АВТОМАТИЗИРОВАННАЯ УСТАНОВКА ДЛЯ ЛАЗЕРНОЙ ЛОКАЦИИ ЛУНЫ.

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

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

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

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

Лазерно-локационная система.

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

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

– оптический квантовый усилитель /ОКУ/ на рубиновом стержне /P_2 диаметром I5 мм и длиной 240 мм;

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

Рубиновые стержни P_I и P_2 вместе с двумя импульсными лампами накачки типа ИФП-8000 иотражателями помещены в общий герметический корпус. Охлаждение лазера производится дистиллированной в одой, температура которой поддерживается с точностью $\pm 0,5^oC$.

Фотоприёмник имеет: диэлектрическое отражающее зеркало /$З_3$/, о куляр /O_2/ для визуального контроля, диафрагму /$Д_I$/, определяющую поле зрения приёмника, согласующую линзу /$Л_2$/, настраивающийся интерференционный фильтр /Ф/ и фотоумножитель ФЭУ-77.

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

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

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

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

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

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

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

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

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

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

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

Параметры аппаратуры.

Длина волны лазерного передатчика $\lambda_{пер}$ = 6943Å; энергия в импульсе $W_{пер}$ = 2,0–2,5 дж; длительность импульса по уровню 0,I $\tau_{имп} \approx$ I,5 10^{-8} сек; частота повторения импульсов F = I/3 гц; диаметр светового пучка d =I5 мм; диаметр главного зеркала телескопа D_T =2,6 м; расходимость светового пучка на выходе телескопа θ =6″,0; полоса пропускания интерференционного фильтра $\Delta\lambda_{0,5}$ =5Å; коэффициент пропускания фильтра $k_ф$=0,45; квантовая эффективность фотокатода ФЭУ-77 с учётом призменной насадки k_{q} =8 –9%; относительная стабильность стандарта частоты 10^{-9}; дискретность измерения интервалов времени ∓ 10^{-8} сек; длительность временных ворот T ≤ I00 мксек; точность привязки временной шкалы к сигналам точного времени ± I мсек.

Литература.

I. Ю.Л.Кокурин, В.В.Курбасов, В.Ф.Лобанов, А.Н.Сухановский. "Космические исследования, 9, вып.6, стр.912, I97I.

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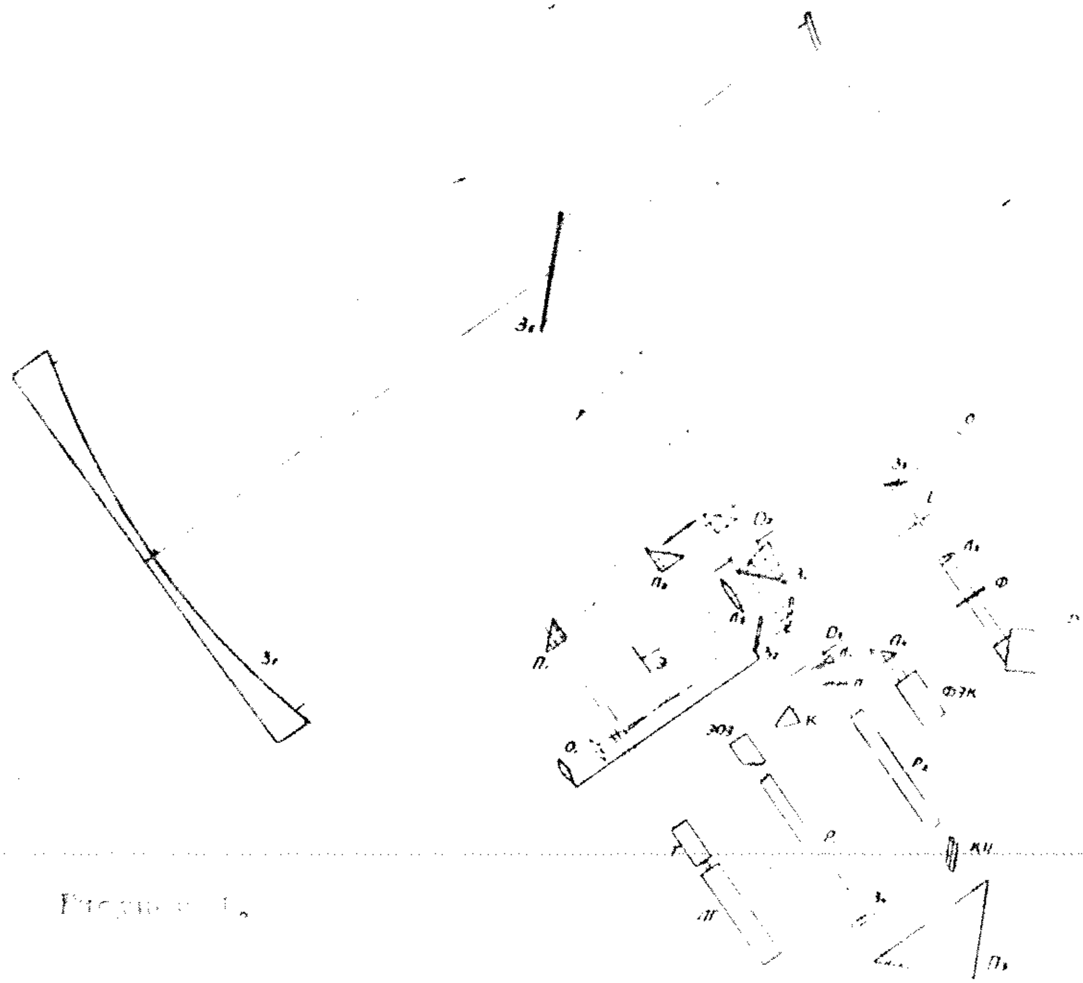


Рисунок 1.

