when performing tests and calibration measurements
- airtraffic protection: an optical airplane detection system with automatic laser inhibiting.

# SUMMARY OF THE CHARACTERISTICS OF THE LASER RANGING SYSTEM AT THE CAGLIARI OBSERVATORY

Owing to the fact that the laser station has not yet been assembled, the following characteristics are only indicative.

1. RANGING ACCURACY

The ranging accuracy is expected to be about 20-30 cm.

2. RANGE CALIBRATION

Two or three targets at different azimuts and distances (500-1500 m) will be placed around the laser dome; however it is not excluded to perform prepass and postpass calibration through an internal light path.

3. EPOCH TIMING

A cesium standard will control the laser-clock. Daily this time base is compared with the LORAN-C station of Simeri Crichi and, by means of TV methods, with the timescale of the Institute "Galileo Ferraris"of Turin. Accuracy within 1 $\mu$s is achieved.

4. LASER SAFETY

For internal security, safety glasses are used. Moreover, all power supplies are disabled and energy storage banks are automatically dumped every time the capacitor box doors or the optical rail cover are opened.

For external security, only visual monitoring on TV system is planned up to now. When operating, both civil (Elmas airport) and military (Nato Decimomannu airport) authorities will be informed.

# ZIMMERWALD SATELLITE RANGING STATION

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Bern, Switzerland

1. Ranging accuracy (see 1 )

   - Without waveform-analysis ∿ 90 cm
   - With waveform-analysis ∿ 40 cm

2. Range-calibration

   Special method, described by I. Bauersima 1 .
   Estimated accuracy ± 14 cm (from 10 single calibrations)

3. Epoch timing

   A HBG-receiver, controlling an internal oscillator is used.
   Estimated accuracy of the epoch $\leq$ 20 μs.

   Control is done by transporting a clock to the Zimmerwald Station.

4. Security

   Internal: An "Interlock-System" allows turning off high voltage from various points of the observatory.

   External: During observation-periods the civil and military flight-control authorities are informed daily about our operation schedules.
   The maintaining of security during operation is granted by visual observation of the sky.

Reference:

1 I. Bauersima: Entwicklung, Zweck und Perspektiven der Satellitengeodäsie, Mitteilungen der Satellitenbeobachtungsstation Zimmerwald Nr. 1

The characteristics of the Metsähovi satellite laser range finder are the following.

1. Estimated ranging accuracy of the system is about 1 m.

2. The system is calibrated in the 332 m long test line. About 20 shots are made for each calibration. The calibration is made with formula

$$\tau_c = \tau_s - \tau_m$$

$$\tau_s = 2224.73 + 0.1785(p/T)$$

$\tau_c$ is the calibration correction factor, p is the athmospheric pressure in mb, T is the temperature in Kelvins, and $\tau_m$ is the mean of all 20 calibration range measurements. The result is in ns. The accuracy of one single shot is from 0.5 to 1 ns corresponding to 7.5 cm to 15 cm. In some cases drift from 1 to 2 ns per hour has been found.

3. The time in UT units has been determined with a LORAN-C phase locked quartz clock. The system has been calibrated with a flying cesium clock (from EISCAT). Accuracy is between 1 and 5 $\mu$s.

4. Maintaining internal and external safety is not yet arranged.

# CHARACTERISTICS OF HELWAN SATELLITE LASER RANGING STATION

BY

M. FAHIM and A. S. ASAAD

1- The charecteristics of Helwan Station is as follows :

| | | | |
|---|---|---|---|
| Active material | : Robyrod 12X150 mm | , Wavelength | : 694.3 mm. |
| Pulse width | : 20 X $10^{-9}$ Sec | , Pulse Energy | : 1 July ( $10^{19}$ phot.) |
| Repetition rate | : 30 pulse / min. | , Beam divergence | : 4 m radian |
| Telescope Divergence | : 0.4 m rad. | , Threshold Voltage | : 2100 V, T=22°C |
| Lamp max voltage | : 2100 V | , Recomended Voltage | : 1900 V |
| Colling | : Circulating distilled water , Q switch ( Double mode ) : retating prism and saturable dye. | | |

2- The range calibration is carried out twice, before and after observation using a fixed wooden target at 495.234 m from Laser van .

3- An Ecco clock calibration by a LORAN System is used as time base. An accuracy of ± 1 microseconds is reached. Signals from EECO clock is synchronized to within ± 1 usec. The time was cheched by portable flying clock two times per year. The signals received by LORAN are transmitted from Rome. The firing time, the repetition rate and the epoch of observations are controled by a laser clock and by an FL 103 time interval unit through an HP calculator.

4- For maintaining saftey at the ranging site , separte lines with over loading switch are used besides a set of battaries is connected with clocks to feed up during electricity failure . Cooling system is checked daily and the circulating water weekly.

# CRIMEAN LUNAR LASER RANGING SYSTEM

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The ranging accuracy of the system is calculated on the basis of measured and calculated errors and delays:

$$\sigma = \sqrt{\sigma_e^2 + \sigma_{ey}^2 + 2\sigma_c^2 + \sigma_p^2} \simeq 1.5 \text{ ns, or } 25\text{cm}$$

where $\sigma_e$, is the mean square value of the error due to laser pulse duration $\simeq$ 0.8 ns; $\sigma_{ey}$, is the error in electronical and geometrical delays $\simeq$ 1 ns; $\sigma_c$, is the error due to the discreteness of the counters $\simeq$ o.3 ns; $\sigma_p$, is the error of the photomultiplier $\simeq$ o.5 ns.

The epoch timing system uses time signals transmitted by TV channels .The propogation time of the TV-channels is measured by means of the transportable clock.

Time parameters of the system:

laser transmitter pulsewidth 2 ns;
resolution time of the counters 1 ns;
time resolution of the photomultiplier 0.5 ns;
time of the laser pulse in UTC(SU) scale $\sim 5\ \mu$s.

Internal safety for personnel is provided by using special spectacles. External safety is provided by manguard at the top of the telescope building.

## DODAIRA SATELLITE AND LUNAR RANGING STATION

1. Ranging Accuracy

   Satellite ( with pulse slicer ) ~ 30 cm

   Moon ~ 1 m

2. Range Calibration

   Several fixed ground targets with the distances about 150 m, 1km, 2 km, 3 km and 4 km, respectively.

   the accuracy is about ± 10 cm.

3. Epoch Timing

   The frequency standard is a crystal oscillator.

   The clock is calibrated by Loran C radio signal, and also linked to the Mitaka Observatory ( the main office of the Tokyo Astronomical Observatory ) through VHF. At the Mitaka Observatory, four cesium frequency standards are installed.

   The accuracy of the epoch is + 10 μs.

4. Security

   Internal: Alarm lamps and sounds when the laser is fired.

   External: Visual watch of surrounding sky. Fortunately, our station is far from regular civil and military air routes. Sometimes, small planes for agriculture and forestry come around our station.

# session 3B lunar ranging systems

*chairman E. Silverberg /co-chairman Yu. Kokurin*

*Silverberg*

*Calame /Gaignebet*

*Kokurin /Kurbasov /Lobanov /Sukhanovsky*

*Cushman*

*Silverberg*

*Kozai /Tsuchiya*

*Wilson*

*Greene*

# LUNAR LASER RANGING SYSTEMS
## SESSION 3B
## REMARKS BY THE SESSION CHAIRMAN

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Despite considerable effort over the last three years, routine lunar ranging by a number of laser tracking facilities is still not available. It is certainly difficult to characterize in a few words the reasons for the slowness of development in this technique. Unlike satellite ranging, no two lunar systems are alike, accounting to some degree for the difficulties, since each must address an almost unique set of problems. It is also regrettable that this technique has such a high threshold of performance before even rudimentary results can be delivered. Even the lack of meaningful intermediate targets over 5 orders of magnitude in signal level must take some credit for the sporadic development. And lastly, the lessening of priority for lunar data relative to very interesting lower targets has, and will continue, to slow progress. Nonetheless, no one would now seriously doubt that routine lunar data can be attained and, in fact, must be attained if the high potential for gain in celestial mechanics, general relativity, and earth dynamics is to be realized.

As pointed out by Mulholland and Calame in Session 1, the scientific goals for lunar ranging cover a wide range of disciplines, some of which are not accessible in the foreseeable future in any other practical manner. From the standpoint of station development, it is important to note that many of these goals can be attained with limited data sets, although a complete solution of the full set of problems requires an ambitious global observing program. The latter observation is important in the context of our present situation. The technology necessary to track lunar targets varies greatly according to the required coverage of the lunation. Furthermore, there is an increasing importance that lunar systems attain compatibility with jointly sponsored satellite efforts. While it is highly desirable that daily observations be attained whenever possible, even modest amounts of lunar data from widely scattered institutions can be of great importance in many instances. Station development need not be predicated on the full time supply of data to expect to be an extremely important contributor to the scientific goals of this technique.

The immediate goal at this time is to begin to collect lunar data, however limited, from more locations. It is particularly important that these data be well calibrated for, if this is true, even a dozen range measurements can produce a scientifically meaningful baseline and earth orientation solution. It is equally important to start the preliminary data transfers to exercise the technical capabilities at the station and to test analysis capability for this technique at many analysis centers. Most importantly, the meaningful results which can be attained with even a few well calibrated data points should have tremendous scientific and political consequences for all of the nationalities associated with lunar laser ranging.

# FRENCH LUNAR LASER RANGING STATION

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## INTRODUCTION

After an initial operating period, partially successful, at the Pic-du-Midi Observatory, the French lunar laser ranging experiment started a new development with the establishment of the CERGA installation (Centre d'Etudes et de Recherches Géodynamiques et Astronomiques) at Grasse.

The construction of this new station is the responsibility of a laser team, housed at both CERGA locations, with funding supplied from various organizations. The equipment is installed at the Calern plateau, while the scientific work is performed at Grasse. This is a unique situation for a lunar laser station in that the entire computation string (prediction computations, observations, data processing and the scientific analyses) is performed by the same group. In this paper, only the experimental portions will be described in some detail.

## HARDWARE SYSTEM

The overall system is entirely new and was designed and constructed specifically for this station, including a new telescope dedicated to this experiment.

### Telescope

The 1.5 meter (f/20) Cassegrain telescope provides the transmitting and receiving optics. A dichroic mirror splits the return beam between a guiding system and the receiving ensemble. The resolution of the optics is about 3 arcseconds. The azimuth-altitude configuration is driven by a continuous system using worm gears, torque motors, and incremental encoders, in a closed loop, computer-driven mode. The pointing and the guiding are managed by a mini-computer (NOVA 1220) which supplies positioning increments, second by second, to the drive system and checks the position assumed by the mount.

## Guiding System

A computer-driven guiding system is placed in the beam passed by the dichroic mirror. This apparatus is able to offset a television camera in a polar coordinate system, allowing a visual tracking of lunar reference features, while the main optical axis follows the reflector direction.

## Laser Transmitter

The configuration of the QUANTEL ruby laser system consists of an oscillator, a double-pass amplifier and a power amplifier. It generates pulses of 3 nsec length, with an energy of 4 joules, at a repetition rate of 1 pulse every 4 seconds. Coupled to the mount by four mirrors in a Coude arrangement, the beam is directed through the telescope via a flip mirror selecting the transmitting/receiving mode. Fixed at the back of the first Coude mirror, an optical fiber picks up a sample of transmitted light and routs it to a photodiode within the ranging system electronics for the timing of the pulse start.

## Receiving System

The receiving system is placed near the telescope's main focal point. It is designed to contain principally the multidielectric filters (3-5 Å), the collimating lenses, a mechanical shutter and the photomultiplier tube. This device is maintained in temperature to within 1°C to allow the use of narrow-band Fabry-Perot filter (about 0.3 Å), now under test. The system is designed to have the capability of being equipped with two photomultipliers.

## Ranging System Electronics

The ranging system consists primarily of a range optical gate control and an event-timer. The range gate, which eliminates all pulse detection outside a preselected channel, can be chosen with a length from 200 microsec to 20 nsec. The range and range rate predictions are supplied by the main computer in real time.

The event-timer is a very accurate clock which is able to time 5 successive events (extension to 10 is anticipated) representing either the laser start or photon stop or clock stop signals. The precision of the measured epochs is 100 psec and the recovery time between two consecutive measures is 4 nsec. These event times are recorded in memory and thereafter processed by the main computer for establishment of an histogram.

To minimize the errors introduced by the fixed threshold detection, pulse centroid detectors are used for both the start (photodiode) and stop

(PMT) pulses, so that the accuracy of the time delay measures can be significantly better than the laser pulse length.

Computing Facilities

The CERGA lunar laser station is equipped with two computers working in real time:

a) a Data General ECLIPSE serves as the main computer. Its configuration includes:

- CPU (32 K memory)
- disk package
- double cassette driver
- alphanumeric Tektronix display
- Texas Instruments Silent 700, with modem
- teletype

b) a DG NOVA 1220 is slaved to the ECLIPSE for the telescope guiding.

## SOFTWARE SYSTEM

Four principal tasks have to be performed in real time by the computer system in the course of observation runs.

Predictions

For both the telescope driving and the determination of the range gate, as well as for the construction of an histogram, it is necessary to know, at each moment, the position in space of the observed reflector with respect to the operating station and the position in the guiding focal plane of the reference craters. These computations are required at a high accuracy level, such that the programs have a great complexity and require a long computing time. Thus, the predictions are evaluated in advance on a CDC 7600 computer, using a very accurate ephemeris and mathematical model, taking into account the small effects acting on the motions of the reflector with respect to the station. To conserve computer cost, these predictions are calculated at large intervals (every 20-30 minutes) and recorded on cassettes. In the course of an observing run, the ECLIPSE computer reads these data, interpolates between them and transmits the results either to the NOVA computer for the driving and guiding system, or to the ranging electronics for the opening of the range gate. Also, these computed range values are used by the ECLIPSE for the pre-processing of the photon return data.

### Driving and Guiding

These tasks are performed by the NOVA computer which converts the coordinates (equatorial to horizontal), computes the refraction effects and transmits the deduced position of the reflector to the driving system, each second. At the same time, it checks the values of the encoders, takes into account the eventual manual offsets, the instrumental flexures and driving inaccuracies, before making a correction to update subsequent predictions. In addition, the computer selects the reference points corresponding to the observed reflector and the lunar phase; then, it transmits the calculated positions to the guiding system so that the TV camera is positioned on the selected crater.

### Management of the Experiment

The ECLIPSE computer works as a master control for all the other devices, both for inputs and outputs. Indeed, in several aspects, it ensures the ties between the various elements themselves and the external world. The principal linkages are with the prediction cassettes, the NOVA computer, the ranging electronics, the event-timer, and various devices for data such as temperature, pressure, humidity.

### Data Processing

In addition to the general control, the ECLIPSE must perform some data processing. For the lunar laser ranging, it is necessary to integrate several shots, and detect the eventual signal by a statistical process. It is important to have that capability in real time in order to properly direct the experiment. Therefore, the laser shot and the four photon stop times are recorded; the corresponding time delays are computed; and, at each firing the results are compared with the predicted range. Using a statistical process based generally on a Poisson distribution, an histogram can be built over the course of a series of shots.

A series of shots is stopped when the probability that an event can be attributed to the statistics of noise is sufficiently small. Those results are then recorded on cassettes and are later processed by the CDC computer for the construction of normal points, which represent the observation data, intended for the scientific analyses.

## CONCLUSION

At this moment, this station is in course of completion and under test. It is envisioned that it will be in functioning in a near future.

# CRIMEAN LUNAR LASER RANGING SYSTEM

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## LASER TRANSMITTER

In paper /1/ a laser ranging system has been described with the laser placed in the coude configuration of the telescope. However, due to high losses in the optical system as well as the lack of observing time, work on further improving this system has been suspended.

For these reasons and with accompanying progress in testing a telesopic amplifier, a new laser transmitter is now being prepared for ranging. The new system may be placed on the rotating polar platform as described earlier /2/.

