CENTRAL BUREAU FOR SATELLITE GEODESY
OF THE INTERNATIONAL ASSOCIATION OF GEODESY

laser workshop

third international workshop on laser ranging instrumentation

proceedings

Lagonissi, may 23_27 1978

National Technical University of Athens / Higher Geodesy and Cartography

Athens 1978

List of Participants

Aardoom	NL	Kovalevsky	F
Alley	USA	Kremers	D
Asaad	ET	Latief	Indonesia
Ashkenazi	GB	Loukideli	GR
Babili	GR	Makris	GR
Balodimos	GR	Mangin	F
Beutler	CH	Manzoni	I
Billiris	GR	Mendis	USA
Bret	USA	Michaelides	GR
Cooke	USA	Mulholland	USA
Cugusi	I	Naugle	USA
Currie	USA	Nottarp	D
Economou	USA	Nouel	F
Fahim	ET	Novotny	CS
Gaignebet	F	Paunonen	SF
Gaposchkin	USA	Pearlman	USA
Greene	GB	Pesec	A
McGunigal	USA	Ramsden	GB
Hadgigeorge	USA	Rayner	USA
Hamal	CS	Schutz	USA
Hatat	E	Seeger	D
Hereti	GR	Silverberg	USA
Holmes	USA	Sinet	F
Hyde	GB	Sinclair	GB
Imbier	USA	Soegilo	Indonesia
Jankiewicz	PL	Souchanovsky	USSR
Johansson	S	Tatevian	USSR
Johnson	GR	Tsoflias	GR
Kakuta	Japan	Tsolakis	GR
Kalligerou	GR	Tsochiya	Japan
Kardos	H	Veis	GR
Kielek	PL	Yumi	Japan
Kissell	USA	Whitehead	GB
Klockler	CH	Zeeman	NL
Kokurin	USSR		

Preface

The Third International Workshop on Laser Ranging was held in Athens 23-27 May 1978, under the auspices of COSPAR, IAG and URSI.

Rapid progress in laser technology and their applications to satellite ranging has considerably increased the expectation of accuracies of few centimeters and the anticipation of the solutions of practical problems related with the kinematics and dynamics of the Earth and of the Earth-Moon system.

However the needed instrumentation is quite expensive and the exchange of ideas and experience as well as the coordination of efforts is necessary in order to arrive at an optimal solution at a mimimum cost. With this in mind a series of Laser Workshop are organised every few years in order to bring together the specialists whetherthey are theoreticians, engineers or users.

Due to the importance of the papers presented during this Third Symposium for the international satellite geodesy scientific community, the Central Bureau for Satellite Geodesy of the International Association of Geodesy, has edited and published in a special volume the Proceedings of this workshop, with the financial assistance of the National Technical University of Athens.

Following the tradition of the two previous Laser Workshops (Athens 1973, Prague 1975) Dr. K.Hamal and Dr. M.Pearlman acted as convenors of the Workshop. Thanks are due to them as well as to the chairmen and co-chairmen of the panels for their assistance concerning this publication.

George Veis
Athens, December 1978

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session 1 satellite tracking requirements

chairman M. Pearlman /co-chairman G. Veis

Pearlman

Tatevian

Kovalevsky

Mulholland /Calame

THIRD WORKSHOP ON LASER RANGING INSTRUMENTATION

M. R. Pearlman
Smithsonian Astrophysical Observatory
Cambridge, MA

INTRODUCTORY REMARKS

During the decade of the 1970s, we have witnessed the transition of satellite geodesy into geophysics. Where once we were trying to measure "fixed" quantities, now we are trying to measure how quantities change. Workers in the field of geodesy embraced optical-tracking techniques as a means of connecting points over large distances. Now, we are dealing with a new community with far more stringent requirements, but more exciting science. In earth dynamics, geophysicists are trying to measure a number of things: gravity field, plate motion, fault motion, uplift, subsidence, earth tides, polar motion, earth rotation, and other crustal and solid-earth motions. In oceanography, workers are studying ocean dynamics, ocean-surface topography, tides, currents, and general circulation. Each of these studies uses satellite dynamics and position either as the fundamental measured quantity or as a means to unravel data from specialized sensors. Laser ranging to satellites and to the moon is one of the fundamental tools for these pursuits.