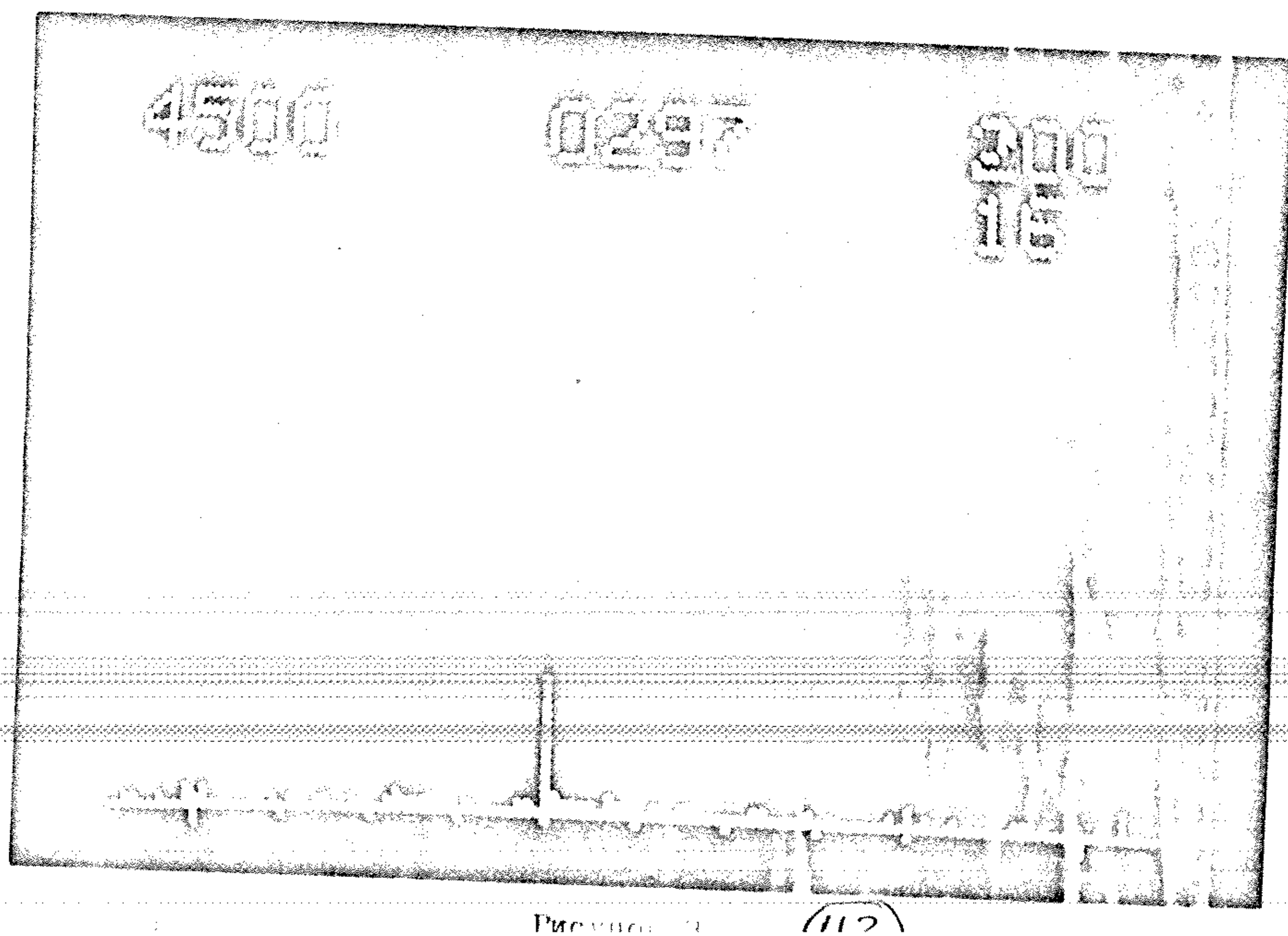


Рисунок 3

The U. S. Lunar Laser Ranging Stations

The McDonald Observatory Station

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

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

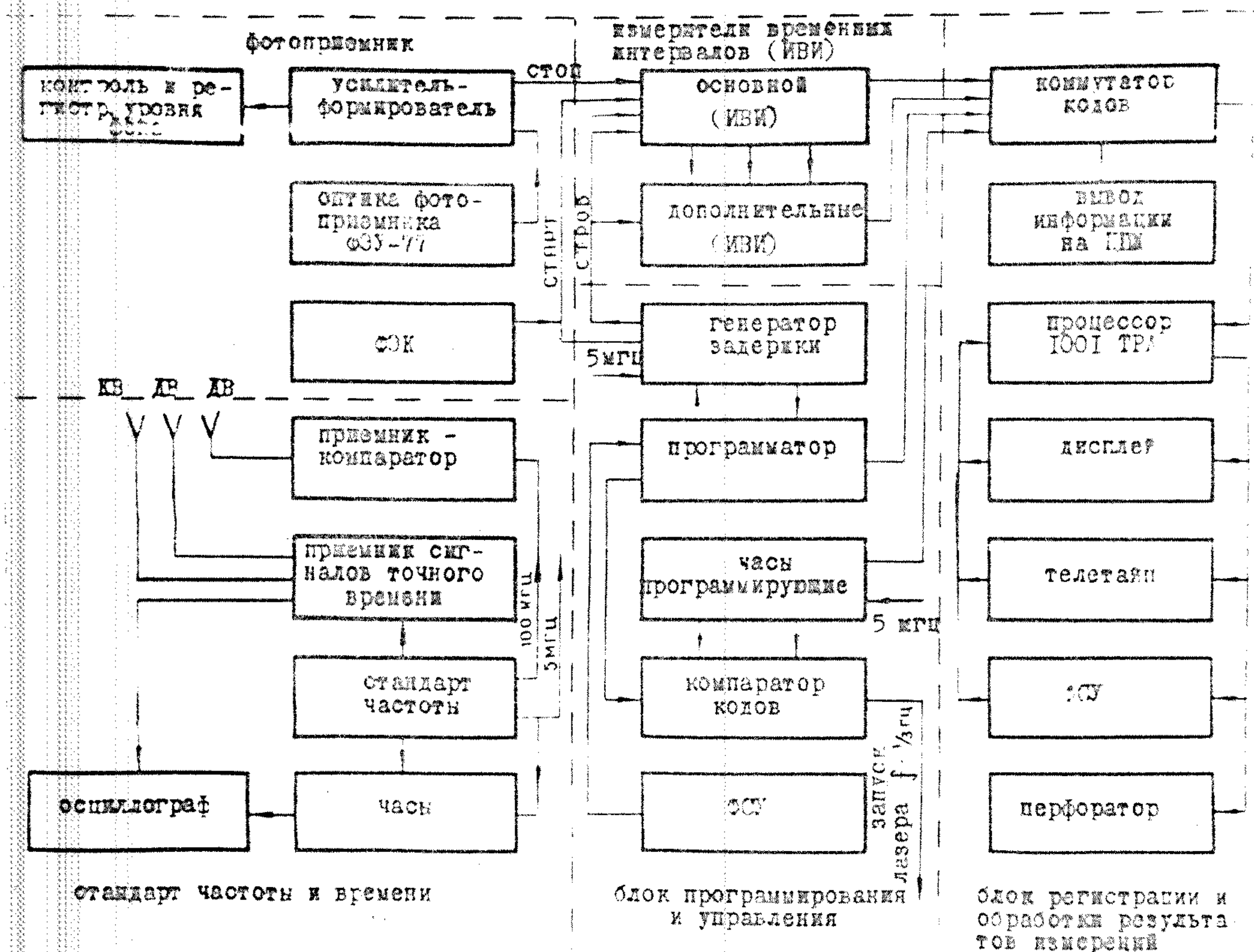
a) The average signal for the best month of operation was approximately 0.1 photoelectron for each laser shot.

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

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

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

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



БЛОК-СХЕМА ПРИЕМНО-РЕГИСТРИРУЮЩЕЙ АППАРАТУРЫ РИС.2

Table I

Important Parameters of the McDonald Station

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

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

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

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

The Hawaii Station

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

Table II

Specifications of the Haleakala Lunar Laser Station

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

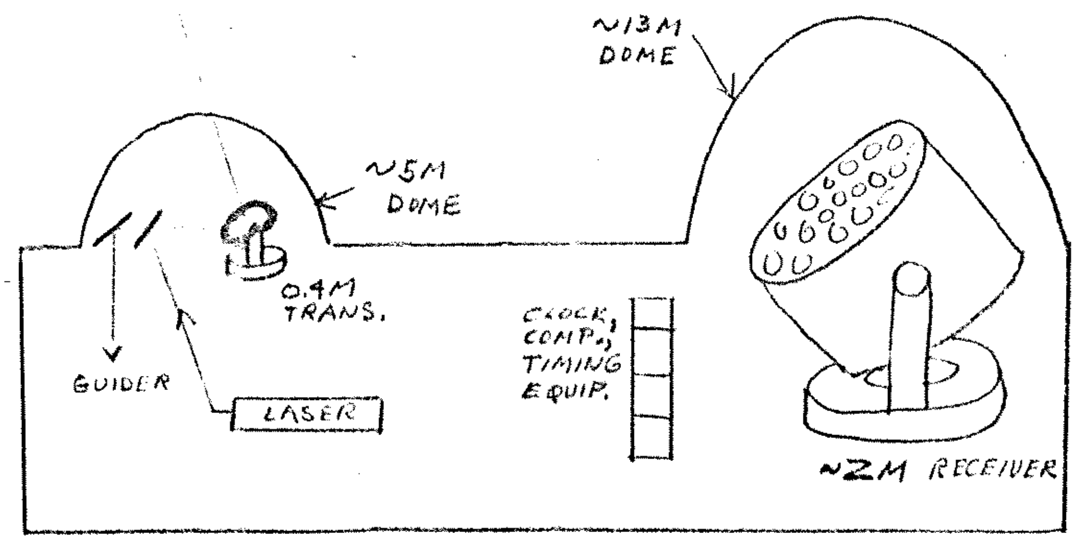


Figure I: The Haleakala Laser Station

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

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

E. C. Silverberg
Aug. 12, 1975

LUNAR AND SATELLITE RANGING SYSTEM AT TOKYO ASTRONOMICAL OBSERVATORY

ATSUSHI TSUCHIYA
TOKYO ASTRONOMICAL OBSERVATORY,
UNIVERSITY OF TOKYO

1. INTRODUCTION

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

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

2. SYSTEM

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

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

i/ Lunar Receiving Telescope /Fig. 1/

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

ii/ Lunar transmitting telescope /Fig. 2/

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

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

iii/ Lunar Laser

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

iv/ Satellite Laser

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

v/ Range counter

Accuracy	1 ns
Resolution	0.1 ns

vi/ Range Gate

Accuracy	± 10 ns
Resolution	100 ns
Digits	8 Digits

vii/ Pulse distribution analyzer

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

viii/ Timing

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

The timing accuracy is about ± 5 μs for USNO.