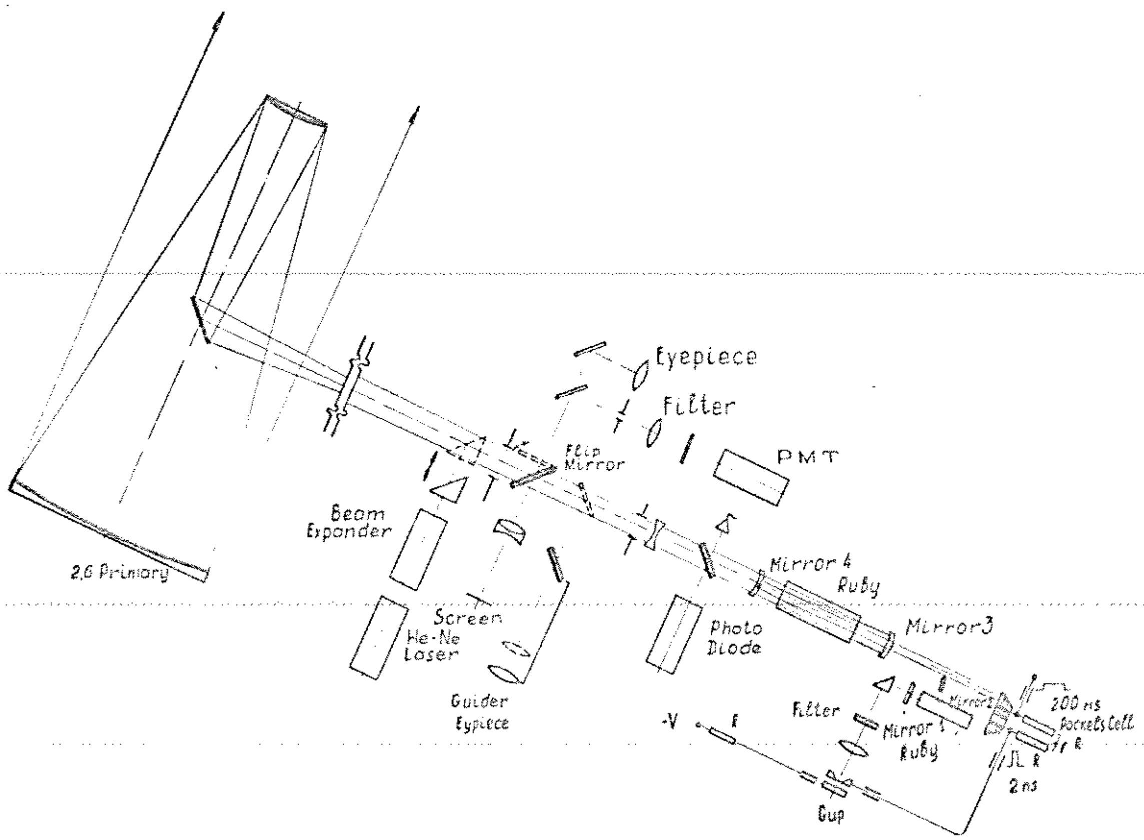
A schematic diagram of the system is shown in Figure 1. A driving oscillator, developed on the basis of /3/, consists of two cavity mirrors, 1 and 2, with reflection factors 100% and 80%, a ruby crystal 7 mm in diameter and 120 mm long, and Q-switch cell with two triggering channels. One of the control channels is used for Q-switching of a giant pulse, and with the help of the second one that utilizes a laser-triggered spark gap, cavity-dumping is carried out for time duration ≈ 2 ns. The resulting oscillator beam is directed into a telescopic amplifier. The energy of the tailored pulse is ≈ 50 mJ with a pulse-width ≈ 2 ns. The telescopic amplifier consists of the mirrors 3 and 4 and a ruby crystal 16 mm in diameter and 240 mm long. The gain of the amplifier is ≈ 60. For details on the other parts of Figure 1, see reference /1/.

A summary of parameters for the laser transmitter are as follows: pulse-width $\tau_{0.5}$ = 2 ns; pulse energy W = 2.5 J; wavelength $\lambda$ = 6943 Å; full linewidth $\Delta\lambda$ = 0.4 Å; beam divergence $\theta_{0.5}$ = 7″; output aperture d = 1.6 cm; pulse repetition frequency F = 0.33 cps.

## RECEIVING AND RECORDING EQUIPMENT

An FEU-77 photomultiplier is used in the photodetector. By selecting among many samples and by a thorough choice of operating conditions, a time

Fig. 1. Schematic diagram of the laser ranging system.



resolution of $\pm 0.5$ ns has been obtained for the photomultiplier. The guiding system was repeatedly described in our papers, and remains unchanged.

The measuring and recording equipment are based on a TPA-1001-i minicomputer and are modernized in comparison with 1975. The system permitted us to improve the accuracy for measuring the time of laser signal propagation to $\simeq 10^{-9}$ s. Moreover, the system performs lunar ephemeris interpolation for each 3 seconds using reference points with an interval of 0.5h /1/. There are three independent time counters, having 1 ns resolution, which may operate parallel as well as in series.

The epoch timing system uses time signals transmitted by TV channels. This system permits measuring the time of the laser pulse in UTC (SU) scale with an accuracy $\pm 5$-6 μsec.

## ACCURACY

The ranging accuracy of the system is calculated on the basis of measured and calculated errors and delays:

$$\sigma = \sqrt{\sigma_e^{\,2} + \sigma_{eg}^{\,2} + 2\sigma_c^{\,2} + \sigma_p^{\,2}} \approx 1.5 \text{ ns, or } 25 \text{ cm}$$

where $\sigma_e$ is the mean square value of the error due to laser pulse duration $\approx 0.8$ ns; $\sigma_{eg}$ is the error in electronical and geometrical delays $\approx 1$ ns; $\sigma_c$ is the error due to the discreteness of the counters $\approx 0.3$ ns; and, $\sigma_p$ is the error of the photomultiplier $\approx 0.5$ ns.

## SAFETY

Internal safety for personnel is provided by using special spectacles. External safety is provided by an observer at the top of the telescope building.

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# STATUS OF MAUI LURE OBSERVATORY

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Essentially, the observatory is complete as designed by the LURE team. The transmitter has been in operation for several years, with minor down time. It consists of a 41 cm aperture, fixed telescope with a 72 cm flat mounted as a coelostat in front of it. The telescope points due north, thereby permitting the flat to direct the laser beam, without diminution, to the moon at all aspects for an observatory at 20° latitude.

Attached to it is a neodymium:YAG laser which is presently operated at three hertz, with pulse width of three quarters of a nanosecond, and about one third joule per pulse. After considerable trouble getting this device operational, the laser technicians can now use it virtually as desired. A full year of operation has required approximately twelve thousand dollars of supplies, not including necessary power.

At the opposite end of the building is the multi-eyed telescope consisting of eighty refractors of 19 cm aperture on a common suspension. Optically, this telescope has performed well; much time was required to align it initially, but alignment has held well. Mechanically, this telescope has not yet achieved a satisfactory state. Full operation is expected before the end of the year.

To control these devices and to record data, two Nova computers were chosen. While these seem able to do the job, by hindsight, a single, faster computer would have been a better choice. Complete software has not yet been developed for the ranging routine, mainly because software provided by others has been difficult to debug. As the system stands, much manipulation is required by the operators which could be eliminated with a single computer.

For all the shortcomings, the system works as has been demonstrated on several occasions during 1977 and once in 1978.

The station is now being modified slightly to permit ranging to satellites. The transmitter is being made into a transceiver, and its dome is being fitted with better motors. Lunar ranging is temporarily being suspended until these changes are effected. It is hoped that a combined program of ranging to both the moon and near earth satellites will become routine within a few months.

At present there is an unexplained spreading of lunar ranging data, which limits the confidence of the data to about five nanoseconds in round trip time. Range calibrations are performed during ranging by a fibre optic cable between the two telescopes which transmits the laser pulse directly to the photomultiplier. The same spreading of data is observed. In addition, ranging is performed to a retroprism mounted on Mauna Kea Observatory, the round trip time to which is 853,371 nanoseconds. Since a slightly different system must be used, uncertainties are on the order of a nanosecond, and this increased precision is also observed in the fibre optic cable results. The difference between lunar ranging and range calibration has generated much research, which is as yet unrewarded.

The epoch timing is performed by an Event Timer developed by the University of Maryland, which is driven by an Austron Model 1200 Frequency Standard. Continuous check on the drift of the oscillator is made against a Loran-C signal originating barely one hundred miles away with about 60% over-water transmission, with daily calibrations performed during ranging periods.

Internal safety is governed by OSHA and University of Hawaii Radiation Safety Office regulations. External safety is governed by visual observation of the sky in the region of firing before and during laser firing. At an elevation of over three thousand meters, few airplanes pass near the observatory.

# MCDONALD OBSERVATORY STATION REPORT

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The University of Texas, McDonald Observatory lunar laser system in Fort Davis has been in regular operation since September of 1970. The system has produced over 2300 ranges to the reflectors on the lunar surface using the 2.7 meter reflecting telescope as both transmitter and receiver. The recently upgraded pulse-transmission-mode ruby laser permits transmitting approximately 1.2 joules of energy from the telescope once every three seconds, with a pulse width of 2.5 nsec, FWHM. The epoch recording timing system is based on an EG&G TDC 100, time digitizing module. Guiding is done either manually or by computer-driven offsets from lunar features. The system is operational three times daily, for 21 days per lunation.

The range precision with the McDonald system for a single shot is estimated at $\pm 20$ cms, with range-averaged normal points precise to approximately 7 cms. Annual signal levels average about 0.04 photoelectrons per shot, although a signal of 0.2 photoelectrons per shot is not infrequent. The calibration of the system is maintained during ranging by routing a highly attenuated portion of the transmitted beam onto the receiver detector at the single photoelectron level. Scatter in the calibration data, in the returns from the lunar reflectors and in the analysis of the data from run to run indicates that the actual ranging precision is very close to, if not identical with, the estimates, with the exception of a few points affected by laser pulse shape anomalies. However, a constant bias offset of up to 30 cms due to telescope geometry is possible in the entire seven year data span.

The relative epoch at the station is maintained to $\pm 2$ µsec by continuous recording of the Loran-C transmissions from a central U.S. station. Occasional visits by a travelling cesium standard have calibrated the propagation delay. Internally, the site follows the ANSI-prescribed standards for the maintenance of laser safety. Since there is little commercial air traffic in the area and the transmitted beam has an energy density of only 24 µjoules $\cdot$ cm$^{-2}$, the site has been permitted to limit air surveillance procedures to visual observers.

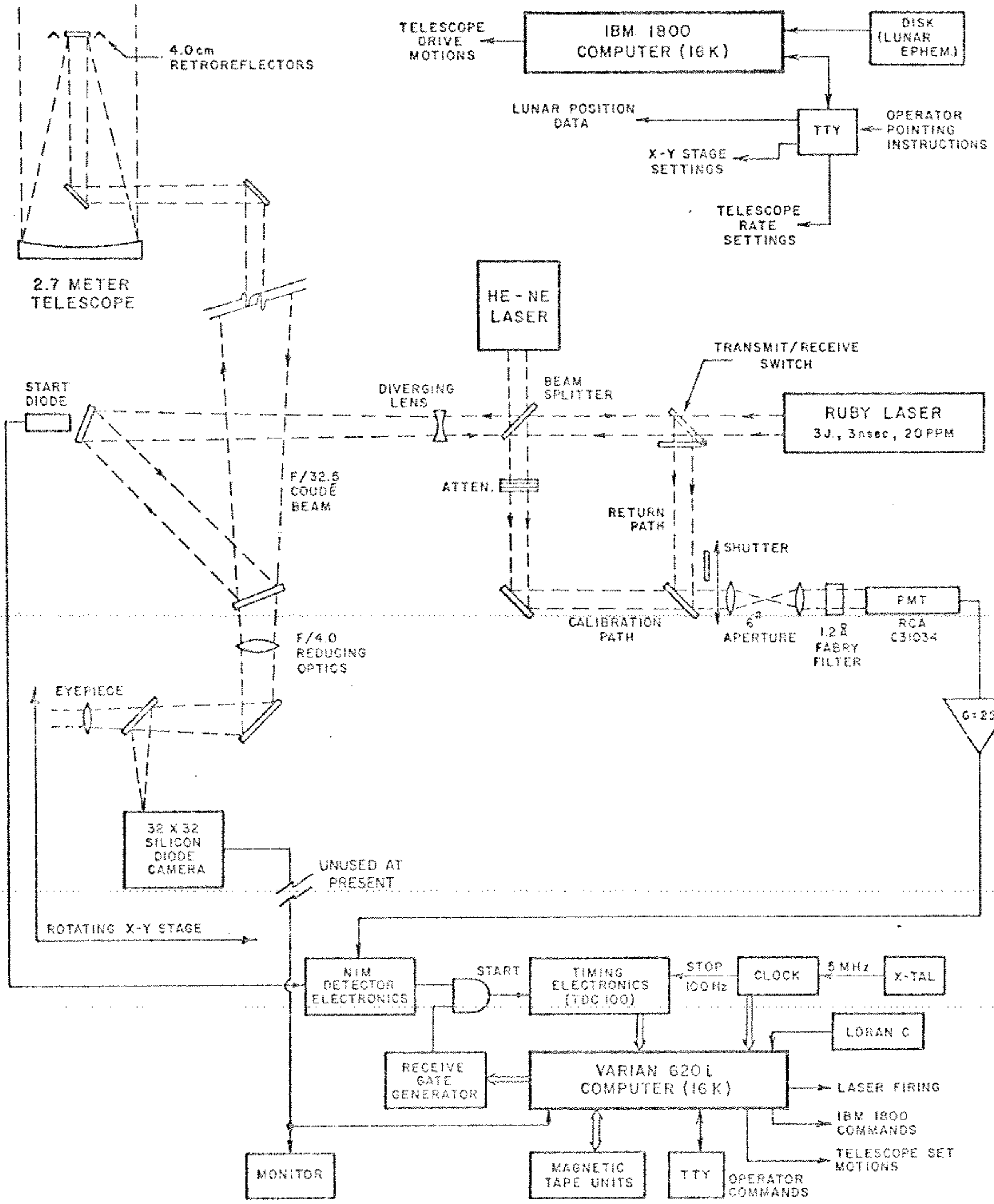


FIGURE 1: THE MAJOR COMPONENTS IN THE CURRENT McDONALD OBSERVATORY LUNAR LASER STATION AT FORT DAVIS, TEXAS

The University of Texas, McDonald Observatory Laser Station is supported by NASA Grant NGR 44-012-165.

# LASER RANGING SYSTEM AT THE TOKYO ASTRONOMICAL OBSERVATORY

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Mitaka, Tokyo, 181 Japan

## INTRODUCTION

The TAO laser ranging system is a combined system for lunar and satellite ranging; that is, the electronic system and computer are commonly used for both lunar and satellite observations. The system is installed at the Dodaira Observatory, which is located about 100 Km north-west of downtown Tokyo. A 3.8 m telescope is used solely for receiving the lunar signal, while a 0.5 m telescope is used for both satellites and the moon.

## 3.8 M TELESCOPE

The 3.8 m telescope uses a metal mirror with the diameter of 3.8 m mounted on an azimuth-elevation drive mechanism. The primary focal length is 3.8 m, i.e., the f number is 1. The combined focal length with the 40 cm Cassegrain mirror is 30 m. The filter has a bandwidth of 0.1 nm at 0.6943 µm. The photo-detector is an RCA-8852.

## 50 CM TELESCOPE

A 50 cm off-axis Cassegrain telescope is used for transmitting the laser beam to the moon and also used for receiving the satellite return signal. For satellite observations, the laser beam is transmitted by a small telescope commonly mounted on the 50 cm telescope. In both cases, the laser beam is transmitted through coude optics from the two lasers. This telescope is mounted on an X-Y drive mechanism.

## LASER

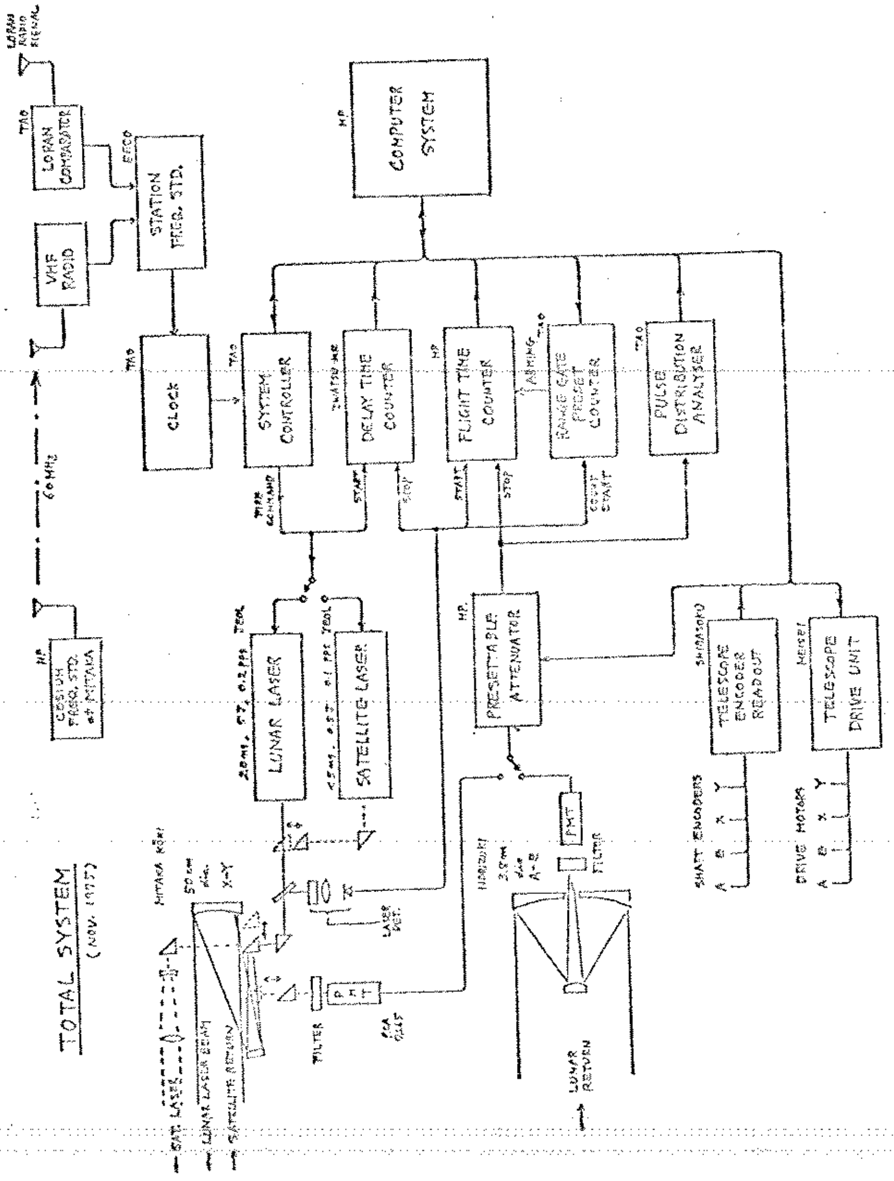
The lunar laser is a three-stage amplified ruby system. The pulse width is about 20 ns, and the maximum output power is about 8 J. With a mode-locked oscillator, the beam divergence is less than 1 m-rad.