As we have seen during the last two Workshops, the development of laser ranging systems has been very rapid in response to the needs of the geophysical community. Workers are taking advantage of the newer laser techniques and fast electronics to improve system performance. Short-pulse lasers, pulse processors, minicomputers, and sophisticated optical hardware are being developed and applied to these programs. Lasers now in operation are already measuring baselines and earth rotation to decimeter accuracies. Indeed, we expect that laser ranging equipment with accuracies of 2 cm will soon be available and in routine operation. With such a tool, we will be able to measure global plate-tectonic and other crustal motions to the 1-cm/year accuracy required to understand the dynamic processes.

In addition to the dramatic improvement in ranging accuracy during the current decade, there has also been an increase in participation in routine laser ranging activities. Not only have new groups joined the laser ranging community, but most have brought new concepts and improved hardware to bear in this field. A list of stations is shown in Tables 1 and 2. Although these stations have been built and are being operated by many different groups, all recognize the need for improved range accuracy and performance to meet on-going and projected program needs.

Laser ranging activities have received great impetus from five new retroreflector-equipped satellites that have been placed in orbit during the past three years. The Starlette satellite, launched by the Centre National d'Etudes Spatiales in February 1975, is now a major element in the development of refined geodetic models. The National Aeronautics and Space Administration's (NASA) Geos 3 satellite, in orbit since April 1975, is the first global test of a radar altimeter, while NASA's Lageos satellite, launched in May 1976, is already being used to measure interstation baselines and polar motion. The Navigation Technology Satellite (NTS-2), placed in orbit last June by the U.S. Navy, has applications similar to Lageos. In addition, the Interkosmos 17 satellite, launched by the USSR in September 1977, is playing an important role in the Interkosmos geodetic and geophysics program.

In June of this year, NASA's Seasat satellite will be launched to support investigations in ocean dynamics. This spacecraft is equipped with an improved radar altimeter for ocean-surface topography measurements and a retroreflector array for precision orbit determination.

The total complex of retroreflectors on satellites in orbit and on the moon (see Table 3) represents a wide distribution in orbital parameters and geometries. As such, they give investigators a broad set of conditions on which to base their research and to design their measurements (see Table 4). For instance, the lower orbiting satellites at many different orbital inclinations are the basis of gravity-field development, tidal studies, and short-term positional geodesy. The higher satellites and the moon are fundamental to precision long-baseline measurements and crustal- and polar-motion studies.

Because of the new capabilities and opportunities that have been available in this decade, plus the growth of programs to study geophysics through laser ranging, the Workshop on Laser Ranging Instrumentation has been a prominent activity of both the COSPAR Panel 1A and the IAG Special Study Group 2.33.

Once again, the Third Laser Workshop will provide a critical review of laser ranging systems based on the accumulated experiences of workers in the field. The meeting will provide a forum to discuss problems encountered in setting up, operating, and upgrading ranging systems. To encourage free and open discussions, the Workshop will be conducted on an informal basis. There will, however, be prepared presentations on system descriptions and other specific areas during the sessions (see Figure 1). While the specific format of each session will be arranged by its chairman, the success of the Workshop, as in the past, depends on active participation by all who are present.

In recognition of the evolving needs of laser ranging groups, sessions concentrating on several new areas are being introduced at this Workshop. In Session 1, the meeting will be addressed by several members of the geophysical community who will review work now in progress, together with current data-acquisition requirements and projections of future needs. This overview is intended to give us a better feeling for the scientific motivations for our laser ranging efforts and also to let us understand what is expected of these new measurements. Once again, we must stress the fact that our objective is not merely to develop sophisticated equipment but rather to provide the geophysical community with a data-acquisition tool that can be used on a routine basis.

A session on software and data processing has been included in the Workshop with the recognition that this area is as fundamental to the laser systems as any piece of hardware. We have also included a session on station timing. As in the past, significant attention will also be devoted to new concepts and system ideas.

Table 1. Satellite laser ranging stations.

LASER RANGING STATIONS

SATELLITES

(AS OF 1 JULY 1978)