ix/ Computer Interface

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

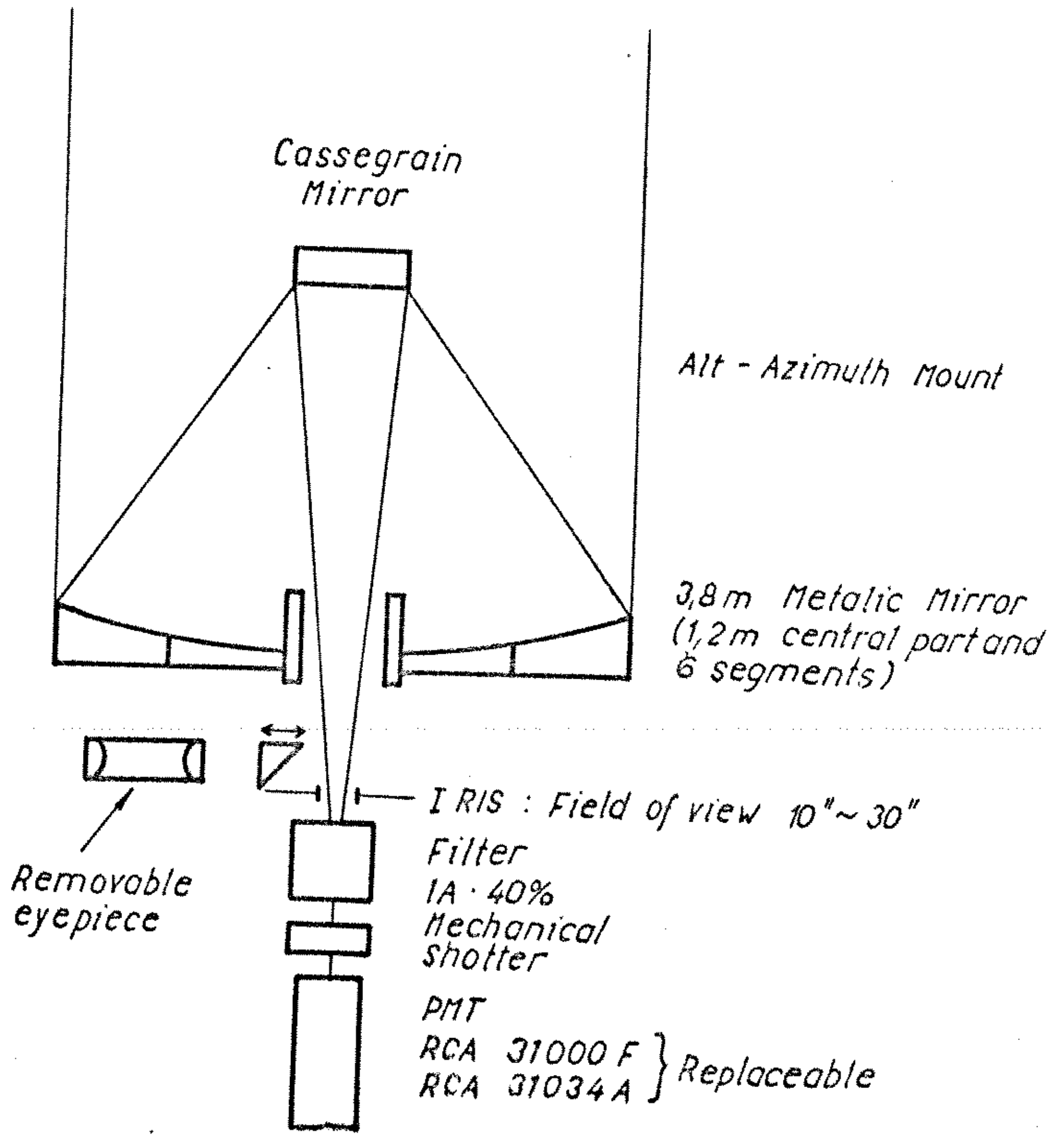


Fig. 1 Receiving telescope for Moon.

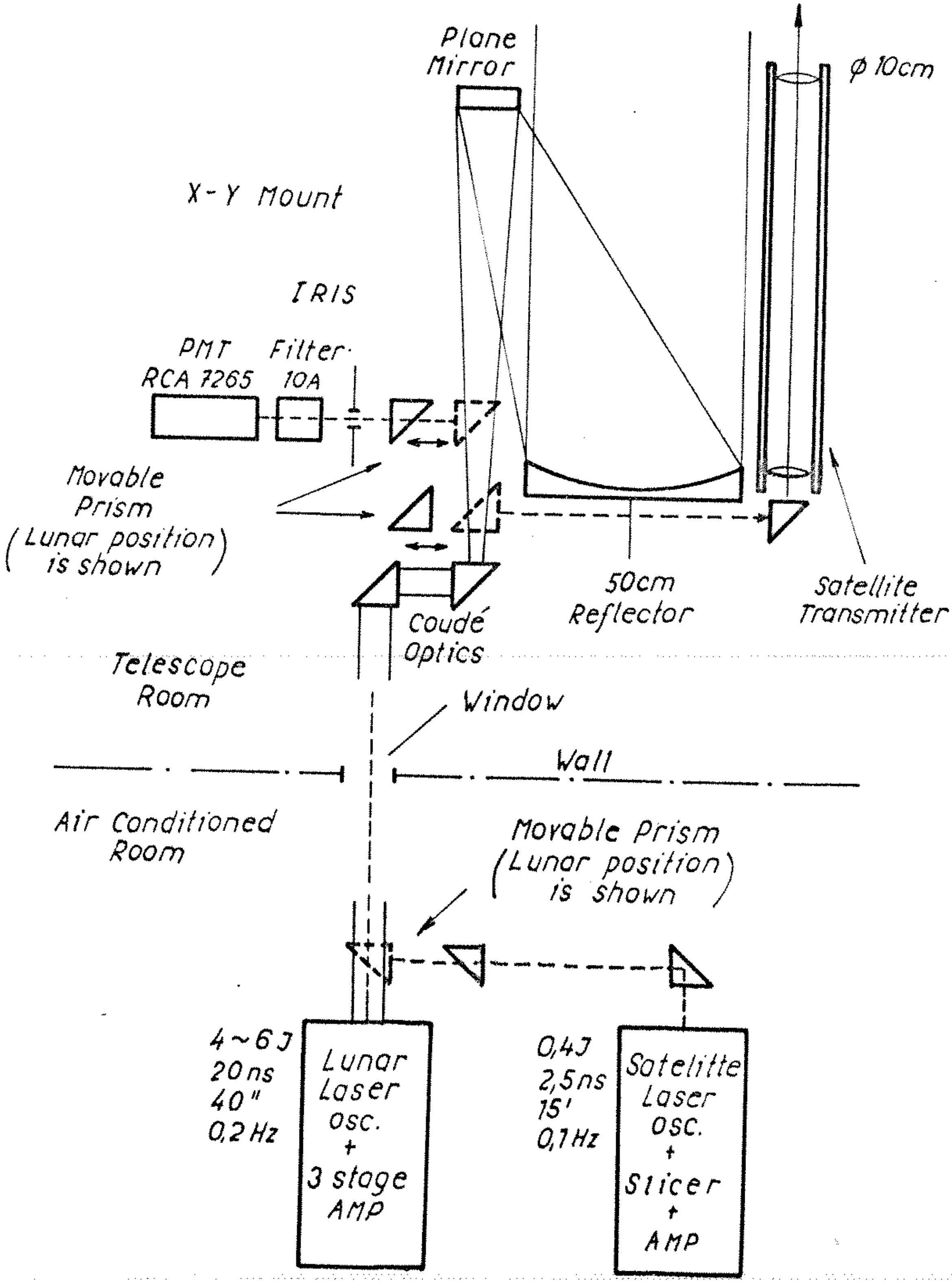
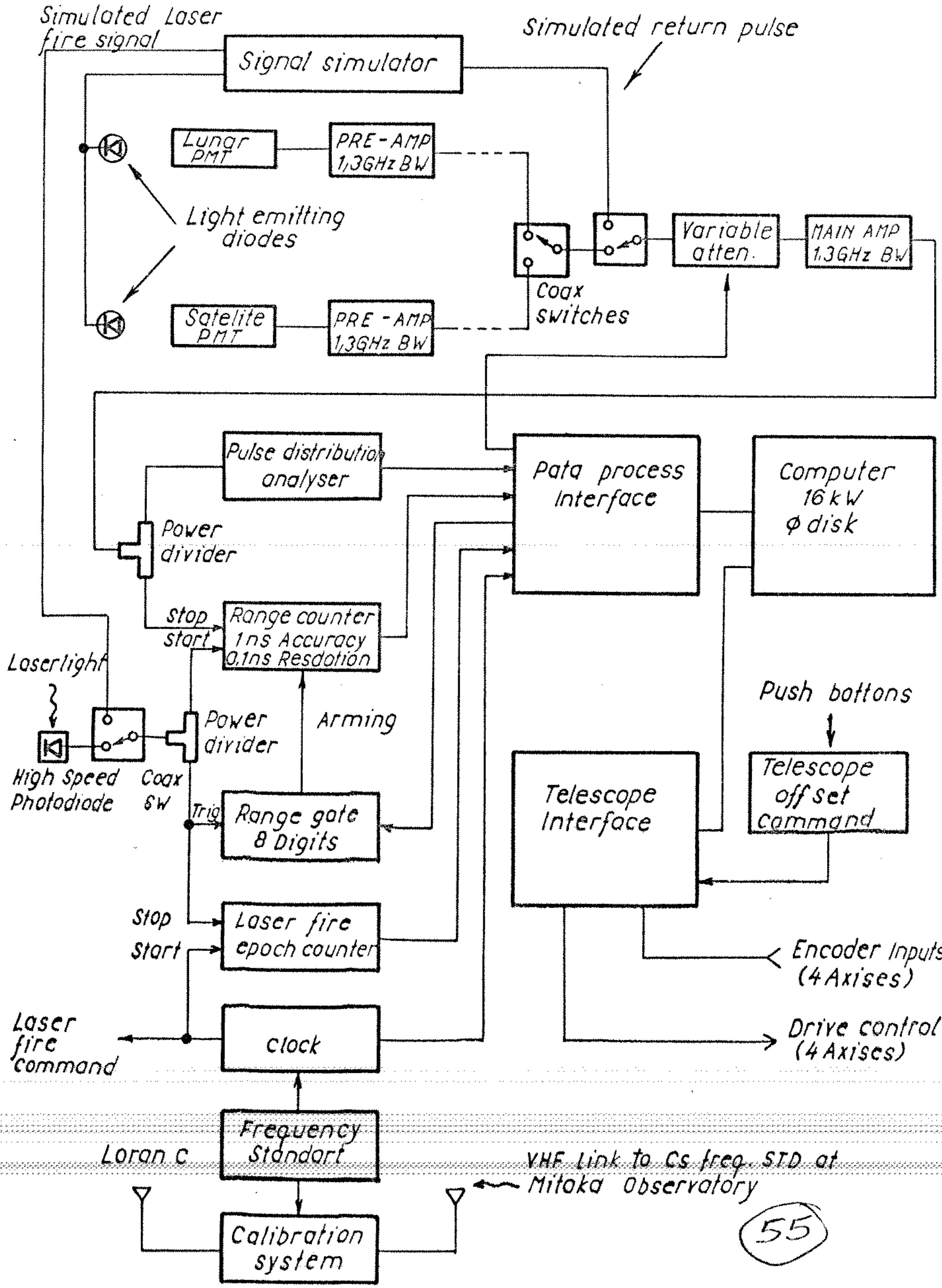