The satellite laser is one-stage amplified ruby laser with pulse-slicer. The pulse width is about 3 ns and the output power is about 0.5 J. The beam divergence is about 5 m-rad. The lasers are installed in an air-conditioned room and the output laser beams are led to the telescopes through coude optics.

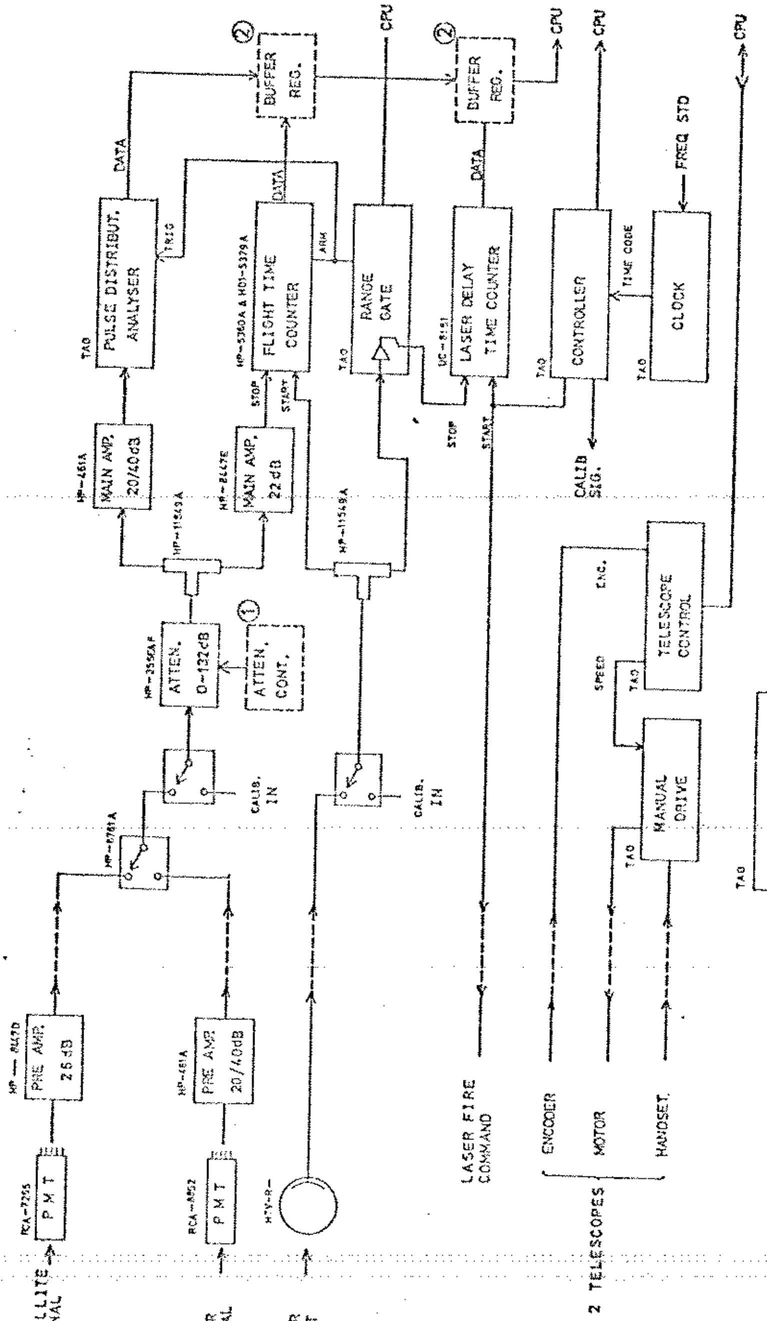
## ELECTRONICS SYSTEM

The main flight time counter is HP-5360A computing counter with 1 ns accuracy. The resolution of the range gate is 0.1 μs with the whole system controlled by an HP-2100 mini-computer.

The timing is controlled by a crystal frequency standard, which is linked to cesium frequency standards at Mitaka (main office of the Tokyo Astronomical Observatory) by VHF radio, and also, is calibrated by Loran-C radio signal.




第2図　レーザ測距装置の構成




第3図 レーザ測距装置の計測系統

# LUNAR RANGING MODIFICATIONS FOR THE LASER RANGING SYSTEM IN WETTZELL, FED. REP. OF GERMANY

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## HARDWARE

### Introduction

Already prior to installation of the new laser ranging system in Wettzell, it was recognized that the system has potentially the capability for ranging to the moon. The computation of the energy balance, assuming the laser to be operating at full energy, showed that the transmitted energy per second, divergence, receiver diameter and detector efficiency more than meet the minimum requirements for lunar ranging. However, to implement this capability a number of hardware modifications are necessary and the techniques for applying the system have to be defined.

### Hardware Modifications

The hardware modifications may be considered under the following grouping:

- changes in the computer interface unit, system control and modification of the servo amplifier to achieve the optimally smoothed low-rate pointing of the mount required for lunar ranging;
- introduction of a lunar range gate unit and modification of the system range timing counter to permit event timing, since some 12 laser pulses will be in flight before the return signal associated with the first one is detected;
- modification of the receiver control unit permitting operation in the normal satellite mode (using a range-time counter) and in lunar mode (event timing);
- introduction of remote mount control to permit fine pointing, e.g., to starts, from the observers telescope position;
- reduction of the laser firing jitter from currently 125 msec to approximately 150 µsec;

- upgrading of the photomultiplier by introduction of the newest Varian static crossed field unit, with 25% guaranteed minimum quantum efficiency (35% typical);
- introduction of a thermostatically controlled 3 Å narrow-band filter to replace the current 25Å unit;
- introduction of a video tracker to permit optimal target pointing during the calibration procedures.

## SOFTWARE

Besides the software support to be described implicitly during the session on calibration, an extensive software package is being developed in support of the lunar ranging modifications. This package is being planned as an independent operating system.

The lunar ranging procedures controlled by this software visualize the computation of the lunar ephemerides, system calibration, ranging execution, preliminary data precessing and system diagnostics. The ranging execution consists of the selection of and pointing to a suitable star towards which the lunar reflector is moving, to determine the momentary differential offsets due to instantaneous refraction and optical deformations. The differential offset will then be extrapolated to the predicted lunar pointing angles to obtain the anticipated reflector position. In the event that returns are still not possible an automatic search pattern can be introduced.

STATION DESCRIPTION
ORRORAL, AUSTRALIA
OPERATED BY THE DIVISION OF NATIONAL MAPPING

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Queanbeyan, New South Wales 2620

The Orroral astro-geodetic complex has, as its basic aims, the provision of observations relating to the changes in the earth's size and shape: the inclination of its pole and the rate of rotation; and the movement of crust. These aims are being tackled by optical (laser) and radio frequency ranging. The former is to be used for all precise determinations of geodetic quantities, such as geocentric coordinates, position of the instantaneous pole, universal time, and other similar parameters. The latter is used for time transfer, time scale and lower order geodetic work.

The central feature of the Orroral complex is its HP-21M/X computer which operates under a real time executive, currently RTE-3, which allows it to provide both control and analysis capacity to system users. In particular, it has the capacity to provide all ranging activity with differences between observed and predicted ranges. The residuals, termed deltas, violate the Poisson distribution law and hence they can be detected against this background. Satellite observations, at this instant derived from radio frequency observations, usually obey the classical Doppler S shape curve, as the greatest error is the along-track error. This allows a different but useful criteria to be adopted. A marriage of the current lunar laser technology and the current NTS radio frequency technology appears to be necessary for single photon detection of high altitude satellites.

HP-21M/X HARDWARE

CPU - 64K words of 16 bits
- semiconductor memory, 750 nanosec cycle time
- hardware arithmetic unit

* Mr. Greene is on leave to The University of Hull, Hull, England.

| | |
|---|---|
| | - firmware implementation of double precision and common FORTRAN functions |
| | - DMA at 1.5 megabytes per second |
| Mass Storage | - 4 discs each of 2.5 megabytes |
| | - magnetic tape unit, 9-track, 800 BPI, NZRI standard |
| Peripherals and Terminals | - paper tape reader |
| | - two visual display units operating at 2400 Baud, terminals have local memory and enhanced character sets |
| | - 300 Baud hard copy terminal |
| | - 200 line per minute printer |

The second common system in the Orroral complex is the time scale. At Orroral we are not blessed with access to global time systems such as Loran-C and hence we have been forced into the art of time keeping with the necessary ancillary function of performing time transfers. This function of time keeping provides us with a time base capable of measuring time of flight of a photon package to a relative precision greater than 1:10,000,000,000. It is to be noted that 1 nanosecond in 2.5 seconds is 4:10,000,000,000. The time scale also provides us with epoch of event capacity which is limited by the long-term stability of the clock system. This is about 5 microseconds per year relative to the UTC scale.

TIME SCALE HARDWARE

| | |
|---|---|
| Cesium Clocks | - 4 HP5061A type units to provide long-term stability |
| Rubidium Clocks | - HP5065A type with excellent stability in region up to 1000 seconds |
| Linear Phase Comparators | - two HP units to record at 200 nanoseconds full scale to provide analogue monitoring |
| Distribution Amplifiers | - two HP units to correctly balance loads onto cesium and rubidium clocks; output drives linear phase comparators and counters |
| Counter | - Eldorado one nanosecond counter for time interval comparisons |
| Interfaces | - Specialized interfaces to allow HP-21M/X to interact with cesium and rubidium clocks. |

The radio range system is commonly referred to as the timation or NTS system since it is used exclusively to track this series of satellites. Briefly speaking, the system uses a sequence of range tones from 100 Hz up to 6.4 MHz to resolve a range which is currently accurate to less than 10 nanoseconds if both the L and P bands are available. The system uses both the Hp-21M/X computer and the time scale since the one way range is resolved in terms of the propagation time from the satellite to the ground station. In addition to these components, the following form up the total radio frequency system.

NTS HARDWARE

| | |
|---|---|
| Receiver | - Magnavox dual frequency receiver and associated decoders and storage units. Receiver capable of resolving range to 1% of highest tone - 6.4 MHz |
| Antenna System | - Steerable antenna system comprising helix for P band and dish for L band. |

The optical tracking, laser, portion of the Orroral complex is by far the biggest component. It consists of the laser, the 1.5 meter Cassegrain telescope which doubles as both the transmitter and receiver and a detector consisting of a photomultiplier tube and discriminator. All of these subsystems are connected to the HP-21M/X and clock system. It is appropriate to discuss these subsystems.

The Laser Subsystem

| | |
|---|---|
| Laser Type | - rod size 10 X 100 mm operating at 0.6943 microns |
| Pulse Principles | - reflection mode with on to off pockels cell |
| Oscillator Pulse Characteristics | - 20-25 nsec, FWHM long pulse of about 100 millijoules, low transverse mode content |
| Cavity Parameters | - 0.74 meter long, plano-concave geometry, saphire etalon used as front element, a 10 meter 99% reflecting mirror is the back element, a 3 mms aperture is used to suppress high order transverse modes |
| Amplifiers | - first amplifier - 10 X 100 mm rod pumped to 3.7 Kjoules second amplifier - 15 X 100 mm rod pumped to 3.7 Kjoules, third amplifier - 15 X 100 mm rod pumped to 3.7 Kjoules. |
| Total Power | - about 3 joules into the telescope. |

The Telescope Subsystem

The telescope is driven dynamically by pulse trains which can be applied to both the polar and declination axis. The rates on both axes are infinitely variable with 25 pulses per second on the polar axis approximating the sidereal rate. The rates applied to the respective axes are computed via a program called TRACK which generates lunar rates from Chebyshev coefficients of the moon's right ascension, declination, and horizontal parallax, while satellite rates are generated from fundamental theory. The program is self-scheduling at any required repetition rate, nominally set as once per minute. The telescope is resonance free up to eight times the sidereal rate. Currently, it is not possible to point the telescope in an absolute mode; however, it is possible to drive the telescope from a known position to another position. This is accomplished through an offset facility which operates in conjunction with the track program. The essential feature of method is that a known or determinable position is located on which certain registers are zeroed. Steps representing the desired offsets are then inserted into these registers under computer or manual control and the telescope is then driven until the number of steps applied to each axis equals the number held in the appropriate registers. Program HOWFR does this for lunar features while an independent module does it for offsets which originate from a star position. These latter positions are determined through an interactive program which is capable of searching the SAO catalogue on visual magnitude, right ascension, declination and spectral type. Options are also included for automatic updating of positions. These features allow the telescope to track slow targets such as the moon and the slow high altitude satellites.

The Detection Subsystem

The detection system consists of the following components:

Photomultiplier - The PMT is an RCA 3100E tube operated in the side position at -1950 volts. Measured efficiency is 8%

Amplifier - a quad amp is connected by rigid coax to the PMT. The total gain is 64, the rise time is 1.4 nsec per amplifier

Start Diode - an ITL subnanosecond rise time diode is used to start the counting sequence

| | |
|---|---|
| Calibration | - a small photodiode is mounted in the detector area which can be driven at the single photon rate. In conjunction with a constant range control program and the clock system, it is possible to pre and post calibrate the system electronic delay. |
| Frequency Filter | - a 3 Angstrom interference filter is used |
| Spatial Angle | - the receiver is limited to 12 arcseconds |
| Nanosecond Counter | - the current counter is arranged so that the start diode pulse and the stop PMT pulse both enter the same channel of the Eldorado counter. The stop channel is a 100 KHz pulse from the clock system. This overcomes variations in the levels of the different channels and lowers the requirement for a stable time base in the Eldorado counter. |
| Predicted Event Window | - this is provided by software in the HP-21M/X counter. |

Surveys have recently been done to ensure that the optical and mechanical invariant points of the telescope are known relative to standard external geodetic marks. The precision reached for the optical invariant point was $\pm$ 3 centimeters. The principal problem being the lack of coincidence between the optical and mechanical invariant points.

## CONCLUSION

In conclusion, we have attempted to put together a complex aimed at tackling some of the problems of modern geodesy. We have attempted to make our system as general as possible and to ensure that it is readily switchable from one mode to another.

The system described above has been in operation for about a year, although as with any system, constant improvements are always being made. In particular, we are attempting to refine the laser so that we can deliver more energy to the target without increasing the total power of the laser. We are also attempting to narrow down the laser pulse so that the precision of the system is increased. At this instant, it is the optical part of the Orroral complex that yields the lowest levels of data. Regular several times a week, up to two satellite passes per day are observed with the NTS radio frequency equipment providing us with excellent links to the internationally used UTC and TAI time scales. Similarly, our clock system and time scale function with such reliability that the Orroral system provides coordinated time for the whole of Australia.

In the important optical area, the first statistical lunar ranging events were recorded last June (1977). Since that time a small number of events have been recorded with August 1977 and February 1978 being the most successful months to date. It is hoped that as the next round of modifications and improvements to the system are effected that this data yield will increase. Improvements that will shortly be completed include a TV image enhancement system, a one Angstrom Etalon filter in the receiver/detector area, and hopefully, an improved laser.

# session 4A calibration and system errors

*chairman T. McGunigal /co-chairman M. Paunonen*

*Mangin /Gaignebet*

*Bize /Duchene /Gaignebet*

*Wilson /Nottarp*

*Buffton*

*Pearlman /Lanham*

*Kokurin /Kurbasov /Lobanov /Sukhanovsky*

*Zeeman*

*Billiris /Tsolakis*

*Hamal*

*Silverberg*

# A START-PULSE CENTROÏD DETECTOR

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## INTRODUCTION

The time delay $\tau$ measured (fig.I) by a laser ranging system must be as accurate as possible.

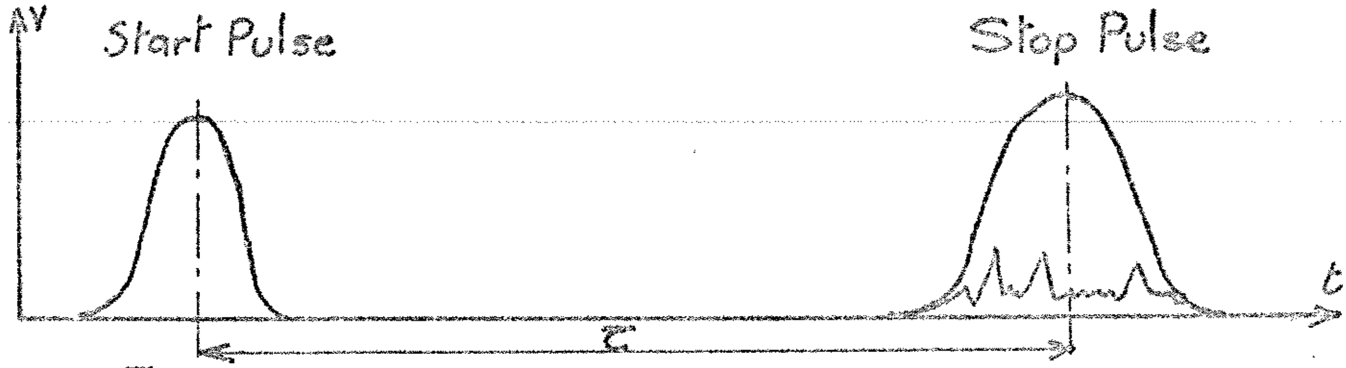



Fig 1 Definition of $\tau$

As the outgoing puls of the laser may change in width and energy a Centroïd detector is developed to minimise the jitter of the signal.

## PRINCIPLE

The device is a combination of an integrating detector and a constant fraction descrimination. The capacity of the photodetector integrates the signal, which is divided in two channels. The level of one of them is divided by two while the second is delayed of more than half of the overall laser pulsewidth (fig.2).

## HARD WARE

A fraction of the emitted light is picked up behind a coated mirror and is routed to a fast response photodiode. To maintain a relatively long time constant, the photodiode load is quite high: 1 MΩ,82 KΩ and a pair of cascaded common collector transistors in parallel. Before its distribution on the entries of an MC1651 double comparator, the integrated output is divided, on one channel by $2N \approx 6$, on a second one by $N \approx 3$ (fig. 3).