STATION	AFFILIATION
AREQUIPA, PERU	SAO/USA
BERMUDA	NASA/USA
BOROWIEC, POLAND	INTERKOSMOS
CAPE CANAVERAL, FLORIDA	NASA/USA
CRIMEA, USSR	INTERKOSMOS
DIONYSOS, GREECE	NTU/GREECE
DODAIRA, JAPAN	TAO/JAPAN
GRAND TURK ISLAND	NASA/USA
GRASSE, FRANCE	GRGS
GREENBELT, MARYLAND	NASA/USA
HELWAN, EGYPT	INTERKOSMOS
HRADEC KRALOVE, CZECHOSLOVAKIA	INTERKOSMOS
KAVALUR, INDIA	INTERKOSMOS
KOOTWIJK, NETHERLANDS	THD/NETHERLANDS
METSAHOVI, FINLAND	HUT/FINLAND
MT. HOPKINS, ARIZONA	SAO/USA
NATAL, BRAZIL	SAO/USA
ONDREJOV, CZECHOSLOVAKIA	INTERKOSMOS
ORRORAL VALLEY, AUSTRALIA	SAO/USA
PATACOMAYA, BOLIVIA	INTERKOSMOS
PENC, HUNGARY	INTERKOSMOS
POTSDAM, GDR	INTERKOSMOS
SAN DIEGO, CALIFORNIA	NASA/USA
SAN FERNANDO, SPAIN	GRGS
SANTIAGO DE CUBA, CUBA	INTERKOSMOS
SIMEIS, USSR	INTERKOSMOS
WETTZELL, FRG	IFAG/FRG
ZVENIGOROD, USSR	INTERKOSMOS

Table 2. Lunar laser ranging stations.

LASER RANGING STATIONS

LUNAR

(AS OF 1 JULY 1978)

STATION	AFFILIATION
CRIMEAN OBSERVATORY	CRIMEAN OBS/USSR
GRASSE, FRANCE	CERGA/FRANCE
MCDONALD OBSERVATORY	U. OF TEX/USA
MT. HALEAKALA, HAWAII	U. OF HAWAII/USA
ORRORAL VALLEY, AUSTRALIA	NATMAP/AUSTRALIA
TOKYO, JAPAN	TAO/JAPAN

Table 3. Retroreflector arrays.

SATELLITE	ORBITAL PARAMETERS			RELATIVE RETURN	TRACKING RATE	VISUAL MAGNITUDE	AVAILABILITY OF ORBITAL ELEMENTS	SPECIAL FEATURES
	a	i	e	(at 45°)				
BE-B	7.3	79.79	.017	$2\text{-}4 \times 10^4$	FAST	7-9		
BE-C	7.50	41.18	.026	$1\text{-}3 \times 10^4$	FAST	7-11	SAO (WEEKLY)	
GEOS-1	8.07	59.38	.071	$0.2\text{-}2 \times 10^4$	FAST	7-10	SAO (WEEKLY)	
D1C	7.36	40.02	.058	$0.4\text{-}10 \times 10^4$	FAST	9-10		
D1D	7.61	39.45	.085	$0.1\text{-}10 \times 10^4$	FAST	10-11		
PEOLE	6.97	15.00	.015	$3\text{-}9 \times 10^4$	FAST	5-6		
D5B	7.05	30.00	.057			5-6		
STARLETTE	7.33	49.80	.02	$3\text{-}7 \times 10^3$	FAST	11	SAO (WEEKLY)	
GEOS-3	7.22	114.90	.0006	10^5	FAST	7-8	SAO (WEEKLY)	ALTIMETER/IR RETRO
LAGEOS	12.3	109.8	.005	20	MEDIUM	12-13	SAO (WEEKLY)	IR RETRO
NTS-II	26.56	63.4	.0004	5	MEDIUM	12-13	NRL (BIWEEKLY)	
INTER-COSMOS 17	6.87	82.96	.0035		FAST	6-7		
SEASAT (TBL)	7.2	108	.001	0.5×10^5	FAST		SAO (WEEKLY)	ALTIMETER
LUNAR ARRAY								
A11				0.6×10^{-3}	SLOW			
A14				0.6×10^{-3}	SLOW			
A15				1.2×10^{-3}	SLOW			
L1				1.5×10^{-3}	SLOW			
L2				1.5×10^{-3}	SLOW			

Table 4. Applications.

SATELLITE	COSPAR NO.	APPLICATION
BE-B	6406401	
BE-C	6503201	
GEOS-1	6508901	Gravity Field, Tides, Positional Geodesy
D1C	6701101	
D1D	6701401	
PEOLE	7010901	Gravity Field
D5B		
STARLETTE	7501001	Gravity Field, Tides, Positional Geodesy
GEOS-3	7502701	Ocean Surface Topography, Gravity Field, Tides, Positional Geodesy
LAGEOS	7603901	Earth Dynamics, Polar Motion, Earth Rotation, Positional Geodesy
NTS-II	7705301	
INTERCOSMOS 17	7709601	Gravity Field, Tides
LUNAR ARRAY		
A11		
A14		
A15		Earth Dynamics, Polar Motion, Earth Rotation, Positional Geodesy, Lunar Science
L1		
L2		