Fig. 2 Lunar Transmitter and/or Satellite Transmit-Receive Telescope.


Simulated Laser fire signal
Signal simulator
Simulated return pulse
Lunar PMT
PRE-AMP 1,3GHz BW
Light emitting diodes
Coax switches
Variable atten.
MAIN AMP 1.3GHz BW
Satelite PMT
PRE-AMP 1,3GHz BW
Pulse distribution analyser
Data process Interface
Computer 16 kW φ disk
Power divider
Stop
Start
Range counter 1ns Accuracy 0,1ns Resdotion
Laserlight
Power divider
Arming
Push bottons
High Speed Photodiode
Coax SW
Trig
Range gate 8 Digits
Telescope Interface
Telescope off set Command
Stop
Start
Laser fire epoch counter
Encoder Inputs (4 Axises)
Laser fire command
clock
Drive control (4 Axises)
Frequency Standart
Loran C
VHF Link to Cs freq. STD at Mitaka Observatory
Calibration system

UNIVERSITY OF MARYLAND LASER RANGING SYSTEM

C. O. Alley

I. Introduction

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

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

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

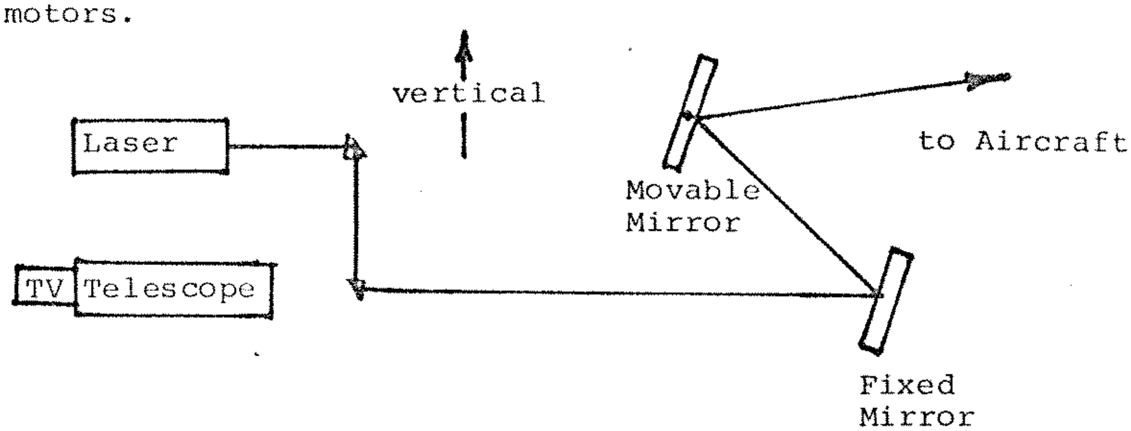
III. "Event Timer" Electronics /Douglas Currie, Charles Steggerda, John Rayner, Al Buennagel/

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

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

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

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



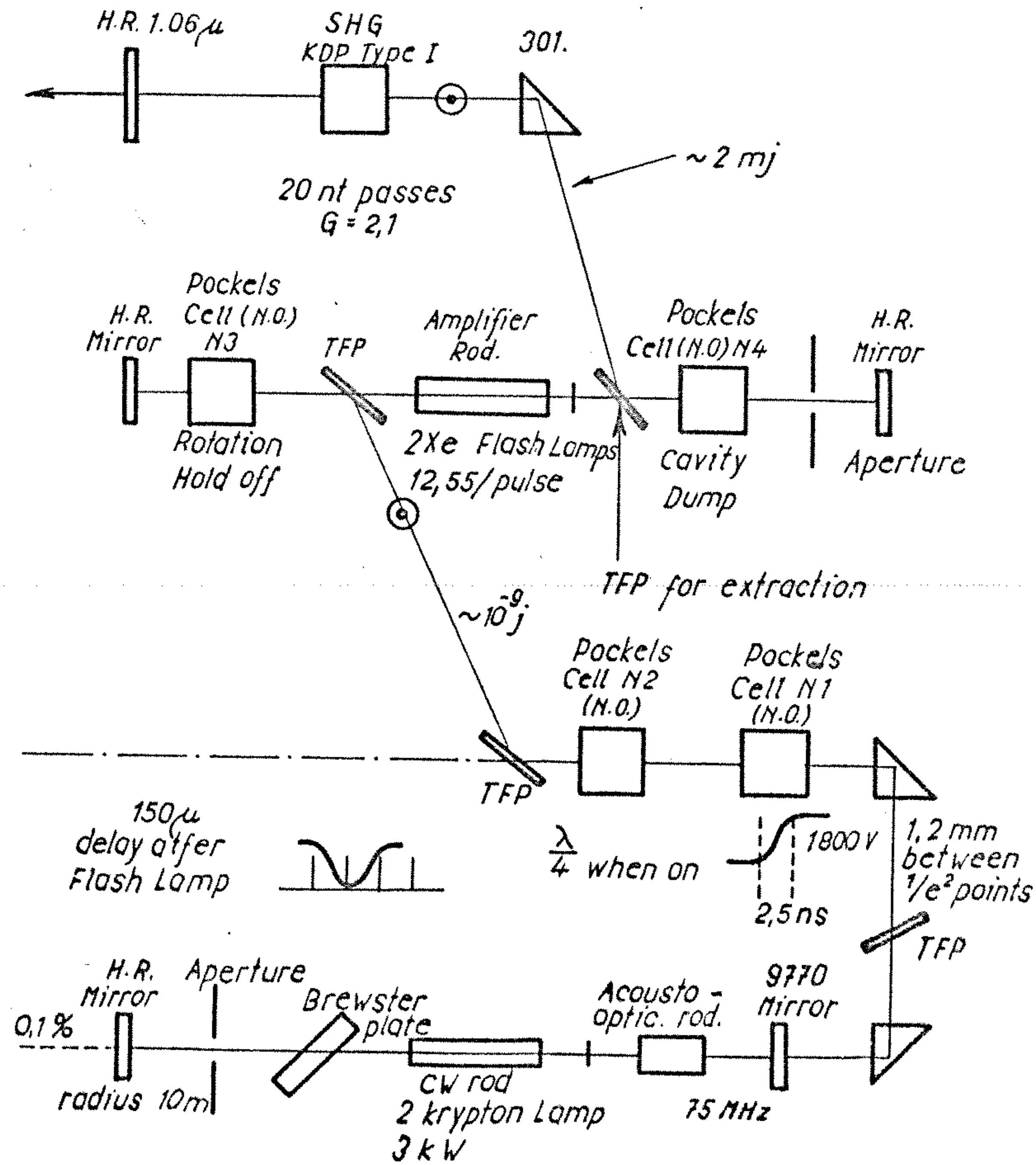
Visual tracking with closed circuit television is used. The laser ranging system performs very reliably in a bus located at the airfield. After transportation from the University in the bus /130 km/ no adjustment of the optics was necessary to achieve satistactory operation. On one occasion the system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