The signal of the first channel is distributed on the entries 6 and 11 while the second channel delayed 12,5ns by a coaxial cable, is wired on entries 5 and 12. To ovaid any noise-triggered outputs, the last entries are prepolarised by a 5.6 KΩ resistance.

There are four output pins: 1, 2, 15, 16 wich must be loaded by 50 Ω to ground.

A test point allows :

a) A visualisation of the integrated pulse on the screen at an oscilloscope

b) A test of comparators by means of injection of calibrated pulses.

PERFORMANCES

The resolution of the comparator is 20mV. If we limit the integrated signal to 4V (12V at the photodiode level) in 4ns (Laser pulse 2ns FWHA ), the theorical time resolution is 20ps.

In fact, as we use the same device for pulses of 2ns, 6ns and 10ns 3 to 12 joules the integrated signal slew rate is of 250V/μs or a time resolution of 80ps.

CONCLUSION

The lack of time has not allowed us to go through a complete study of the stability.

Only some series of comparaisons between two identical devices, and some target calibration have been processed. Nevertheless, we feel that for laser pulses of width ranging from 2ns to 10ns and energies from 2j up to 12j, it is possible to trigger start pulse centered with an accuracy better than 100 ps.

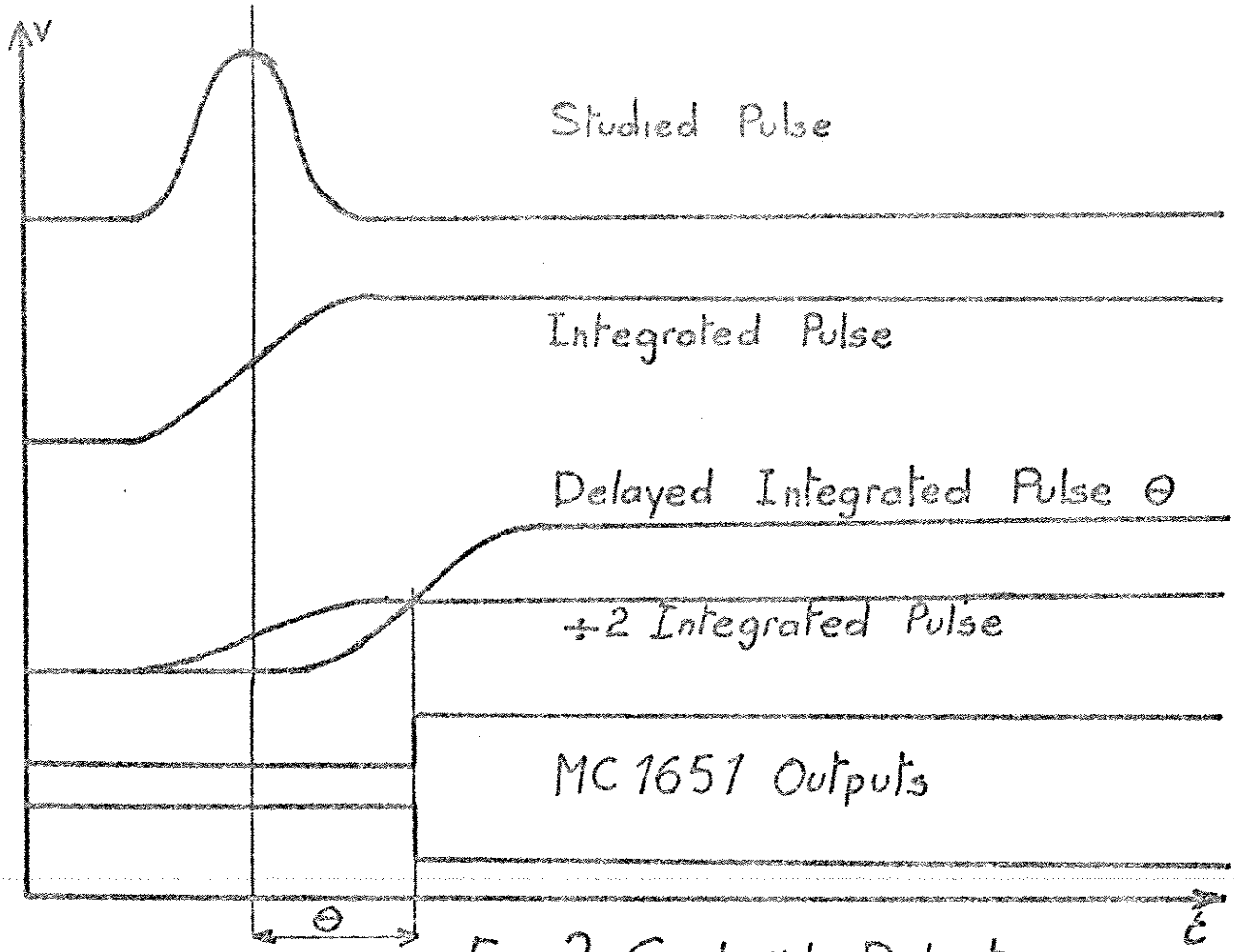



Fig 2 Centroïd Detection

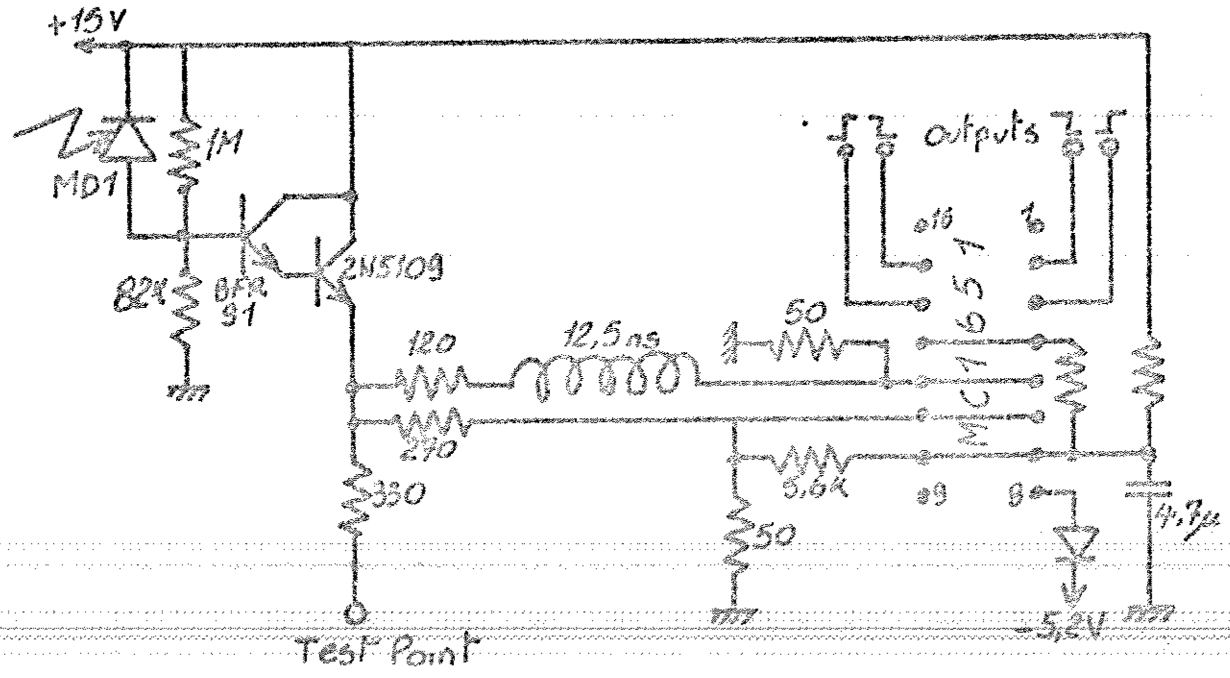
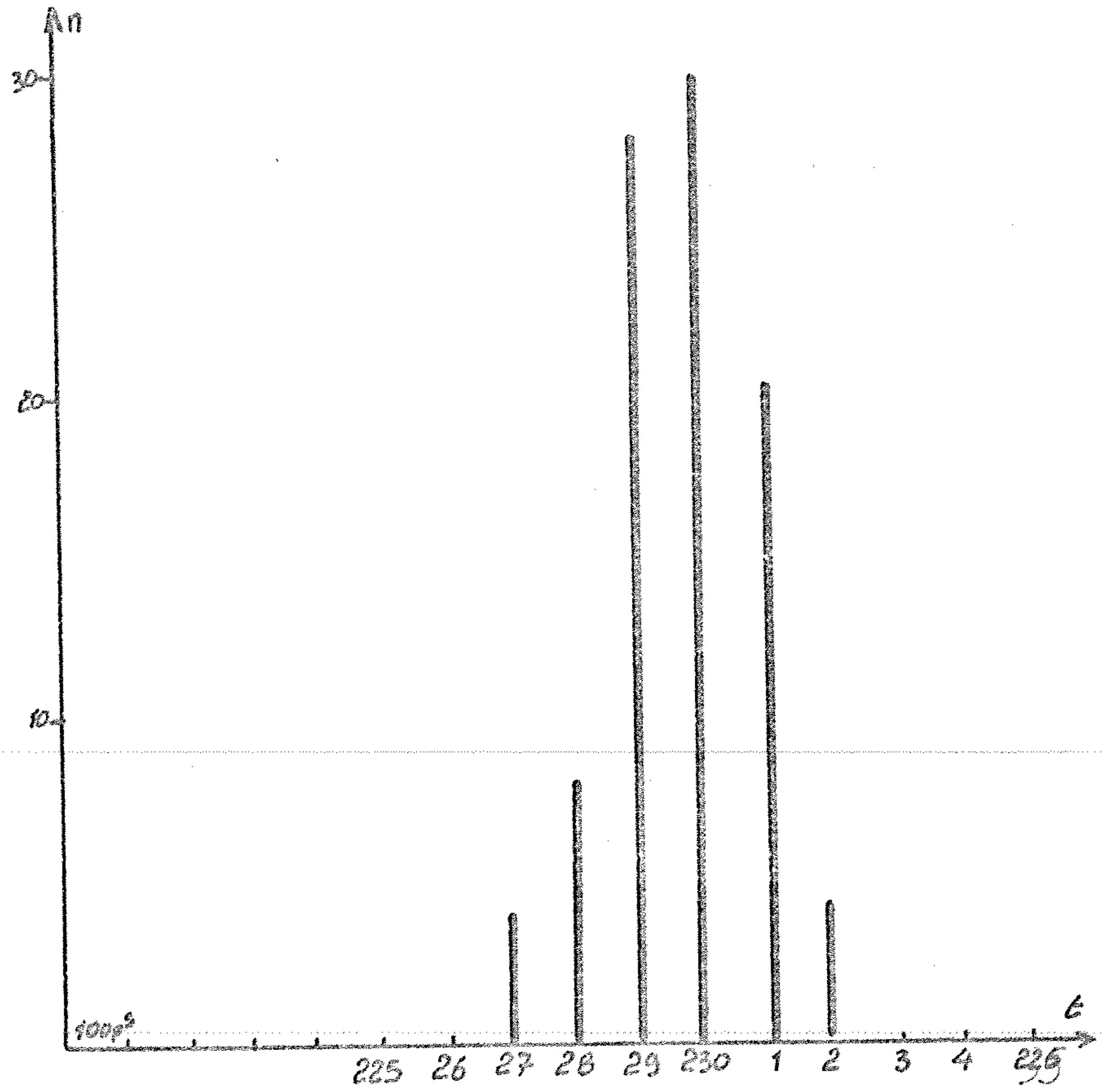



Fig 3 Schematic




Histogram of the first test

# LASER WAVEFRONT DISTORTION MEASUREMENTS

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## INTRODUCTION

In order to improve the accuracy of laser ranging systems two directions are mainly followed :

- Reduction of the pulse width to sub-nanosecond values
- Pulse shape processing

This second way is limited by the wavefront distortion of the transmitted laser beam. The device developped by CERT, to measure these distortions will be described.

## PRINCIPLE

The beam's light is sampled at discrete points by a set of optical fibers. Each of the samples in delayed by $\theta, 2\theta, --- n\theta$ with respect to one of them ($\theta$ is slight by longer than the overall pulse width). They are then focused on a single photodiode and the output displayed on an oscilloscope (fig.1).

The oscillogram allows us to know :

- the pulse width at each point
- the energy partition at the sampled points
- the phase partition of each pulse

## DESCRIPTION

The device is a 25cm-side cubic box. Within the box are stored optical fiber rolls.

One of its faces is drilled with two series of 20 holes displayed in two crosses of 20mm and 20cm width. In each of the holes is fitted the end of an optical fiber (fig.2).

The opposite face shows a single hole where all the second ends of the optical fibers are visible in a single bundle. It is then possible to detect the output of all the fibers with a single photodetector as soon as its sensitive area is homogoneous on a diameter larger than 10mm.

The delay between each way is done for a different length of each optical fiber. The length differences are chosen to give a time delay of 12ns (2.5m of fiber).

Coupled with a fast photodetector (RTC XA 1003 for example), a laser pulse narrower than 10ns is transformed in a succession of 20 separate pulses, allowing the study of the wavefront distortion shot by shot.

The choice of the width of the two crosses is governed by the fact that we want to study :

a) The outgoing pulse at the end of our 20cm collimating telescope

b) The pulse at a focal point of the beam to know the farfield pattern.

## FIRST TRIALS

After an adjustment of the laser and the emitting optical system, the first trials were done :

- on the beam at the output of the first afocal telescope (Ø 45mm)
- at 500m at a focal point obtained by a convergent adjustment of the secondary afocal telescope.

The setting of the overall system is fast. The only care is to avoid triggering the oscilloscope by laser noise.

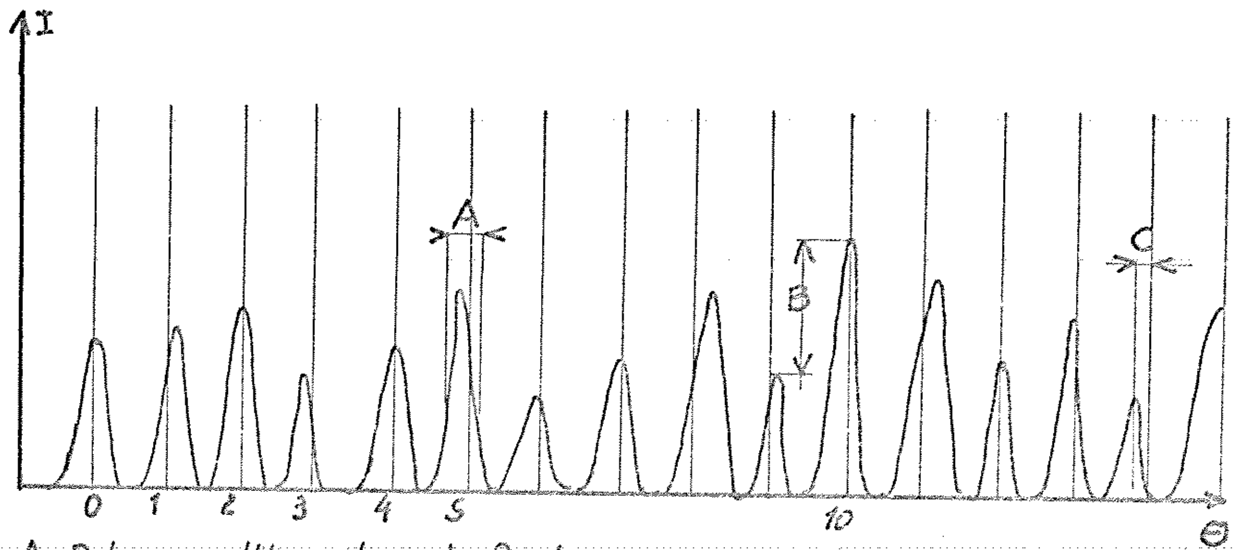
After a series of shots at various energies (2-10j, 10ns) no damage of the fiber ends and holders was found.

The signal at the output is large enough that with sensitive amplifiers (V≤5V) it is necessary to divide the signal (optical attenuation at the fibers output).

With the laser set up to 10ns pulses the recording shows a good phase partition but an irregular amplitude distribution. These irregularities vary from shot to shot.

## CONCLUSION

The device designed by, MM. Bize D. and Duchene B. to study the GRGS/CERGA Second Generation station laser beam, works in a satisfactory way. It seems very promising to determine the laser wavefront distortion allowing a better knowledge of the far field pattern and a more efficient processing of the received pulse.




A Pulse width at each Point

B Energy and power repartition

C Phase distribution

Principle of the laser wavefront measurements

# THE CALIBRATION PROCEDURES FOR USE IN WETTZELL

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Fed. Rep. of Germany

## 1. INTRODUCTION

With the increasing accuracy of ranging it is necessary to adopt more stringent and possibly more time-consuming methods of system calibration. Although, in view of other problems, little time has been spent on practising calibration procedures to date, the techniques described here are being proposed as the foundation of future calibration experiments for the system installed in Wettzell. Experience with the system will then show to what extent the extensive calibration procedures must be repeated for each pass.

## 2. RANGE-CALIBRATION - THE PROBLEM OUTLINED

It is a commonly acknowledged characteristic of such ranging systems, that the range measured varies with certain parameters of the system. These parameters are typically those which in effect determine received power, i.e. divergence, attenuation, laser power etc. It has been assumed to date that the observed change can be expressed as an additive constant determined for each parameter change from a set of calibration ranges to a local (terrestrial) target made prior to and repeated subsequent to the satellite pass, system drift being detected by any visible trend in the two sets of measurements. At this stage it is only reasonable to extrapolate these assumptions to the new systems with higher ranging accuracies.