	May 23 Tuesday	May 24 Wednesday	May 25 Thursday	May 26 Friday	May 27 Saturday
AM		Session 1 (Introduction) Satellite Tracking Requirements	Session 3A Operating Satellite Ranging Systems - - - - - Session 3B Lunar Ranging Systems	Session 5 Special Topics in Hardware	Session 7 Ranging Software and Data Preprocessing
PM	Chairman and Organizing Committee Meeting of the Session Chairmen and the Organizing Committee	Session 2 Operating Satellite Ranging Systems	Session 4A Calibration and System Errors - - - - - Session 4B Station Timing	Session 6A Special Topics in Hardware - - - - - Session 6B Laser Safety	Session 8 Future Systems New Concepts

Figure 1. Itinerary for the Workshop on Laser Ranging.

The Use of Interkosmos Laser Network for Satellite Geodesy

S. K. Tatevian
The Astronomical Council of the USSR Academy of Sciences

Abstract

Satellite geodesy has two tasks: a geometrically defined one and a physical one. The first is the determination of the geometric shape of the earth and its description through coordinates of terrestrial points; and the second is the determination of the main parameters of the gravity field on the earth's surface and in space. These tasks are the basis of activities being carried out by many scientific organizations. Observational equipment, used for these investigations, includes cameras, which make observations relative to star positions, and laser or radio range equipment, which has geocentric reference. From camera observations, a direction from a terrestrial point to a satellite point can be measured with an accuracy of 2–4 arcsec (1 sec under some conditions). At the present time, 1-m range accuracies can be obtained with first-generation laser systems and decimeter accuracies with second-generation lasers.

Of great significance is the question regarding the contribution to the strength of a geodetic solution given by directions and distances. The model calculations show that if photographic and laser range data are utilized together for a determination of the terrestrial vector between two stations, a range accuracy of 1 m is sufficient for our needs. In 1970 the Astronomical Council of the USSR Academy of Sciences proposed to the scientific community "The Large Arc Arctic-Antarctic Project". The objective of this project was to determine the directions and distance between stations, situated along the meridian of the earth using cameras and lasers. The Arctic-Antarctic project

was adapted by COSPAR in 1971 and many other countries have joined in the project. Simultaneously, preliminary work on the "East-West" traverse has also been undertaken.

In general the Observation Program has been carried out step by step, and consists of series of campaigns, one or two each year, with the participation of different sites. There are many applications for the obtained data in tying local geodetic surveys to global reference systems.

For distance determination required for this Program, the construction of laser range equipment was initiated by the Interkosmos participants in 1970. In 1972 the first stationary version of the Interkosmos laser was put into operation in Czechoslovakia. Now there are 8 Interkosmos lasers: Zvenigarod and Simeiz, (USSR), Borowiec (Poland), Santiago (Cuba), Helwan (Egypt), Ondrejov (CSSR), Kavalur (India) and Patakamaja (Bolivia). In Potsdam (DDR), Penc (Hungary), Gradec Kralove (CSSR) and Simeiz (USSR) improved laser systems are also being made operational.

Laser Observations Obtained by the Interkosmos Network
from July 1977 through December 1977

	Simeiz	Helwan	Borowiec	Potsdam
Geos 1	1942	1723	34	259
Geos 2	3912	1773	345	270
BEB			3	102
BEC	413	899		
Starlette				21

The Scientific Objectives of the
Interkosmos Satellite Geodesy Program

Stations positioning ("Large Arc"). Geometric and short arcs methods. Cameras and lasers of the first generation

Precise orbital computations, orbital methods of satellite geodesy. Cameras and lasers of the first generation.

Polar motion studies. Astronomical and satellite methods.

PROSPECTS FOR EUROPEAN PROGRAMS IN SPACE GEODYNAMICS AND OCEANOGRAPHY

J. Kovalevsky
G.R.G.S./C.E.R.G.A.
Grasse, France

HISTORICAL INTRODUCTION

The first european satellite laser was constructed in France in 1964 by the "Service d'Aéronomie". The first returns were obtained in january 1965 on the Beacon B satellite, only a month after the first return obtained in Goddard Space Flight center.

This was the start of a long period of european involvment in building satellite, and lunar laser ranging systems.

During the last ten years, european systems participated to a number of local or world-wide observing campaigns that led to collect a number of good data that was used in most of the successive Earth models (Standard Earth, GEM, GRIM) and in many others studies (European local laser networks, determination of tidal parameters, search for specific resonance, terms in the Earth gravitational field, determination of zonal harmonics, etc...)