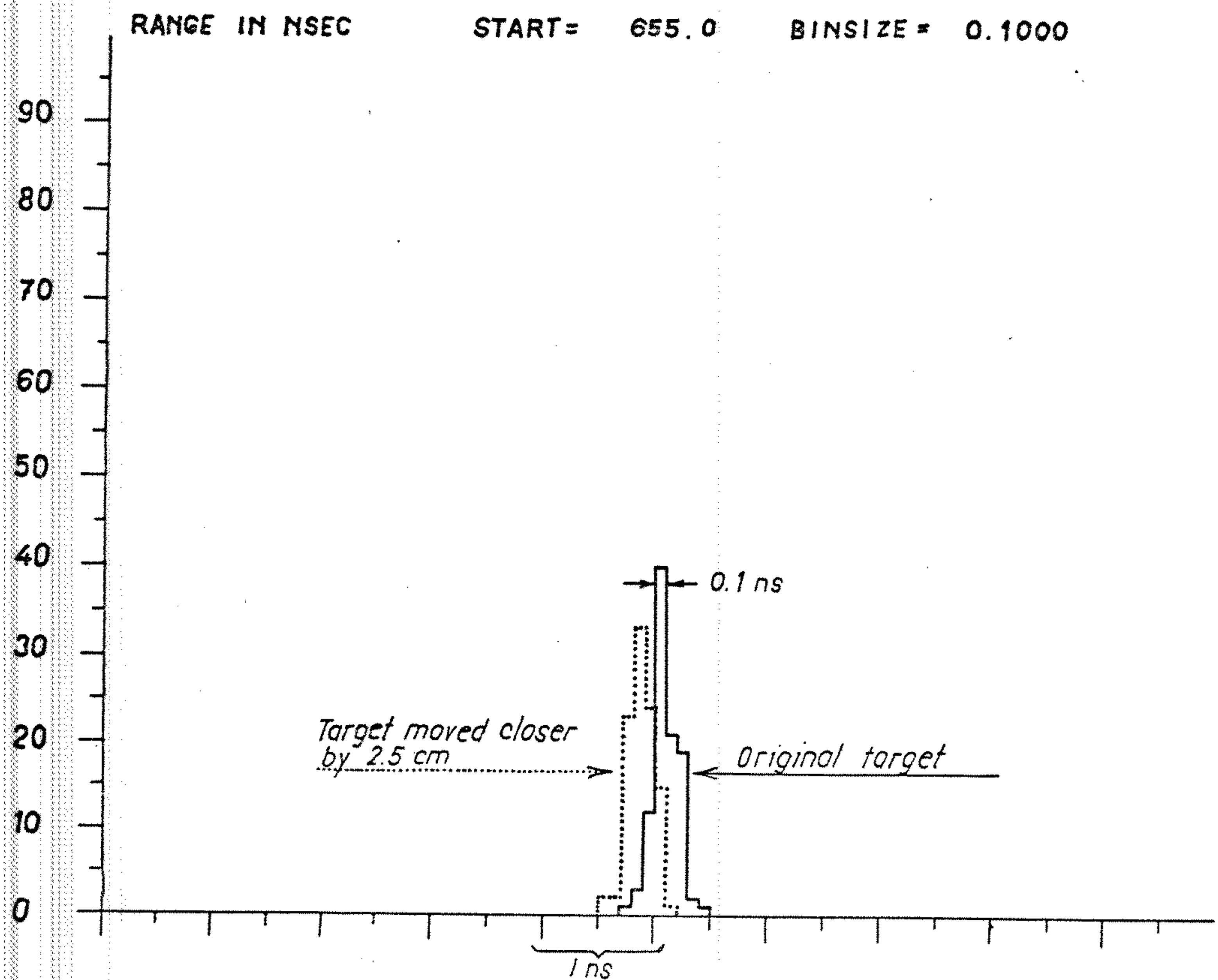
Histograms of 160 laser ranging shots to a stationary target /white diffuse flat plate/ at a distance of about 100 m are shown in Figure 2 to illustrate system performance. The solid lines are the original target position and the dashed lines are for the target moved 2.54 cm /1 inch/ closer to the transmitter.

V. Future plans

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

Steve Davis
John Deguan
Sherman Paultney





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

60

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

Claude VERET

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

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

The main features of this equipment are the following:

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

Two modes of tracking can be used:

<u>Mode 1: Visual tracking</u>

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

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*ONERA: Office National d'Etudes et de Recherches Aérospatiales
92320 Chatillon /France/

Acquisition is done visually from the predictions.

Mode 2: Semi-automatic blind tracking

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

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

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

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

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

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

Calibration procedure

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

An other mode of calibration procedure can be also used.