### 2.1 THE MEASUREMENT PROCEDURE

All significant parameters including transmitted and received power, divergence, attenuation etc. are recorded on magnetic tape for each transmitted pulse. By varying the significant parameters singly over the range of possible settings and recording ranges to the terrestrial target over e.g. 10 seconds (40 shots) per setting, a multi-dimensional matrix of calibration numbers can be recorded. The calibration number, tagged with its characteristic parameters is computed as

additive constant = reference range - observed range

The satellite ranging may then be performed with complete freedom to vary all parameters. Drift and random scattering may be estimated from the changes in observed range monitored over the ranging period and over subsequent ranging periods.

## 2.2 THE CORRECTION PROCEDURE

Each observed range requires the application of a calibration correction. For satellite passes the calibration number is interpolated from the calibration matrix during pre-processing.

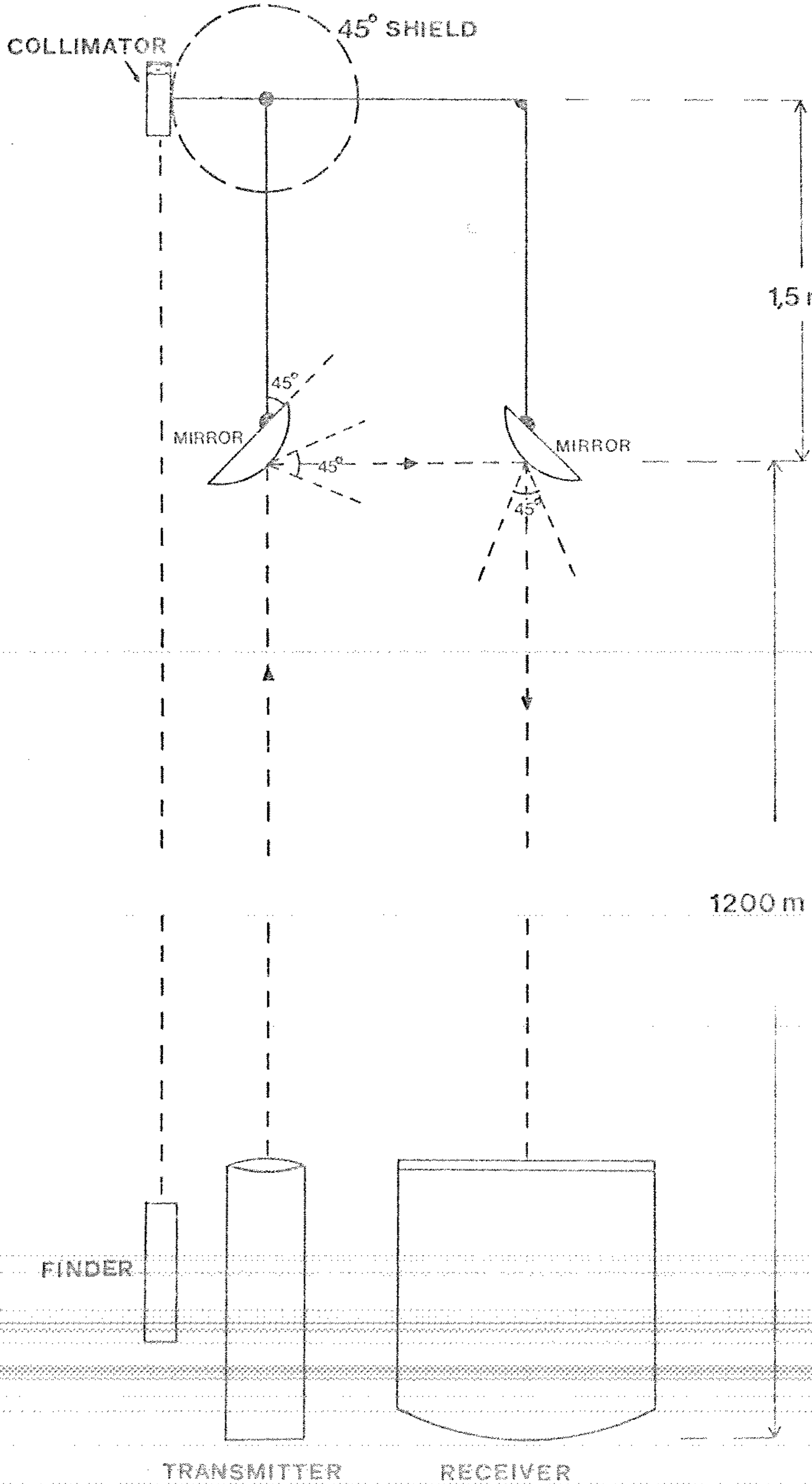
## 2.3 SOME PROBLEMS WITH CURRENT REFLECTOR HARDWARE

Over the restricted distances at which calibration ranges are possible, the parallax resulting from the ex-centric transmitter-receiver relationship results in certain difficulties in ranging. These difficulties are reflected in a high degree of repeatability for each of three different solutions, the differences being only visible on the digitiser. The three solutions characterise the zero-point uncertainty and are seperated by about 1 m. To remove this ambiguity a special reflector is being constructed (see figure), one of the characteristics of which is a significant signal attenuation.

It should also be noted here that in the case where time interval measurements are made, a significant error can occur which results from the delay time inherent in the interval gating interrogator procedures. This error can reach values up to 10 cm.

## 2.4 FURTHER POSSIBILITIES USING SPECIAL HARDWARE DESIGNS

The difficulties and inconvenience of outdoor range-calibration are well known. Atmospheric turbulence, fog, eye-safety and other factors make it desirable to conceive some internal solution to


COLLIMATOR
45° SHIELD
1,5 m
45°
MIRROR
45°
MIRROR
45°
1200 m
FINDER
TRANSMITTER
RECEIVER

the range calibration problem. Two possibilities are worthy of consideration.

## 2.41 PASSIVE METHOD

This involves the use of a fibre-optics light-pipe of pre-determined length. Fibre-optics have the advantage of great stability, conditional upon the light pipe being properly clamped. The current characteristically high attenuation is also advantageous under these conditions. A significant disadvantage lies in the pulse smearing resultant upon winding the fibre optics into a constrained space. This results from the path length deformation, which amounts to about 6 mm/turn for a 1 mm diameter light pipe. Whereas the leading edge characteristic of the transmitted pulse is retained, the pulse becomes very long.

A possible alternative is to use a special n-gradient fibre optic, for which the refractive index varies to compensate for the changes in length. This method is currently too expensive to apply.

## 2.42 THE INTER-ACTIVE METHOD

This method would make use of a fast photo-electric diode shielded by an optical attenuator and driving an ultra-sonic or electrical delay line. The output from the delay line would be used to trigger a pulse generator which in turn drives a fast light emitting diode operating in the appropriate spectral range. The total delay is here given by the sum of the delay line and all remaining component delays, which can be calibrated via a short, straight, fibre-optics light-pipe. The significant advantage of this technique is that calibration lines of the same order of magnitude as the observed ranges could be simulated by adding the appropriate number of delay stages.

# 3. LEVELLING, ORIENTATION AND SYSTEM ERROR CALIBRATION

To control levelling, and a number of systematic error sources such as collimation and residual mislevelling a ring of terrestrial stations has been observed at approximately 1 km average distance. The relative positions of these stations is known with cm accuracy in all three dimensions. A further station at some 7 - 8 km distance is used to control orientation.

These points can be sighted as often as required to check the current condition of the system. Available software is used to make on-line corrections to the momentary setting angles.

## 3.1 PLANNED CONTROL OF SYSTEM SYSTEMATICS FOR LUNAR RANGING

To fulfill the stringent pointing requirements for lunar ranging, improved techniques are being introduced for estimating system angular errors. Based on a model prepared by Brosche (University of Bonn) and implemented by the University of Texas an even distribution of stars is observed across the sky. The observed and predicted elevations, azimuths and times, referenced to a given star catalogue (FK-4), are then used to compute a set of spherical harmonic coefficients which reflect the system errors for each part of the sky. These coefficients can be used to correct the setting angles in real-time during ranging operations.

# REVIEW OF ATMOSPHERIC CORRECTION FOR LASER RANGING DATA

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During the past three years we have devoted considerable effort in time and funds to the improvement of the refractive-index correction to laser ranging data. The starting point for this work was the November 1973 Goddard Space Flight Center Report X-591-73-351, "Correction of Laser Range Tracking Data for Atmospheric Refraction at Elevations above 10 Degrees" by J.W. Marini and C.W. Murray. This report was drawn from the available literature on refractive index corrections and produced an improved formula for correction that is in use to this day for all NASA laser tracking data. The Marini and Murray (MM) formula requires the use of only surface level measurements of pressure, temperature and relative humidity to predict the total range correction for propagation on a vertical path through the atmosphere. The formula is most sensitive to the value of surface atmospheric pressure, since this is in effect a measure of the column density above the surface. the connection between range error in cm and pressure reading is about 0.8cm/mb at $20^{o}$ elevation angle. Marini and Murray checked their formula against a series of ray trace calculations made on radiosonde-based vertical profiles of refractive-index. Agreement between the ray trace results and the formula was found to be better than a few millimeters above $20^{o}$ elevation angle.

Despite this apparent excellent agreement, it was felt that the MM formula and ray trace results could both be in error since they were based on meteorological data taken only at one surface point or on one slant path through the atmosphere. The real atmosphere varies in three dimensions. We felt it was important to investigate the effect of horizontal gradients on the refractive-index correction. At about this time a grant was awarded the University of Illinois with C.S. Gardner, principal investigator, to investigate and improve the refractive-index correction. We supported the Univ. of Illinois under this grant (NSG-5049) by supplying to them extensive radiosonde data taken by AFCRL in a study of clear air turbulence. These data consisted of simultaneous radiosonde measurements at eight locations on a 100 km radius near Washington, D.C. The Univ. of Illinois used their own unique 3-D ray trace program to compute refractive-index corrections for any selected azimuth and elevation angle of propagation through the atmosphere. They compared the 3-D ray trace results with a 1-D (spherically symmetric) ray trace and the MM formula. Results indicated an rms difference of about 1 to 2 cm near 20° elevation angle between the 3-D ray trace and 1-D ray trace. The 1-D ray trace results and MM formula results were much closer in agreement as expected. This indicated a possible 1 to 2 cm error in the MM formula due to horizontal gradients in the atmosphere.

In a parallel effort the Univ. of Illinois reported on turbulence effects on range measurements and concluded that for most combinations of turbulence strength, turbulence scale sizes and propagation path lengths the turbulence-induced errors are below 1 mm. For long, nearly horizontal paths near the earth's surface, such as in calibration links, turbulence-induced errors could be on the order of a cm.

Subsequent work by the Univ. of Illinois showed that, at least in the Washington, D.C. area, the mean difference between the 3-D ray trace and 1-D ray trace or MM formula is a sinusoidal function of azimuth with a maximum to the South and a minimum to the North. This suggests that there is a strong temperature dependence for the azimuthal variation in refractive-index correction. A correction formula was then developed to model these variations. It required temperature and pressure data at a remote point directly underneath the slant path of laser beam propagation to the satellite. The remote data was obtained by interpolation between existing surface weather stations. It was found that residual errors between the 3-D ray trace and the new surface correction formula with azimuthal dependence were reduced to the level of several mm at the worst case of 20° elevation angle. Further data analysis showed that expected errors in the raw meteorological data (±1 mb, ±1 °C) would produce about this same level of uncertainty or more in the range correction. Hence, there was little to be gained by further reduction of model errors. We felt that the MM formula plus the horizontal gradient correction term for azimuthal variations represented the best available range correction formula.

The Univ. of Illinois surface data correction models have also been applied to analyze the refractive-index correction for a spaceborne laser ranging system. In this work, where many separate ground-based targets were planned, it was important to predict the difference in range correction between two ray paths with variable separation at ground level. As a result, a range correction error covariance model was developed. This was used along with expected errors in surface meteorological data to predict the statistics of range error for the intersite vectors of the ground-based laser retroreflector targets. Results indicated that range uncertainties could be held to about the 1 cm level. Once again interpolation techniques were used to estimate surface meteorological data at the required locations when data was available only at a random pattern of existing weather stations. Interpolation proved to be a valuable tool in suppressing the magnitude of meteorological data errors at any particular ground station. This resulted from the least squares weighing of all data from the area surrounding the station.

A detailed review of the Gardner et al refractive-index correction work is available in a series of reports issued by the Radio Research Laboratory (RRL) of the Univ. of Illinois (see attached list). A summary of their major results plus companion GSFC study of the range correction is available in four publications (see attached list) in the open literature.

The major results of this work can be summarized as follows:

(1) Laser range correction based on a formula such as that of Marini and Murray is accurate (within $\pm 2$ cm) under most circumstances for ground-based laser ranging.

(2) The first step to be taken in improving upon the result of (1) is installation of a pressure sensor at the laser site capable of sub-millibar data accuracy (0.3 mb is recommended). Then the limiting errors should be model errors.

(3) The model can be improved by the use of a horizontal gradient correction term such as that developed by the Univ. of Illinois. This term depends largely on the temperature field (within 50 km) surrounding the laser tracking site. At this point model errors and data errors are approximately equal and less than 1 cm in total effect at $20^{\circ}$ elevation angle.

(4) When multiple paths through the atmosphere must be considered, as with spaceborne laser ranging to a series of ground-based targets, a statistical covariance model based on interpolated surface data gives good results. The interpolation has the added advantage of suppressing meteorological measurement errors.

## CUMULATIVE LIST OF RADIO RESEARCH LABORATORY REPORTS PREPARED UNDER NASA GRANT NSG-5049


RRL Rep. No. 469 - Gardner, C.S. (December 1975), The effects of Random Path Fluctuations on the Accuracy of Laser Ranging Systems.

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RRL Rep. No. 477 - Gardner, C.S. and J.R. Rowlett (November 1976), Atmospheric Refraction Errors in Laser Ranging Data.

RRL Rep. No. 478 - Gardner, C.S. and B.E. Hendrickson (December 1976), Correction of Laser Ranging Data for the Effects of Horizontal Refractivity Gradients.

RRL Rep. No. 481 - Gardner, C.S. (January 1977), Statistics of the Residual Refraction Errors in Laser Ranging Data.

RRL Rep. No. 486 - Gardner, C.S. (June 1977), Comparison Between the Refraction Error Covariance Model and Ray Tracing.

RRL Rep. No. 488 - Gardner, C.S. (December 1977), Speckle Noise in Satellite Based Lidar Systems.

RRL Rep. No. 495 - Gardner, C.S. and G.S. Mecherle (April 1978), Speckle Noise in Direct-Detection Lidar Systems.

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SAO CALIBRATION AND SYSTEM ACCURACY

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## CALIBRATION

Calibration procedures for the Smithsonian Astrophysical Observatory lasers fall into three categories: Start-channel calibration, extended-target calibrations, and prepass and postpass target calibrations.

The start-channel calibration procedure is a full electronic test of the pulse-processing system, which provides the routine parameters used in ranging operations. The calibration of the start channel is developed from the dependence of system delay on the output-pulse characteristics. It is performed by entering pulses with a range of 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 functions. System delay is then measured as a function of pulse width or area.

Calibration runs for the 25-nsec-wide pulse range (using electronic pulses with widths of 20, 25, and 30 nsec and ±3 db from nominal amplitude) give linear relationships with measured pulse widths with standard deviations of 0.3 to 0.4 nsec. Similar calibrations for the 6-nsec pulse region (using pulses of 5, 6, 7, and 8 nsec) give linear relationships to measured pulse widths with standard deviations of 0.2 to 0.3 nsec.

Target calibration is used extensively to measure system delay and to verify system stability and performance.

Detailed target calibrations over the full dynamic range of the system (one to several thousand photoelectrons) are performed routinely to monitor system calibration as a function of signal strength. The voltage on each photomultiplier is

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adjusted to avoid saturation and to ensure that the calibration characteristic remains flat (±1.0 nsec) in the range of 5 to 2500 photoelectrons. An example of a detailed target calibration is shown in Figure 1. Each point is the average of approximately 100 laser pulses with the 25-nsec pulse width. Error bars denote the standard deviation of the individual measurement. The dominant contribution to the error is the $1/\sqrt{n}$ fluctuation for the finite number of photoelectrons in a 20- to 25-nsec-wide pulse. The apparent structure at very low signal strengths is due to insufficient sampling of narrow pulses by the digitizer.

To account for any possible changes in system delay, target calibrations of 25 pulses each are performed before and after each satellite pass. The precalibrations and postcalibrations, which are performed at about the 100-photoelectron level, are submitted to processing along with the satellite range data. The system calibration is determined 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 the short-term system stability during a satellite pass; this difference is stored with the data for reference during analysis.

Data taken from the network stations show individual pre- and postcalibration runs with standard deviations of typically 1 nsec. Calibration differences are in the range of 0.5 to 0.7 nsec (see Figure 2). These data contain measurement errors due to pulse width, finite samples, and digitizer sampling spacing. With a narrower laser pulse, we expect to obtain better estimates of system stability.

## SYSTEM ACCURACY

At low signal strength, the random error due to photon quantization at the photomultiplier dominates other noise sources in the system. At higher signal strengths, the noise appears to reach a lower limit of 0.3 to 0.6 nsec. This is probably due to jitter in the photomultiplier and to the large sampling intervals used with the wide laser pulse.

Range noise in satellite data is a combination of random photon quantization effects, laser wavefront distortion, detection-system jitter and sampling, propagation effects, and satellite characteristics. Typical passes for low satellites with the 25-nsec laser pulse have standard deviations from polynomial approximations to short-arc fits of 15 to 30 cm. An example is shown in Figure 3. Return-signal strengths can vary from a few photoelectrons to almost 1000 during a pass; however, the preponderance of data are in the range of 20 to 200 photoelectrons. On higher satellites such as NTS-2, the system is essentially working at the single-photoelectron level with noise in the range of 1.0 to 1.5 m (see Figure 4).