It is also to be mentioned another fundamental european, actually french, contribution to laser ranging : the launch of several satellites with, on board, laser retroreflectors. These were :

DIC and DID, in 1967
PEOLE, in 1970
D5B and STARLETTE, in 1975.

Some of them, especially DIC, DID and more recently STARLETTE were extensively observed by all laser ranging station throughout the world and consequently were and still are used for geodetic and geodynamic studies. Let us also remind that the two retroreflectors deposited by Lunokhod I and II on the Moon are french.

However, although european stationsspecifically participated to many international campaigns, like ISAGEX and "Eurafrique", or to campaigns organized by the Smithonian Astrophysical Observatory, it was always via a direct involvment of various countries in the programs and not as a coordinated european effort. There were many bilateral agreements with the United States, and also with other countries, there were also the agreement given by individual european countries to participate to campaigns generally sponsored by COSPAR, but, till 1977, there were no specific coordinated european effort in the domain of the application of laser ranging to satellites.

This situation had several historical and conjonctural reasons that it is not necessary to discuss here. A major fact, however, was that ESRO (European Space Research Organization) never showed any interest to geodesy, geodynamics, ocean and solid earth physics and related sciences. It is only recently, that its successor, ESA (European Space Agency) started to commit itself in this direction showing its new interest by recently convening, in Schloss Elmau (Germany), a european workshop on Space Oceanography, navigation and Geodynamics (SONG 78 workshop 16-21 January 1978).

The first, and quite successful, attempt to start a european cooperation in Earth Physics was initiated by the Council of Europe in 1971 : a Working Group on Geodynamics was created and played an important role in gathering scientists of various fields of astronomy, satellite geodesy, geophysics and oceanography at the occasion of the now well known "Journées Luxembourgeoises de Géodynamique". No doubt that this group has stirred up european cooperation, in particular in space geodesy. In 1975, a first European Doppler observation campaign (EDOC-1) was organized, followed in 1977 by EDOC 2. In 1977 also, a first European laser campaign (EROS= European Range Observation to satellites) was organized and ran successfully four months with essentially three laser stations in Dionysos, Kootwijk and San Fernando. The satellites that were observed are GEOS 3 and STARLETTE. Finally, at the end of 1976, a group of european scientists made a joint proposal for the european participation to the SEASAT program (SURGE=SEASAT user Research Group for Europe)

PROJECTS IN PROGRESS

Several projects in which european laser stations participate are presently in progress or will start in the nearest future. They are all organized in the frame of cooperative european or world-wide programs. Let us present them

1. Programs coordinated by the COSPAR Ad-Hoc Commitee.

In 1976, COSPAR working group 1 has created an ad-hoc committee under the chairmanship of I I Mueller in order to establish a coordination of the priorities in the observation of satellites. Although there had been difficulties in getting some agencies responsible for the operation of laser stations to apply these recommendations, the three active european stations were following them, to the best of their possibilities (for example, the San Fernando station has not the capabilities to range at LAGEOS). In any case, all the data that has been collected is available for the general use in the scientific community.In Europe, several groups are or have been using these data for the improvment of Earth potential models (GRIM 2),the study of the tidal effects on the Earth, various studies on short arc relative positioning using laser data, the computation of geodetic links between stations, etc...

2. EROS group.

The european cooperation in satellite laser ranging was initiated at a meeting held in Kootwijk in January 1977. Representatives of all west european groups building or already running a satellite laser tracking station were present and agreed to start a long range cooperation between existing and projected european-satellite laser ranging stations. They also expressed "their strong interest in a group representation in the international field". As a start, the EROS preliminary campaign was organized, with a distant goal that all european station could be sufficiently well geodetically linked, so that they may be considered as a unique system of stations. It is expected that this group would continue its cooperative work and coordinate the future european participation to programs involving satellite laser ranging. In particular, this group would coordinate at the european level the participation to the campaigns recommended by the COSPAR ad-hoc committee.

3. SURGE program.

The european participation to SEASAT project is now well defined. During the first stage of the experiment, Northern sea will be used as a test zone for calibration. In this respect, european scientists will provide ground truth concerning gravimetric geoid, model of tides and a levelling network for the Northern sea and its coasts. But also, and this is an essential part of the program, an intensive 6 months tracking campaign will coincide with the calibration period, in order to obtain the best possible trajectories of the satellite to permit the calibration of the altimeter. All european satellite laser stations are to participate to this campaign, together with several Doppler stations. After the calibration period, the laser stations will continue their tracking as a european contribution to the whole project that will permit to many european scientists to obtain and exploit the data acquired by the satellite during its mission.