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

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

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

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

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

LASER BEAM WAVEFRONT DISTORTIONS MEASUREMENTS

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

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

INTRODUCTION

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

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

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

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

EXPERIMENTAL SET UP - MEASUREMENTS AND RESULTS

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

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

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

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

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

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

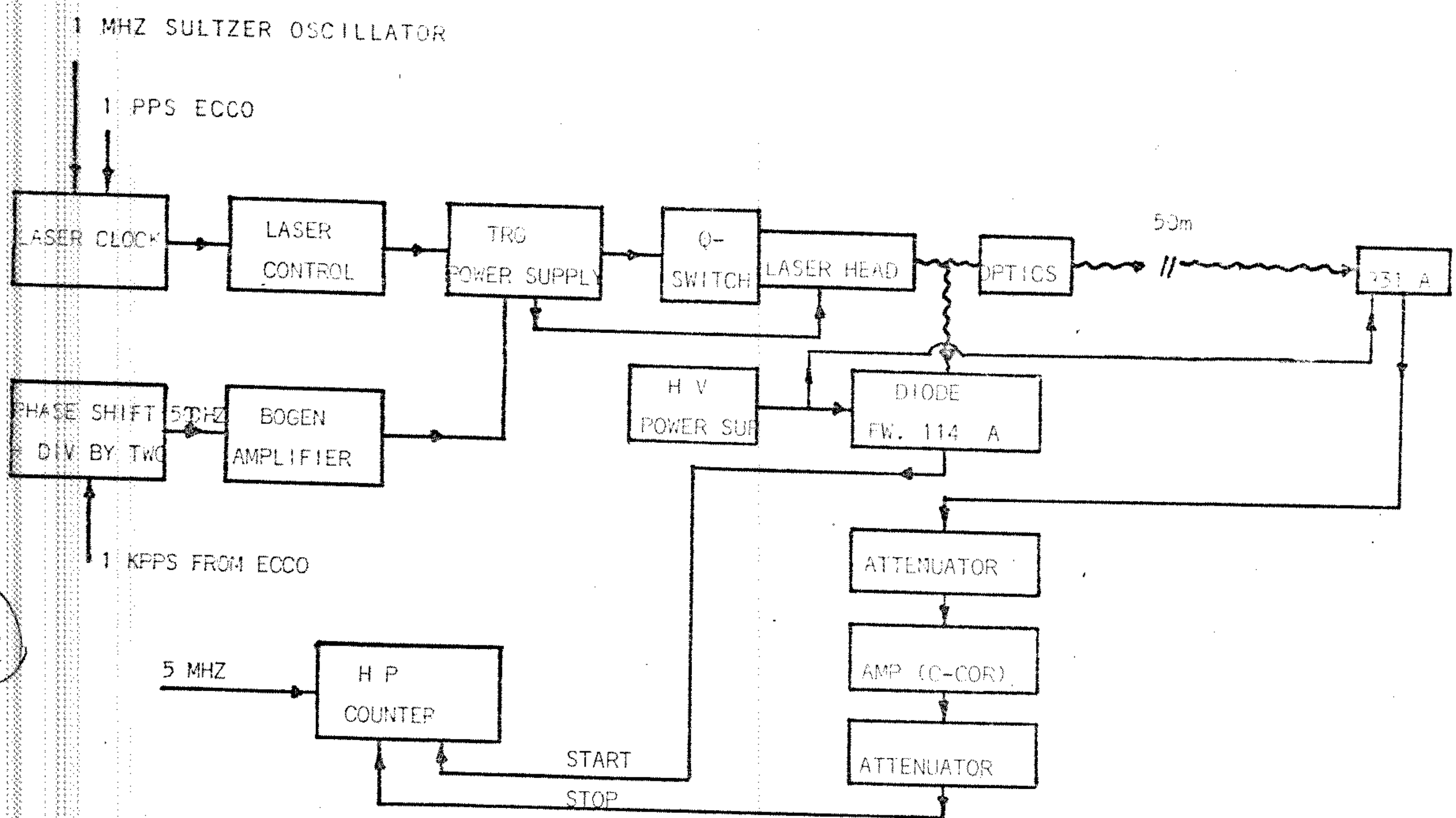

Figure 1 Block diagram of the system used in experiment # 3, # 4, # 5, # 6.

(67)

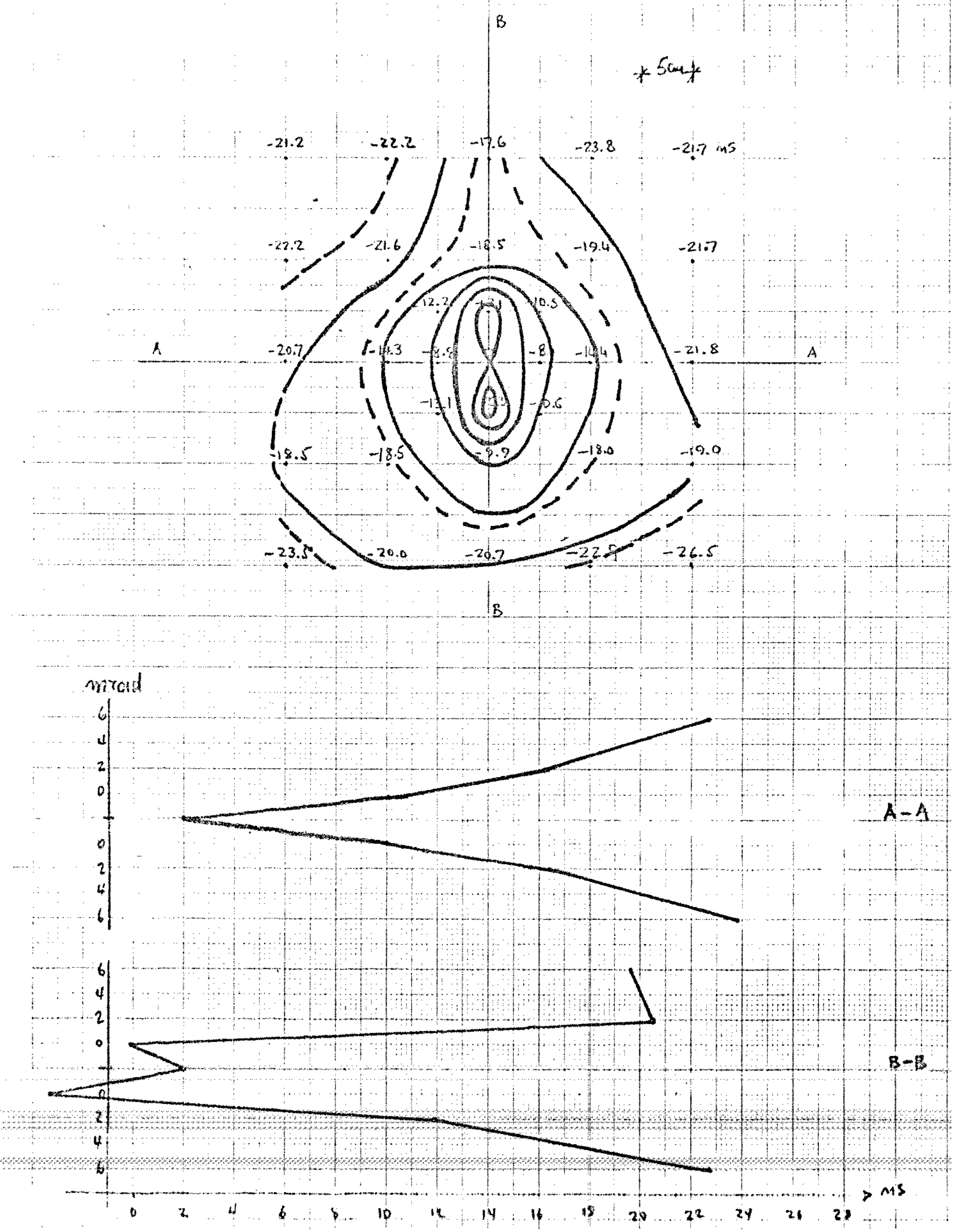

Fig. 2. Wavefront structure as of the experiment of the 22nd of

TABLE 1

RESULTS FROM THE WAVEFRONT'S STRUCTURE EXPERIMENTS

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

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

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A LASER RANGE TRACKING STATION FOR GEODINAMIC SATELLITES

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

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

The Optical-Mechanical System

- -Mount: modified CONTRAVES EOTS-B Cinetheodolite, 15" pointing accuracy; maximum velocity 30°/s, minimum velocity 0°.02/s, maximum acceleration 60°/s²
- -Tracking: manual by joy-stick, monitoring the satellite by a closed circuit television camera (Magneti Marelli CT S/1)
- -Transmitter optic: 12 cm Ø Galilean telescope, 8x
- -Transmitter beamwidth: $4\times10^{-4} \div 3\times10^{-3}$ rad.
- -Receiver optic: 50 cm Ø Cassegrain telescope, 1:2.5 parabolic primary mirror (Duran 50 SCHOTT glass type), 4x hyperbolic secondary, e.f.l. 500 cm
- -Receiver beamwidth: $3\times10^{-4} \div 6\times10^{-3}$ rad. by variable field diaphragm
- -Tracking telescope: 20 cm Ø Maksutov-Newtonian telescope, 1:3 primary mirror, giving a visual angle of 2.5 on 1 inch vidicon
- -Interference filter: 7 to 10 Å bandwith, 50 to 55% peak transmission (ORIEL or BALZERS), working in parallel light