Ranging errors are introduced by the hardware system from three sources: the laser transmitter, the detection system, and calibration.

In the wide-pulse operating mode, the laser transmitter introduces errors due to wavefront distortion. Experiments conducted at Mt. Hopkins show that the wavefront has structure across the laser beam, a structure that is impossible to forecast or model effectively with calibration techniques. Root-mean-square variations in the time of arrival across the beam are in the range of 0.6 to 1.6 nsec (Billiris et al., 1975).

From the results of the extended target calibrations (see Figure 1), we estimate that the systematic errors introduced by the detection system at signal levels above 3 to 5 photoelectrons are typically 1 nsec or less.

Based on the stability of the precalibration and postcalibration differences, ranging errors introduced into the data through system calibration are estimated to be about 0.5 nsec.

These major error sources — wavefront distortion, photoreceiver and detection system, and calibration — could each introduce average systematic range errors of 1.0 nsec or less at high signal strengths. At lower signal levels, however, the larger errors are random, owing to photon quantization introduced by the photoreceiver and the detection system; if we average them over a satellite pass, their influence should be reduced to the 1-nsec error found at high signal strengths. Since these major sources of error are uncorrelated, the total system accuracy is about 20 to 30 cm.

## REFERENCE

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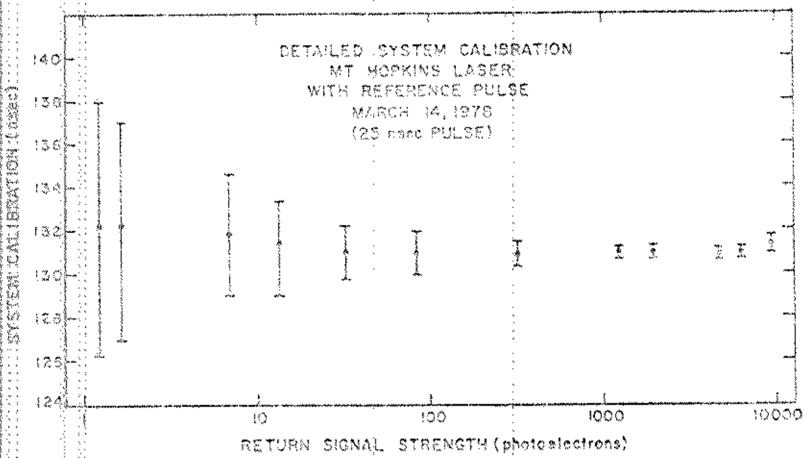


Figure 1.

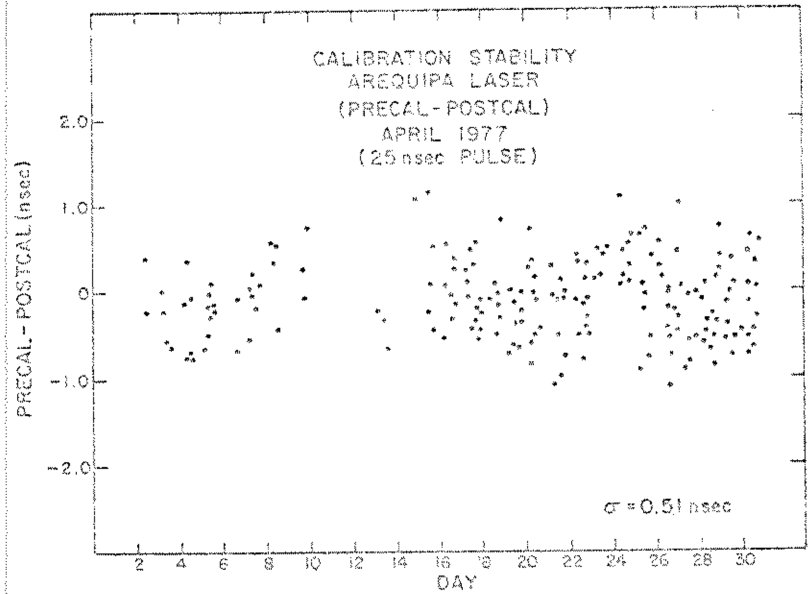


Figure 2.

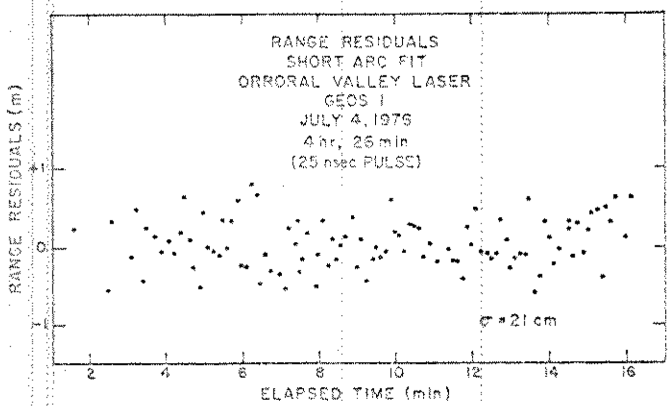


Figure 3.

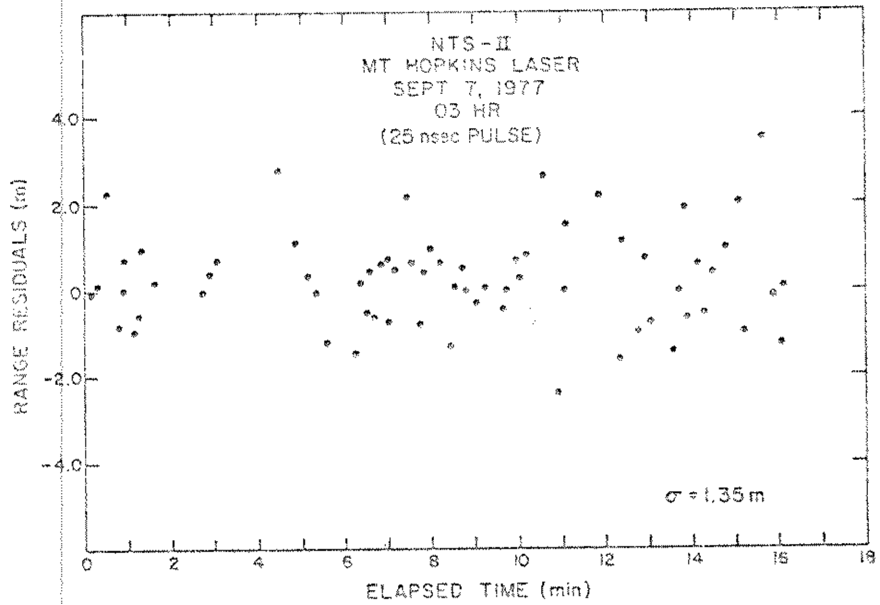


Figure 4.

# CALIBRATION AND ERRORS

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Academy of Sciences of the USSR
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## Calibration

In contrast to the satellite laser systems our lunar laser ranging equipment is not calibrated by the target. One of the reasons here lies in the failure of the telescope to descend to zenith angles $Z > 80^{o}$.

Determination of the equipment corrections and estimation of the system errors are performed as a whole and in parts. The delay in the photodetector (transit time) and the delay in the amplifier constitute the main components of the electronic delay of the "stop" channel in relation to the "start" channel. Besides, there is the correction which is caused by the difference in the length of the coupling cables. The correction as a whole is measured by the time counters at laser action. Here the time counters were as usually initiated by the photodiode, and stopped by the laser pulse (a small part of which is directed to photomultiplier). Measuring of the delay components in parts was performed by the same time counters.

The values of the summary delay, which were determined in parts and as a whole, coincide within the accuracy of the counters.

The error of the counters is determined by measuring time intervals with duration 1-3 sec. It was considered that the counters operated normally, if the maximum deviation, determined by the run of measurements, did not exceed $\pm 1.0$ ns, i.e. if this deviation was caused only by the time resolution of the counters.

Those tests were performed before and after each laser run. As a rule, after one hour operation there is no systematic drift of the counters. To refer the measurements to immovable point of the telescope, i.e. to the centre of the diagonal mirror, the measured time intervals are corrected for the path of light inside the telescope (Fig. 1). This path is measured directly with accuracy $\pm$ 3 cm or $\pm$ 0.1 ns.

Atmospheric refraction.

The trajectory of the laser beam in the atmosphere is curved because of the atmospheric refraction. It may be demonstrated that the path's extension due to curvature for zenith angles up to $70^{\circ}$ is negligible. Besides, the optical path of the beam in the atmosphere is extended in comparison with the geometrical one, because of the nonunity refraction index value. This extension may reach some meters.

The calculation of the extension is carried out by the method, taking into account the temperature, pressure and humidity near the surface of the earth, and which was developed in /1,2/. For the Crimean observatory (550 m above sea level) at $20^{\circ}$C temperature and the pressure 1013 Mb this extension is 225 cm.

At changes of meteorological conditions this value may change for 15 cm. Taking into account, that up to now the measurements of lunar distances have been performed with an accuracy of $\pm$ 60 cm (laser of the first generation, electronics of the second generation), it was not expedient to determine the atmospheric correction more accurately. This correction was calculated, therefore for two way propagation by the formula: $\Delta\tau_{atm} = (15 \pm 1.0)$ SecZ ns.

To obtain a possibility for more accurate calculation of atmospheric corrections we have been carrying out for the last two years the measurements of pressure (with an accuracy 1 mm Hg) and of temperature (with accuracy 0.2°C). That permits one, if necessary, to find the atmospheric correction with an error $\simeq$ 0.3 nsec /1,2/.

Epoch Timing.

The propogation time of the light signals from the telescope to lunar corner reflector and back must be referred to the moments of the laser pulses. For the formation of the local time scale the rubidium frequency standard is used. Long period of instability of the standard is $2\text{-}5.10^{-11}$. Hence, for one day period the local clock may give an error $\sim$ 2-5 usec.

To relate the local time scale to the UTC (SU) scale the time signals transmitted by the TV-channels are used. The correction is introduced here for the propogation time of the TV-signal from TV-transmitter to the observatory. This correction is measured with an accuracy 1.0 $\mu$sec by means of transportable clock. The correction for the delay in receiving system is also estimated with an accuracy 0.2 $\mu$sec. The summary error of the moment of the laser pulse in UTC (SU) scale is not higher than 5-6 $\mu$sec.

Overall System Errors.

The summary error in the propogation time consists of: a) an error due to laser pulse duration, its mean square value is $\sigma_1$ = 0.8 ns; b) an error in electronical and geometrical delays $\sigma_{eg}$ =1nsec: c) an error due to the time resolution of the counters $\sigma_c$=0.3 $\varepsilon$=0.3 ns, where $\varepsilon$=1.0ns, this error arises twice, that is, at the beginning and at the end of measured time interval: d) an error of photomultiplier $\sigma_p$ = 0.5 ns: e) an error in the atmospheric correction, which may be $\sigma_c$ = 0.3 ns: Thus, the summary error of the system may be $\sigma$= 1.5 ns or = 25 cm.

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2. H. S. Hopfield, Radio Science, 6, 3, 357 (1971).

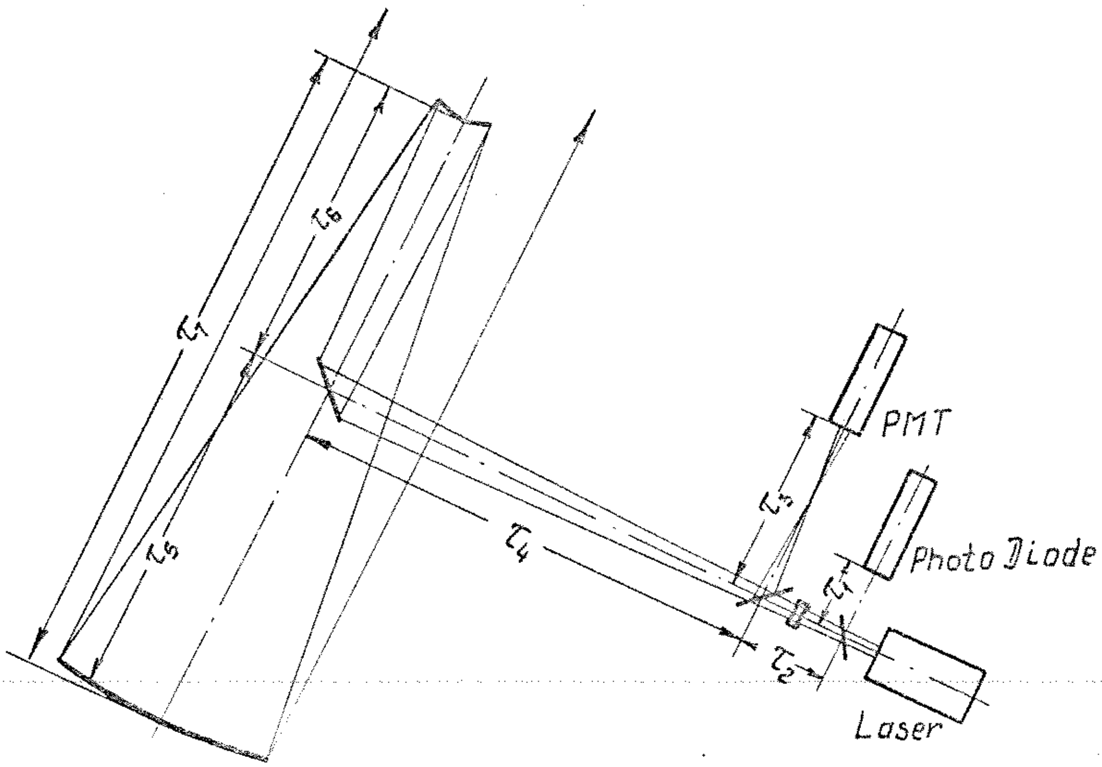


Figure 1. The optical paths in the telescope

# CALIBRATION PROCEDURE AT KOOTWIJK

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Calibration of the Kootwijk ranging system is based on range measurements (prepass and postpass) along a short internal light path. This light path has been measured with an AGA 700 laser geodimeter to a preliminary accuracy of 3 cm.

To reduce the total dynamic range of the signal at the anode of the photomultiplier different cathode voltages are used for measurements on different satellites (i.c. -1600 V, -1700 V, -2250 V), in combination with different beam divergences.
The calibration values for these three voltages are determined from a minimum of 10 prepass and postpass calibration measurements at a standard average return signal level (- 600 mV) at the discriminator. The electrical attenuation in the detection circuitry is set according to the average value used during the satellite pass; the optical aatenuation is adjusted then to reach the standard -600 mV pulse amplitude. The trigger level of the return signal discriminator is constant at -250 mV.
During the actual satellite pass the operator tries to keep the average return signal strength at the same -600 mV by giving manual corrections to the predicted attenuator settings.

Figure 1 gives examples of prepass and postpass calibration measurements for the three photomultiplier voltages.
Figure 2 gives a summary of the mean values of the two calibration runs for all passes in the period 1. March to 11. May 1978.
The differences in the mean value of each of the two calibration runs, for all passes in the period 1. March to 11. May 1978, are given in figure 3.

The main cause of the spread in these calibration measurements is time walk along the leading edge resulting from changes in pulse amplitude (risetime of the pulses: ∿ 2.5 ns). Improved performance can be expected when pulse analysis will be applied.

The main source of systematic error in the present system is the rather poor relation between the average return pulse ampltude during calibration and the average return pulse amplitude during actual satellite ranging. This error can easily be greater than 1 ns ( 15 cm ) in spite of the effort of the operator to keep the signal within limits.
Pulse analysis will also improve this situation.