The Laser

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

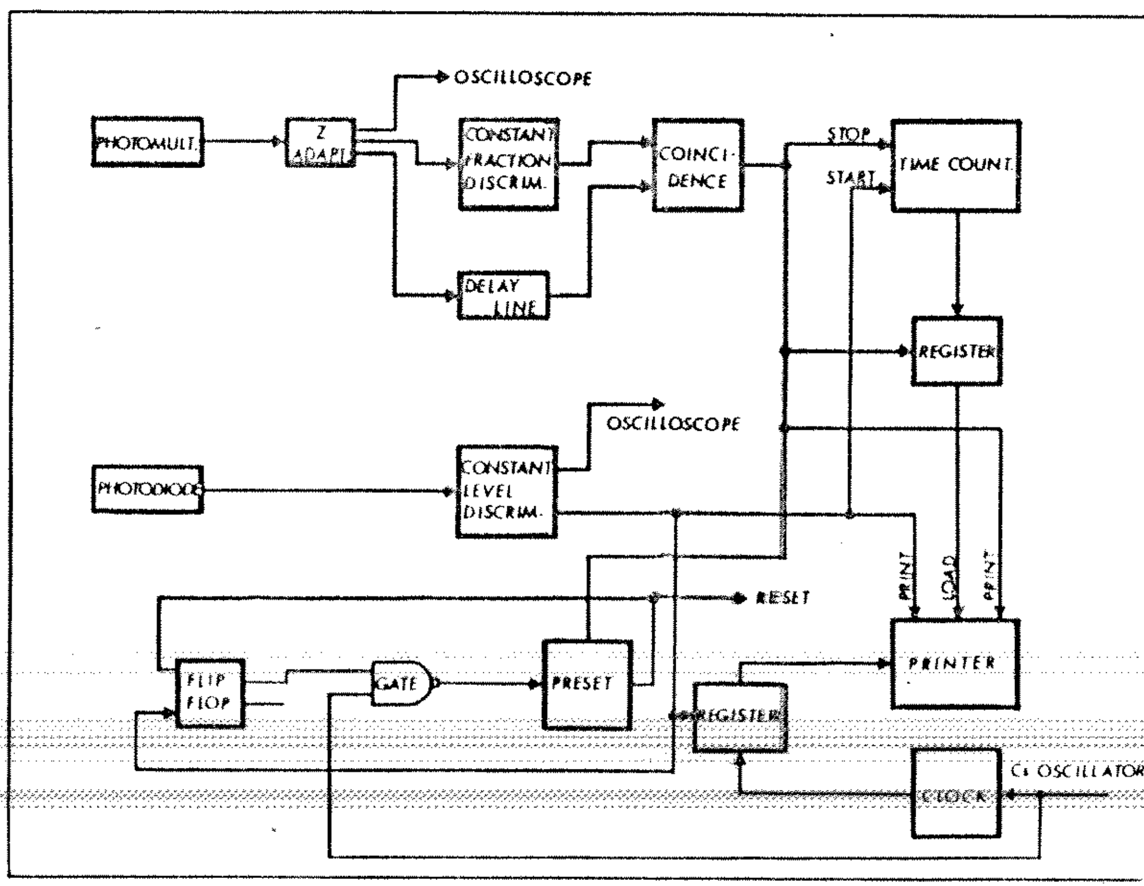
The Electronics (see the block-diagram)

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

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

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

* Istituto di Astronomia, Università di Cagliari, ITALY
** Stazione Astronomica Internazionale di Latitudine, Cagliari-Carloforte, ITALY



Block diagram for pulse detection

Performance of the Potsdam laser rangefinder

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

Workshop on Laser Tracking Instrumentation

11. - 15. August 1975

Prague

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The Instrument

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

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

Transmitter

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

Receiver

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

Oper[illegible]

[illegible] first successful satellite echos [illegible]
March 1974 [illegible]
[illegible]
relative [illegible]
[illegible] the [illegible]
[illegible]

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

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

Ranging error

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

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

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

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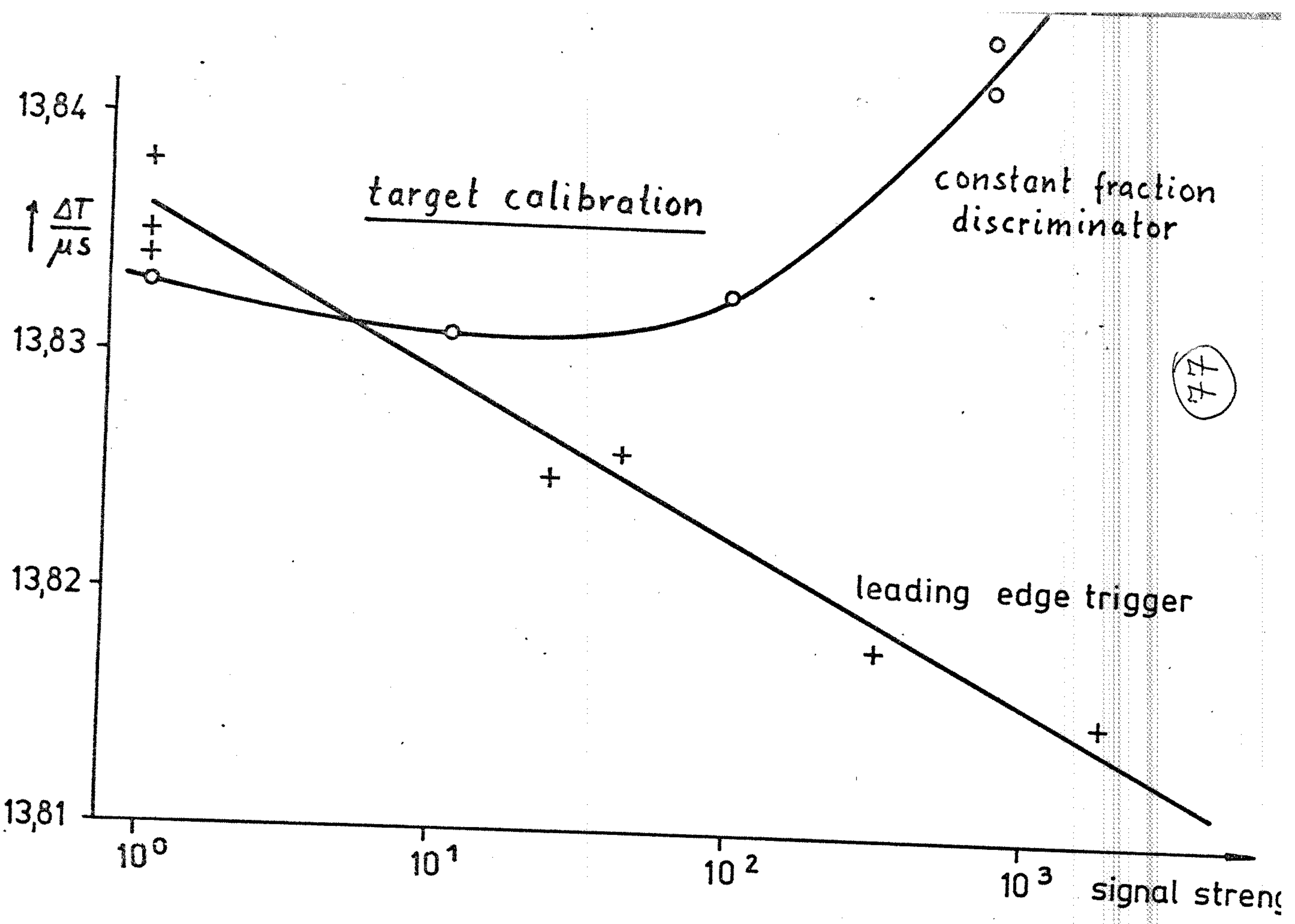

13,84
13,83
13,82
13,81
↑ ΔT/μs
target calibration
constant fraction discriminator
leading edge trigger
10^0
10^1
10^2
10^3
signal streng