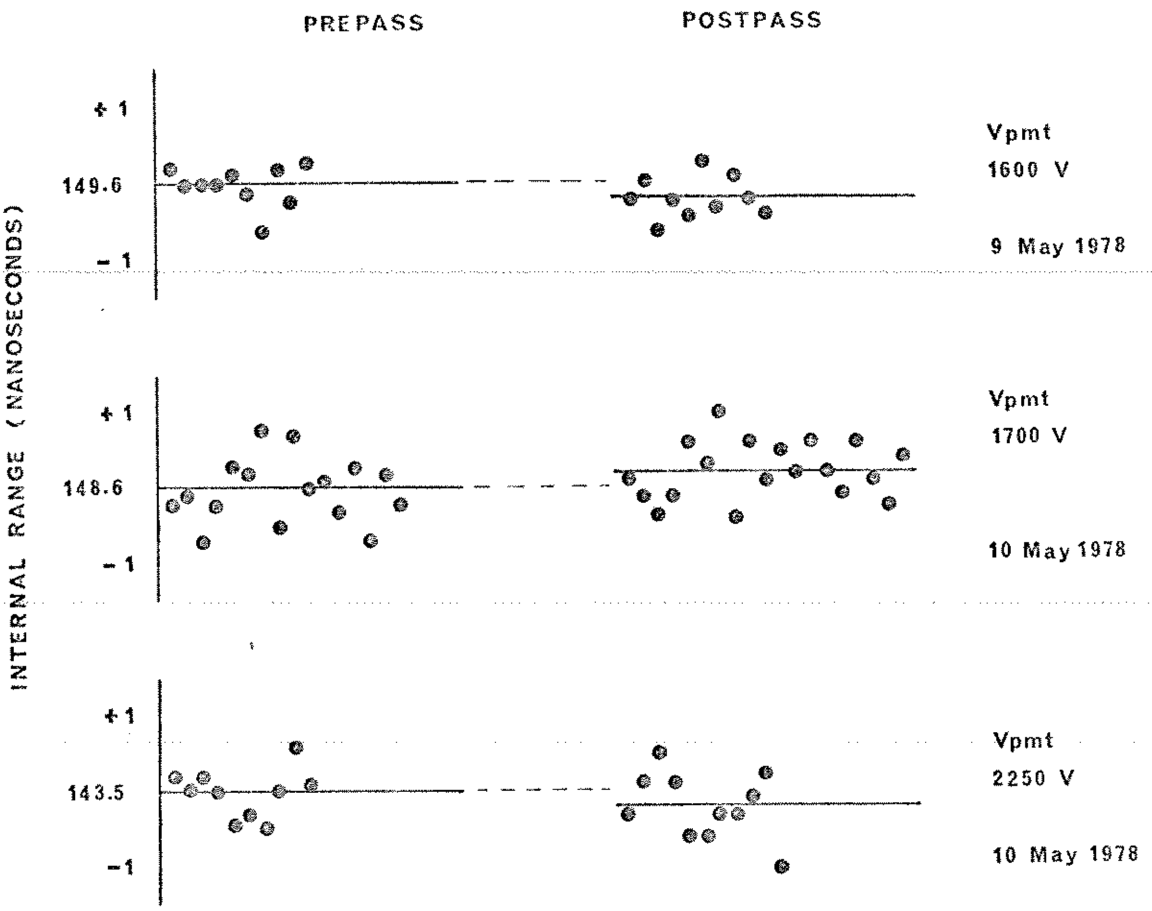


fig. 1 CALIBRATION MEASUREMENTS

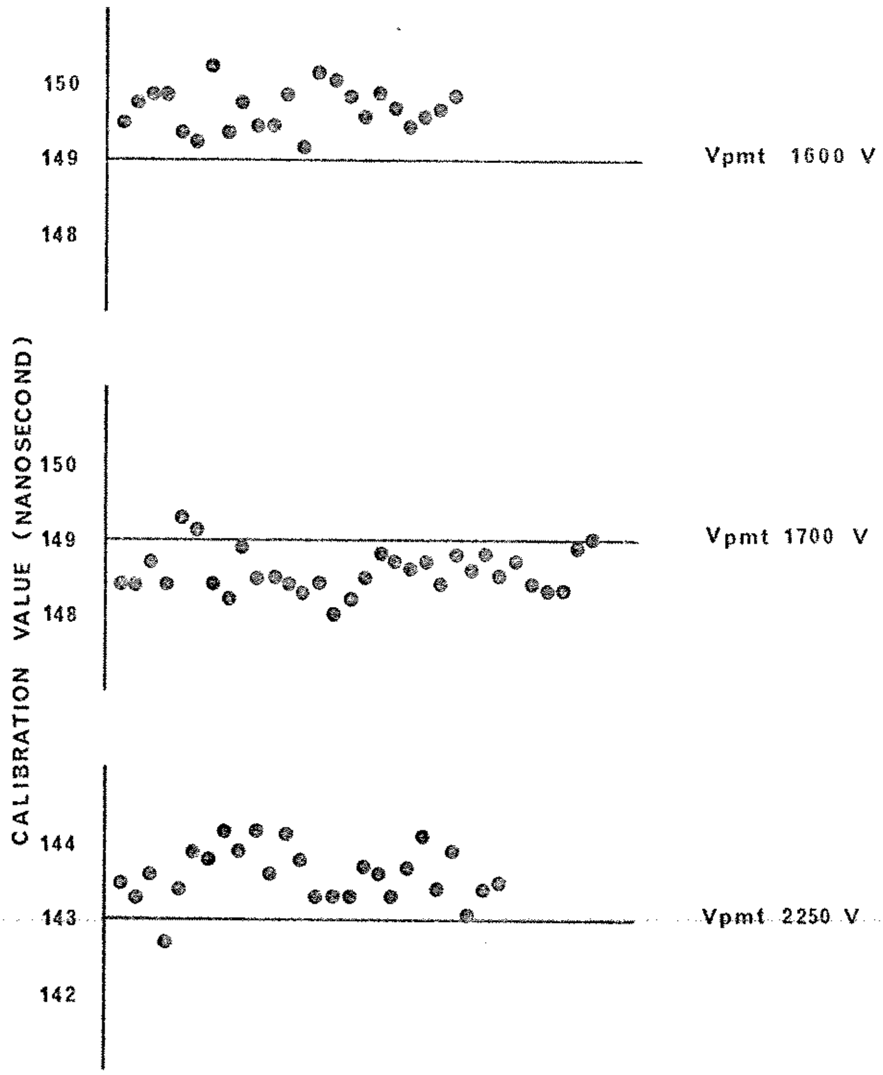


Fig 2 CALIBRATION VALUES 1. March – 11. May 1978

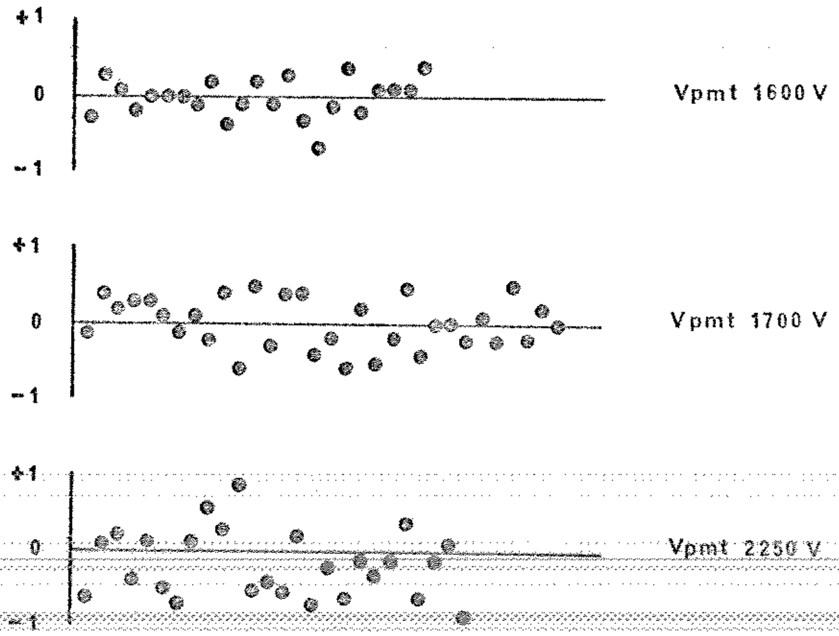


Fig 3 PREPASS minus POSTPASS CALIBRATION VALUES 1. March – 11. May 1978

# CALIBRATION OF A PULSE LASER RANGING SYSTEM

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## ABSTRACT

The Pulse Laser Ranging System Calibration is one of the most important activities in Laser Range measurements and we must pay the right attention to it. It has been showed experimentally that the system delay has not a "constant" value but it changes with the various conditions of the experiments. In this paper we give a new procedure for the system calibration which takes into account the basic factors which influence the value of the system delay.

## INTRODUCTION

The experiments took place in Dionysos Satellite Center using its own old Pulse Laser Ranging System, consisting of the following basic units:

a. The transmitter which consists of a TRG type 104A ruby laser head with an output pulse of about 60 MW and a half power width of about 25 ns. It is an air cooled unit with a rate of two firings per minute. As a monitor it uses a FW 114A photodiode.

b. The receiver: It consists of a cassegrain mirror telescope designed for maximum light gathering capacity and of a PMT type RÇA-7265 multiplier phototube.

c. The Time-Interval Counter which is made by Hewlett Packard, HP Computing Counter Model 5360A, with the HP model 5379A Time Interval Plug-in unit.

d. The associated electronics which mainly consist of a laser clock, the unit of laser Control, the unit of Range Gate Generator, the Tektronix-454 Oscillator and the C-COR Electronics, Inc. Model 4375 pulse amplifier, coupled with an attenuator so that we can amplify any laser pulse up to 60 db with a step of one db.

Although we had used a "first generation" laser head, we believe all the pulse Laser Ranging Systems have similar behaviour so that the proposed procedure can be used for any of those systems in order to find the "instant" system delay.

## FACTORS WHICH INFLUENCE THE SYSTEM DELAY

Studies of Korobkin et al. 1966 ,1967, Billiris and Tsolakis 1975, and Billiris, 1977, showed that the laser pulse has a corrugated wavefront. Figures 1 and 2, show the laser pulse wavefront as derived experimentally using different methods.

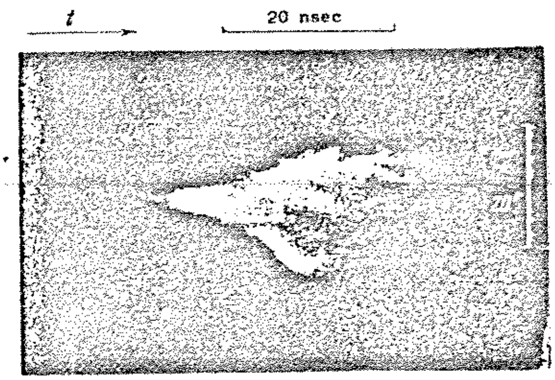


Fig. 1. Laser beam waverfront as was photografed by a streak camera (Korobkin and all, 1966).

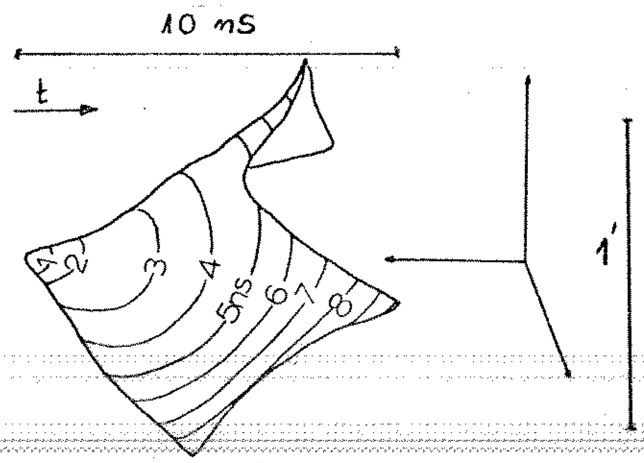


Fig. 2. Laser beam waverfront as was measured by using a matrix on a target (Billiris, 1977).

This wavefront characterizes basically the laser transmitter, but, in general, it depends in some way on the whole system. So it might be better to discuss about "an effective pulse wavefront" which depends on the special conditions of each measurement or experiment. Every laser ranging system generates its own "effective pulse wavefront" which influences all distance measurements according to the degree of development of its unit. Their close study and confrontment will improve the accuracy of the distance measurements and the value of the "real" system delay.

Figure 3, shows the rate of change of counter readings vs pulse height by using different neutral density (ND) filters before

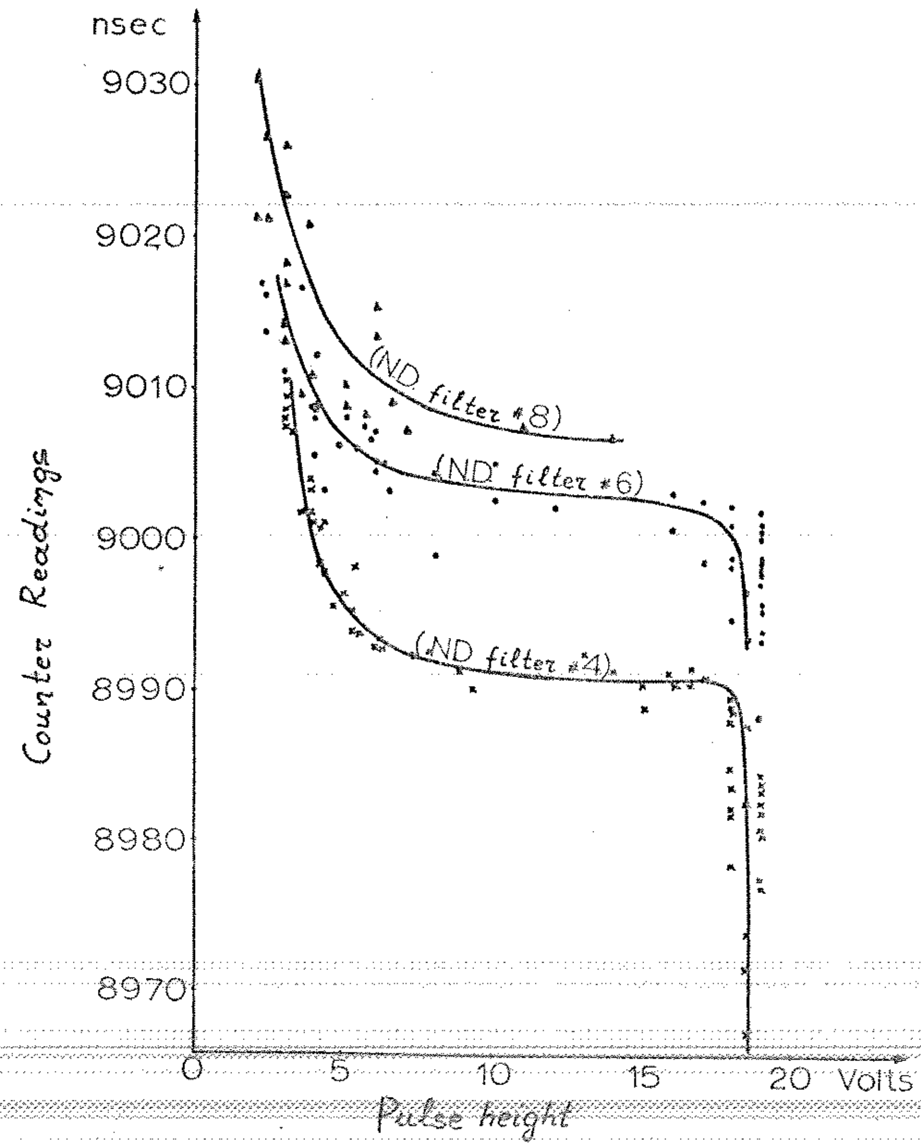


Fig. 3. Counter readings (from the close target) vs Pulse height for various ND filters.

the system's PMT. An explanation of the differences in counter reading is given in figure 4, for the various filters. This means that the choice of the right ND filter is of great importance in measuring the system delay, for a given number of range measurements.

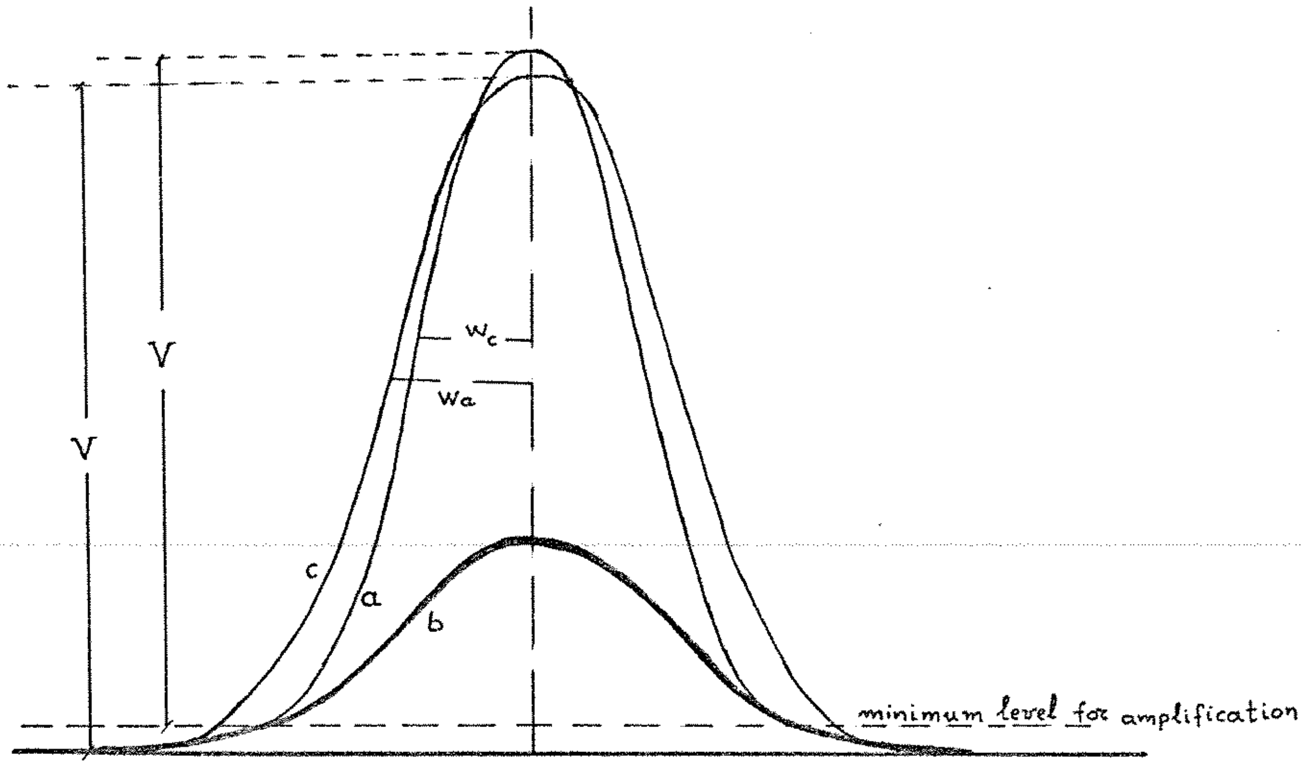


Fig. 4. An ND filter "absorbes" a given laser pulse, some parts of which remain with very low energy which is below the threshold of been amplified. In this way the pulse (a) coming out of a, ND filter from (b), behaves as having less width "bigger" after the amplification (c) (but with the same final pulse height), than the one coming out of a "smaller" ND filter.

## CALIBRATION PROCEDURE

In order to take into consideration the influence of the "effective pulse wavefront" in measuring experimentally the value of system delay we run a large number of system delay measurements to close and distant targets. The close target was consisted of one cube corner at a distance of about 1.3 km., and the distant targets were consisted each, of 6 cube corners at a distance of 19 km, over the land the first, and at 26 km, most over the sea, the second one.

During every working night we run measurements to all three targets, by using a matrix of nine points with the aid of horizontal and vertical movements of the laser system's mount.

The movement step was the same in all targets. In its point we measured 5 times and we were chaged the amplification in each point so that the STOP pulse had the same height in every measurement.

System delay was computed from the mean value of all 45 measurements. In this way we "substituted" the corrugated pulse wavefront with a mean flat one, Fig. 5.

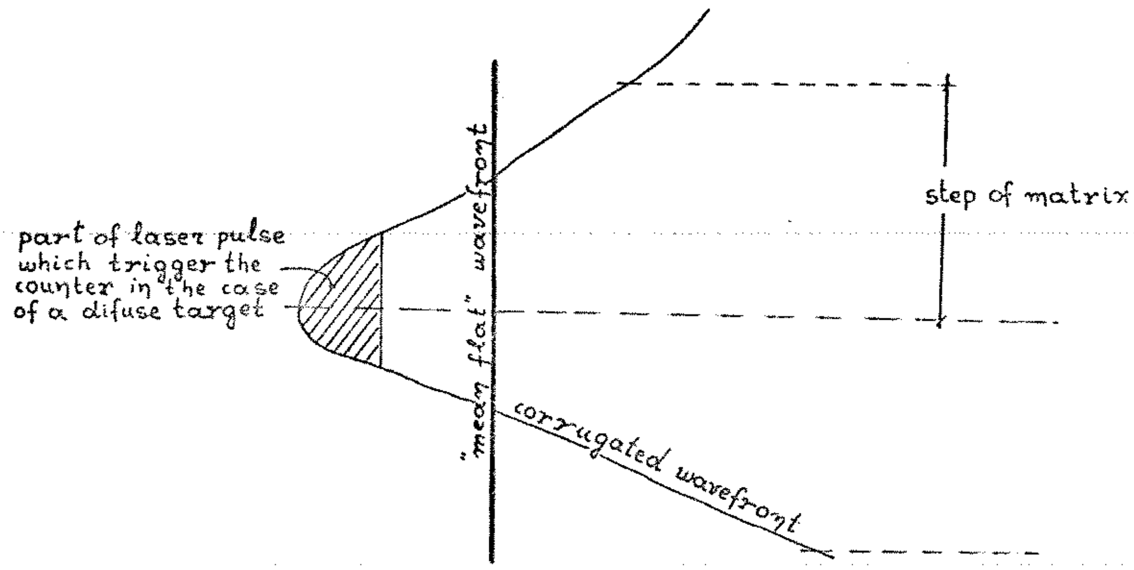


Fig. 5. The mean flat wavefront.

The step of the matrix is suggested to be of the orger of the inaccuracy which results from the errorin orientation of the mount and the error in pointing to satellite, plus the inaccuracy of the satellite orbit. This means that any measurement to satellite will be occured in the angle subtented to the calibration matrix. The value of system delay computed in this way we believe that "statistically" gives a more "realistic" value than that of using a flat difuse target from which the value of system delay is measured using a small part from the front of the pulse only which is required to trigger the counter.

On the other hand we chose the ND filter for every target with the following procedure. The detection and amplification of laser pulse in any case must be done under the same conditions, which means that the absorption of ND filter plus the atmospheric absorption (and other losses) for the two way transmission of the laser pulses from the system to target must be equal in every target case. The "right" ND filter can be calculated analytically or can be found experimentally by changing ND filters for a given STOP pulse height and pulse amplificattion.

The distance to each target was measured, at the same time, by an AGA Model 8 geodimeter, which is one of the most accurate instruments for distance measurements and it uses a CW-laser at 0.632 m. In this way the error from atmospheric correction was reduced to minimum.

Table I, gives the results of three experiments. The difference of the value of the system delay of the last value occured because we had performed a laser head maintenance including parts replacement, like flash tube, as well as replacement of some wires between units.

TABLE I

VALUES OF SYSTEM DELAY AS MEASURED BY USING THE SUGGESTED PROCEDURE.

| DATE | Target at ~1.3km (ns) | Target at ~19km (ns) | Target at ~26km (ns) | Mean Value (ns) $\frac{[PT]}{[P]}$ | $\pm 6$ (ns) $= \sqrt{\frac{[Pvv]}{(n-1)[P]}}$ |
|---|---|---|---|---|---|
| 15.5.76 | -63.00 ± 0.71 | -62.98 ± 0.67 | -62.86 ± 0.58 | -62.94 | ± 0.04 |
| 17.5.76 | -63.41 ± 1.02 | -63.70 ± 0.59 | -62.97 ± 0.46 | -63.26 | ± 0.24 |
| 17.6.76 | -71.10 ± 0.76 | -71.35 ± 0.55 | -71.35 ± 0.48 | -71.30 | ± 0.07 |
| ND filter | # 6 | # 4 | # 3 | | |
| Amplification at the Center of matrix | ~20 db | ~20 db | ~20 db | | |
| Step of matrix | 0°,010 | 0°,010 | 0°,010 | | |

From Table I, we can see that the system delay as was measured from all three targets was about the same for each night independing from the distance to target, and its standard deviation is low.

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# CALIBRATION OF THE INTERKOSMOS LASER RADAR NO 12

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Using a counter to measure the time interval at the laser radar station, one can select either "common" or "separate" mode. At single photoelectron retrosignal level, the "common" mode is used /1/. At multifotoelectron retrosignal level,because of pulse shape distorsion due to the quantum response of PMT, according to McGunigal /2/, 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 dynamics range expected on a satellite pass. Similar procedure is used at SAO stations, at Dionysos /4/ and some other stations, to return the pulse, the permanent target is used.

At Interkosmos Laser Radar No 12 we use two fibers of different length between the laser transmitter and the receiver. The counter is operated in "common" for both the calibration and ranging. If "separate" mode is preferable for some reason, just one fibre is used.

The calibration at different signal level has to indicate possible error and to verify the computer simulation because of difficulties to simulate signal processing (adaptive threshold, centroid etc.). Once the performances are known, one can introduce them to postpass signal processing.

To analyze the calibration error budget for a permanent target retropulse, one can consider:

1) the calibration via geodometr
2) the atmospheric propagation correction
3) the precision of the time measurement
4) the illumination of a target versus a beam structure
5) the scattered laser light from the atmosphere overlaping the reflected pulse;

When "separate" mode, additionally:

6) different jitter of detectors to start and stop the counter (the voltage dependence of a PMT)

7) different signal processing channels

8) different channels and possible delay in a counter;

There are existing observing sites where it is difficult

9) to build a target

10) to garantee safety.

To decrease the error contribution caused by

11) system stability |2| we have the time interval measuring system |6| with two stops. First stop is to calibrate the system via fibre retropulse, the second to range the satellite. Because of shielded PMT during first 3 msec, the reflected pulse is not influenced by scattered light. When prepass and postpass calibration is applied, the system stability must be considered for 20 min interval at least, while for the suggested *each shot technique* for the range time only. Each shot may be corrected individually.

12) The prize of a calibration shot may be of interest.

The start signal level for "common" can be adjusted via neutral density filters and either matched to the expected retrosignal level or simply chosen to be high enough to avoid the influence of the pulse distorsion. The bandwidth of the fibre is appr. 20 MHz/km. Having ten meter fibre,

13) the signal distortion due to the fibre is negligible.

The error contributions have to be considered for different techniques are summarized in Tab. 1.

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|5| Hamal K. et al.:Computer Simulation of Pulse Centroid Correction Procedure,in lit.2

|6| Hiršl P. at al.:Long Distances Measurement Electronic System, in lit.2.

Tab.1.

Error contributions have to be considered for different technique

| | permanent target | fiber |
|---|---|---|
| "separate" | 1,2,3,4,5,6, 7,8,9,10,11,12 | 3,11,12,13,6,7,8 |
| "common" | 1,2,3,4,5,6, 7,8,9,10,11,12 | 3,11,12,13 |
| each shot | cannot be applied | 3,13 |

# session 4B station timing

*chairman K. Nottarp /co-chairman B. Greene*

*Imbier /Lanham /Pearlman*
*Nottarp /Wilson*
*Nottarp /Wilson*

# COMMENTS ON THE FEEDBACK CALIBRATION METHOD

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Due to the great distances involved, a meaningful remote calibration target for lunar ranging systems is not available. As a result, a feedback calibration method, suggested by D. G. Currie, has been in use at McDonald Observatory since 1971. The system works by routing an attenuated portion of the outgoing laser beam back to the receiver detector. In this manner, the delay between the start diode and the receiver photomultiplier can be statistically measured during each laser run. Since lunar systems operate at the single photoelectron level, the feedback return is highly attenuated. In theory, any signal level could be calibrated or the feedback varied electro-optically from shot to shot so that varying intensity return signals could be accommodated. (See McDonald Station Report, Session 1.)

As long as the intensity of the feedback is maintained at the same level as the returns from the target and the electronics measures the very short ranges with the same bias as the long ranges, the feedback system is foolproof. It is almost impossible for the McDonald ranging crew to change any timing cable or timing parameter and not have the results automatically calibrated at the next ranging session. More than once the automated feedback calibration system has saved data which might otherwise be lost by an operator error. The disadvantage of the feedback calibration system is the much more complex electronic routing required to accomplish the timing as well as the necessity to completely eliminate any RFI in the photomultiplier circuitry during laser fire. With the advent of mode-locked lasers not requiring pulse shape analysis and the increased use of low level returns for satellite ranging, we expect this method to gain wider acceptance in the laser ranging community. Circuit diagrams for the McDonald timing system are available on request from the author.

# SAO NETWORK TIMING

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## INTRODUCTION

The Smithsonian Astrophysical Observatory (SAO) timekeeping hardware is located at all four SAO laser tracking sites (Mt. Hopkins, Arizona; Natal, Brazil; Orroral Valley, Australia; and Arequipa, Peru) plus the cooperating laser sites (San Fernando, Spain; Athens, Greece; Dodaira, Japan; and Helwan, Egypt). While the equipment was originally built for Baker-Nunn camera operation, the hardware system and the time-reduction procedures have been upgraded to meet the higher accuracy requirements of laser tracking.

## TIMING SYSTEM HARDWARE

### A. Clock System

All tracking stations have a timekeeping system to provide epoch time data for each laser observation. Each station clock is comprised of an epoch counter/display, time and frequency monitoring equipment, and a frequency standard. Arizona, Peru, Brazil, and Greece have rubidium standards; Australia and Spain have access to on-site reference timing signals from cesium standards; the other stations use crystal oscillators. Dual timing channels, duplicate time accumulators, spare running rubidium and/or crystal oscillators, and a battery backup power system guard against any loss of time continuity. Digital phase-shifting circuitry for precise timing control permits epoch adjustment in 0.1-μsec steps. All the clocks use VLF or Omega for frequency/phase-tracking reference. During the past year, one clock at each laser station has been converted to Omega reception because of recent changes in the VLF transmission format and lapses in VLF station operational reliability. [See Pearlman et al. (1973) for further details.]

### 2. Epoch Time Transfer Equipment

To date, the network has relied primarily on portable crystal clocks for epoch transfer and verification. Portable-clock comparisons provide epoch checks throughout the network with accuracies from ±1 to ±8 μsec, depending on the proximity of a reliable timekeeping facility. On occasion, the United States Naval Observatory (USNO), The National Aeronautics and Space Administration, and the Rio Observatorio in Brazil have provided comparisons with portable cesium clocks in addition to our routine annual crystal portable comparisons.

This work was supported in part by Grant NGR 09-015-002 from the National Aeronautics and Space Administration.

The SAO laser stations will soon be using the U.S. Navy's Navigational Technology Satellite (NTS) system for one-way time transfers for epoch reference. NTS receivers measure the range to the NTS-1 (crystal oscillator) and NTS-2 (cesium oscillator) satellites through a sidetone ranging system. From these measurements plus satellite clock offsets determined by the Naval Research Laboratory (NRL), station time can be determined to ±1 μsec. Operationally, NTS measurements are made at least once a day over a 20-min period centered on time of closest approach. At our stations, the data will be recorded on cassette tapes for transmission to SAO and forwarding to NRL in Washington, D. C., for reduction. The stations in Arizona, Peru, and Brazil are being equipped with NTS timing receivers this year; Orroral Valley already has access to an NTS receiver on site.

The stations in Greece, Egypt, Spain, and Japan use Loran C for epoch reference. Once the propagation delay has been accurately determined with a portable-clock comparison, Loran C provides ±4-μsec accuracies for direct-wave Loran reception and ±15 μsec for multihop sky-wave reception.

## TIME REDUCTION

Epoch data are recorded digitally along with the laser observation data. Time-interval measurements, frequency tracking data, and VLF chart recordings are recorded and plotted. These data sheets and graphs are submitted biweekly to SAO Headquarters in Cambridge, Massachusetts.

The epoch time data of the laser observations are then corrected for the following: 1) Clock jumps or malfunctions, 2) results of epoch checks by portable clocks and NTS satellite measurements, 3) variations in transmitted VLF, Omega, and Loran signals relative to USNO, from published USNO reports, and 4) variations in time due to master-clock oscillator drift. These straight-line time approximations are submitted to SAO Data Services.

## NETWORK SYNCHRONIZATION

Synchronization of all station clocks is achieved by relating all the time and frequency references to UTC as maintained by USNO. Clock frequencies are steered by noting daily variations in Omega, VLF, and Loran measurements. NTS measurements will be used after results have been obtained from an NRL computer evaluation. Portable-clock comparisons are conducted routinely once a year, and more frequently as required. From all these techniques, epoch time at each station is normally maintained to ±25 μsec. Through reduction, time is currently recoverable after the fact to ±10 μsec. With the implementation of the NTS receivers, accuracies of 1 to 2 μsec are anticipated.

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EPOCH TIMING
A REVIEW

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## 1. INTRODUCTION

The problem of epoch-timing, with which we are confronted in making range observations has two aspects, viz.

- the Synchronisation of a local clock to an acceptable (global) standard
- the extraction of the momentary epoch of the measurement as an integral part of the range information.

Current techniques deliver typically:

| | | | |
|---|---|---|---|
| VLF | + | quartz | 200 μsec (with care) |
| VLF | + | rubidium | 100 μsec |
| Loran-C | + | rubidium | |
| | + | portable clock transfer | 2 - 3 μsec (with care) |
| Loran-C | + | rubidium | |
| | + | cesium | |
| | + | portable clock transfer | 1 μsec |

The present status at the different ranging stations will be reviewed during the subsequent discussion in this session.

## 2. Future needs

Future needs are dominated by the aspect of overall system mobility and range-accuracy. For this, new and promising synchronisation techniques are being tested which will also have a profound influence on time dissemination. The combination of NTS-type Synchronisation techniques with rubidium frequency standards for the mobile systems will permit epoch timing of unprecedented accuracy with respect to a truly global time scale.

## 3. Some Experimental Projects of Significance for the Future

Although it should not be forgotten that time in the context of these discussions is used as supplementary data to the ranging, the following topics have a particular relevance to the ranging community, which will be asked to perform calibration measurements for experimental purposes:

- the European Lasso experiment;
- possible accelerated clock system experiments;
- relativity experiments;
- possible verification experiments for new clock designs.

These topics should be addressed during the discussions and a summary of details of these and other known experiments would be welcome for the proceedings.

# EPOCH TIMING FOR THE STATION WETTZELL, FED. REP. OF GERMANY

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Fed. Rep. of Germany

## 1. HISTORICAL DEVELOPMENT

The first ranging system at the satellite observation station in Wettzell was installed in 1972. A first generation ruby laser was used and for the ranging accuracy of 1 - 2 m it was sufficient to use VLF for daily time comparisons against the two station rubidium standards. This combination delivered epoch times to 100 µsec, which was also the clock resolution at that time. The epoch setting was made by occasional portable clock comparisons. With the introduction of the new ranging system, with an anticipated ranging accuracy of 2 - 5 cm Loran-C replaced VLF for the daily control and an additional rubidium clock was introduced at the station to upgrade the reliability. The rubidium standard integral to the system has a resolution of 10 µsec with an internal epoch interpolation independent of the clock to obtain the single microsecond. Again, clock transfers have been used for epoch setting.

More recently, a cesium standard has been added to improve the long term frequency stability.

## 2. CURRENT ACTIVITIES

To ensure better epoch synchronisation on the global time scale an NTS-II receiver is currently being installed at the station. Linked to the cesium via a time interval counter with 100 psec resolution (200 psec repeatability) a synchronisation to better than 100 nanoseconds is assured.

## 3. FUTURE

The station Wettzell has been asked to participate in calibration experiments to NTS-II. The range observations from Wettzell will be used as orbit determination control for time transfers between the US Naval Observatory and the station. The station has also been approached to participate in the Lasso experiments planned for the early 1980s, whereby the NTS controlled time scale can be used to monitor the success of Lasso.

Finally, it is intended to automate the time comparison procedures at the station. For this, 4 comparisons will be conducted daily, with results recorded on a suitable data carrier (probably punched tape).

# session 5 / 6A special topics in hardware

*5 chairman D. Currie /co-chairman G. Bret*

*Gaignebet /Sinet*

*6A chairman S. Ramsden /co-chairman J. Gaignebet*

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*Dewhurst /Jacoby /Ramsden*
*Gaignebet*
*Hamal /Jelinkova*
*Kokurin /Kurbasov /Lobanov /Sukhanovsky*
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*Johnson /Degnan /McGunigal*
*Hamal*
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