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COMPUTER SIMULATION OF PULSE CENTROID CORRECTION PROCEDURE

K. Hamal, M. Vrbová

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

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

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

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

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

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

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

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

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

Table 1. Theoretical limit of accuracy

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

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

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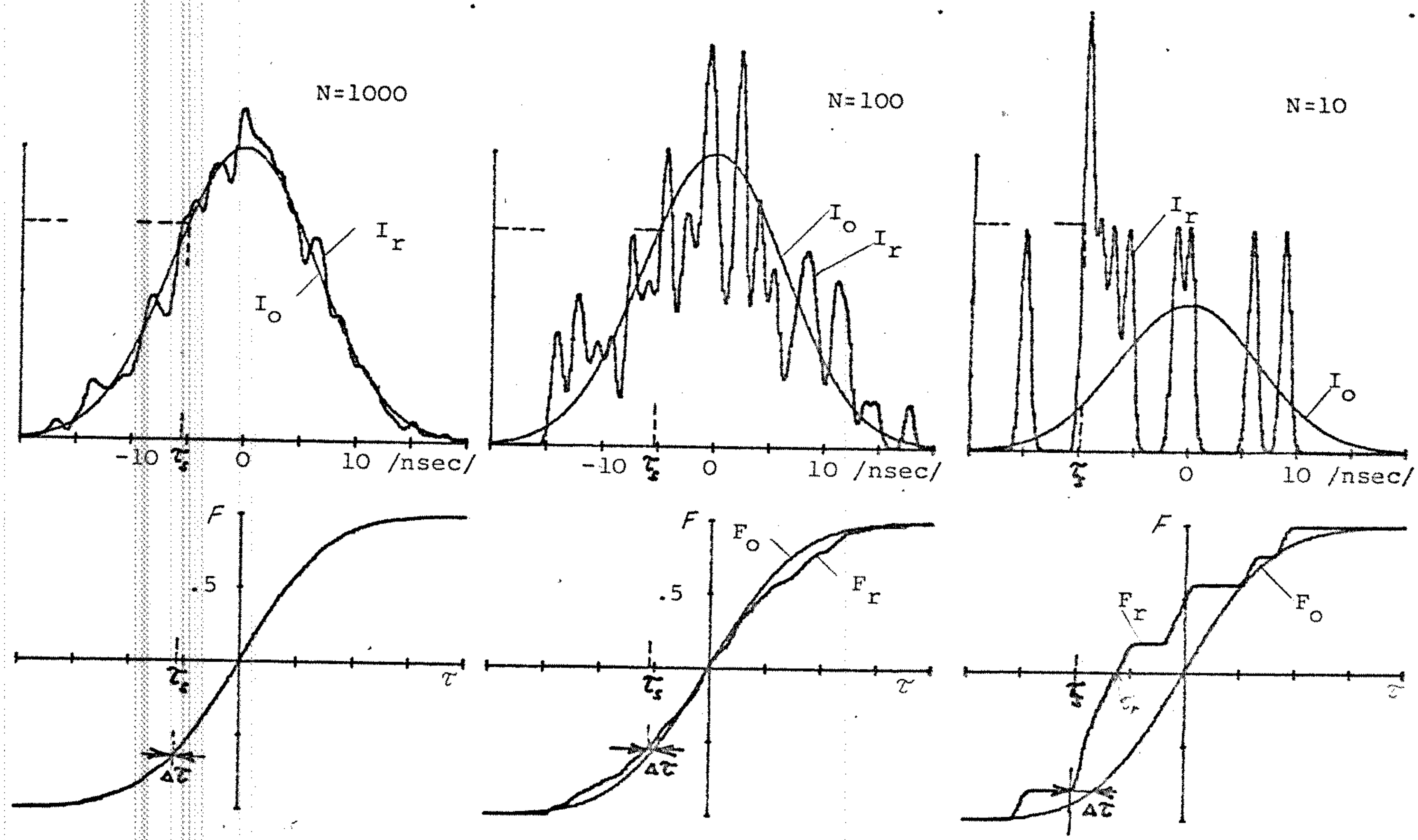

Fig. 1. Stochastic signal realizations and functional characteristics

The Satellite Ranging Station at Kootwijk (Holland)

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

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

1 MEASURING SYSTEM SET-UP

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

2 TRANSMITTING AND RECEIVING TELESCOPE

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

3 LASER SYSTEM (Apollo, USA)

Specifications

Optical Train	
Oscillator Rod	3/8" x 6" AR coated ruby
Amplifier 1	1/2" x 6" AR coated ruby
Amplifier 2	5/8" x 6" AR coated ruby
Output Mirror	3/4" x 1/8" 0^{o} sapphire etalon
Q-Switch	0,45"clear aperture, KD*P Pockels cell, fluid immersed
Q-Switch Polarizers	Two Brewster plate stacks, five plates per stack
Rear Mirrors	100% dielectric-coated, 1" diameter
Cavity Configuration	Flat-flat, 26" mirror separation, pulse-on switching
Electro-optical Shutter	0,45"aperture, KD*P Pockels cell with dielectric polarizer. Transverse laser-triggered spark gap switch with coaxial transmission line pulse forming network.
Output Polarization	Plane of polarization perpendicular to mounting plane of optical train
Oscillator Power Monitor	ITT F4000 biplanar photodiode, S-1 surface
Amplifier 1 Energy Monitor	10 mm PIN silicon photodiode, UDT Type PIN10D
Amplifier 2 Power Monitor	Same as oscillator monitor
Performance Characteristics	
Wavelength	6943 Å
Linewidth	0,3 Å fwhm
Output Energy:	
4 ns shuttered mode	3 joules
20 ns Q-switched mode	10 joules
Long pulse mode	15 joules
Beam Divergence	3 mrad between half energy points 5/8" maximum diameter
Output Stability	± 20% within one minute ± 10% within five minutes
Repetition Rate	15 per minute, maximum

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4. AIRCRAFT DETECTION SYSTEM

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

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

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

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

5 CONCLUSION

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

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

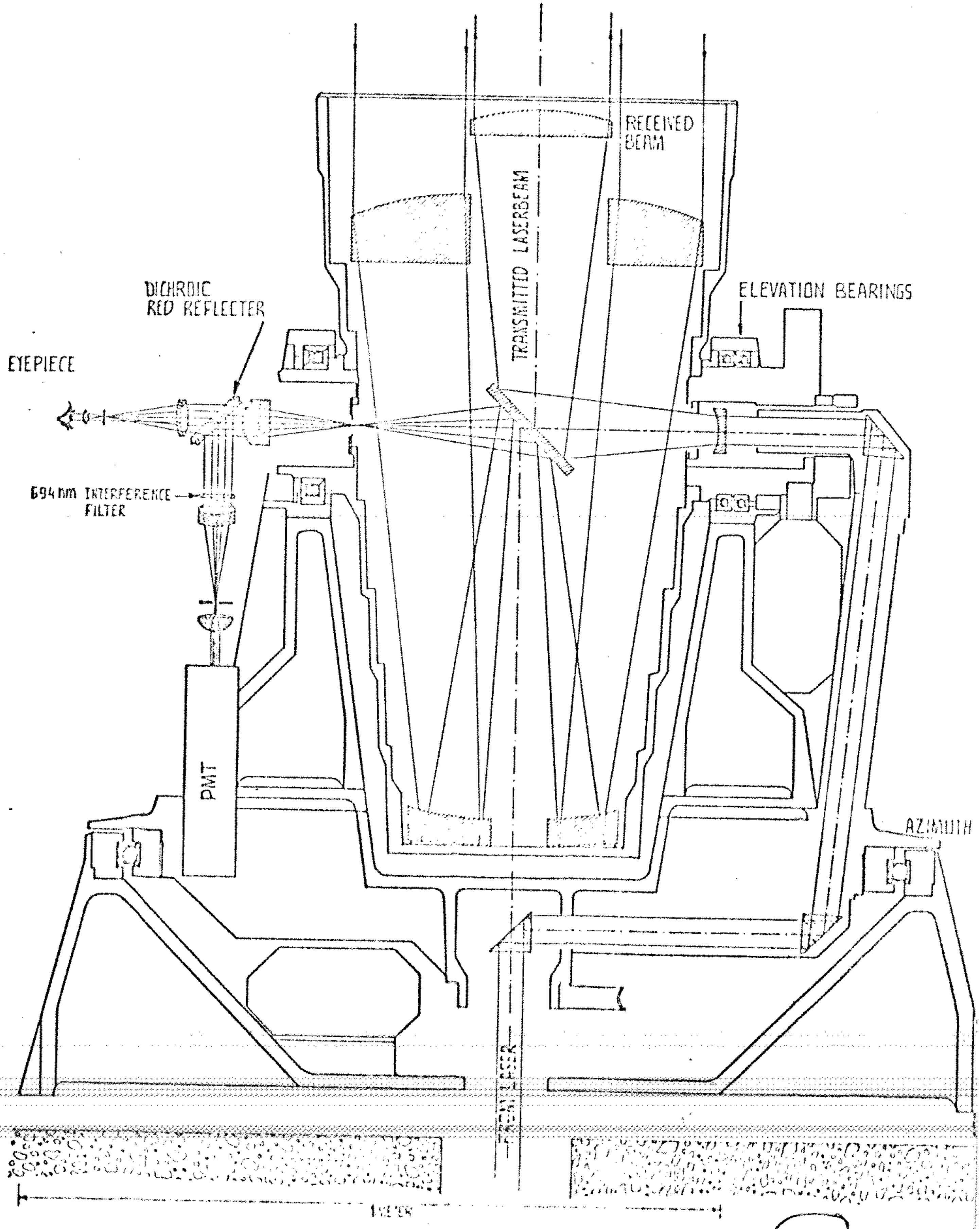
RECEIVED BEAM
TRANSMITTED LASERBEAM
DICHROIC RED REFLECTER
EYEPIECE
ELEVATION BEARINGS
694nm INTERFERENCE FILTER
PMT
AZIMUTH
FROM LASER

figure 1

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