More generally, it is important to note that in many cases, the ranging data obtained by european stations are not sufficient for independent investigations. They will serve as an exchange for data obtained by non-european countries. It is evident that the more data are collected and the more precise it is, the more it will be valuable for other countries out of Europe, and the more data european scientists will obtain. This is why, european satellite ranging stations play an extremely important role for the european scientific community. The future scientific achievements in space geodesy, geodynamics, oceanography and related fields are dependent on the activity of these stations.

4. Lunar laser ranging

No west-european station is yet engaged in this activity, though some returns have been obtained between 1971 and 1974 from the prototype station in Pic du Midi. Until future stations in Grasse and Wetzell will be ready, the general management of EROLD campaign (Earth Rotation by Lunar Distances) is done by the Bureau International de l'Heure with the cooperation of CERGA in France. This campaign is still pending since still only one lunar laser is operational in the world. So Europe can still expect to play an important role in the world wide network of lunar laser stations which have applications to dynamics of the Moon and of the Earth-Moon system as well as to the study of the rotation of the Earth and the motion of its poles.

PROSPECTS FOR THE FUTURE

The programs described in the proceeding section are by all means important and are effort consuming projects that will guarantee the full time operation of stations and many scientific returns of the european laser stations during the years to come. However, they represent mostly european participation to operations that were generally initiated outside the european community and that are not part of a consistent general scheme.

The task of the SONG 78 workshop in Schloss Elmau was indeed to propose a comprehensive space-oriented program for a european solid Earth physics, oceanography, navigation and geodesy and to identify detailed objectives for this program. As an outcome of this meeting, such a proposal was formulated and although it has not been approuved, several actions may soon be taken by ESA along its lines. This is why I wish to report on this proposal which indicates what might be the direction of the european efforts in space geodynamics and oceanography during the future 10-15 years. As you will see, many space techniques will be involved among which laser ranging plays a major role.

One of the specific features of this proposal is that Europe has a dense coverage by geodetic and geophysical ground networks, so that it should be used as a test area of an exceptional quality. This fact also implies that Europe should have a dense and very accurate tracking support. The proposal splits into two main programs : a solid Earth program and a surface studies program.

1. Solid Earth program (tectonics, positioning system)

The ultimate goal of this program is to have a satellite that can monitor local, regional and - possibly - global relative motions of passive markers installed on ground, ice, etc... Among the scientific objectives of this satellite, there are detailed studies of crustal motions, creep, crustal loading effects, Earth tides, etc... Together with an important network of ground based automatic geophysical stations supplemented by a relay satellite system with sufficient data collection capacity, it is expected to contribute to a recognition of possible correlations of such movements with the occurence of earthquakes. The satellite will also measure vertical and horizontal motions of large glaciers and ice sheets in order to study ice dynamics, ice mass balance, etc...

The preparation of such a precise position determination system is a long term project, estimated to be operational around 1990. It involves three actions that should be conducted in parallel (see fig.1).

A. Earth Rotation and Polar Motion Monitoring Service. Such a service is a must for precise localization systems. A daily precision of 0.2 ms and 0".001 is necessary for the compatibility with 3 cm tracking operations. Three various techniques are envisaged and should be tested in a competitive way.

- A Doppler system, extension of the present MEDOC system, later to be improved for accuracy.

- A laser tracking system including LAGEOS tracking for short period precision and lunar ranging for long term consistency of the measurements.

- A european VLBI system that is already studied by ESA for astronomical and geodynamical applications.

This action is of the world wide importance and it is hoped that european actions will be coordinated with similar programs in other countries, especially in the U.S.

B. Development of a Precise Position Determination System. This part is a technological development project for the next 5 years. It includes space tests in order to make a choice between microwave and laser techniques. It includes also the development of an improved time synchronization system. A first step could be to launch the LASSO-SIRIO II experiment. The principle of this experiment proposed by J. Gaignebet and M. Lefebvre is that the satellite has retroreflectors that permit to determine the distance of stations and a detector which measures, on board, the time separating the arrival of laser pulses coming from the two stations to be synchronized.

C. Ground Based Segment of the Mission. All kind of geophysical instruments, able to register perturbations in the Earth's crust (gravimeters, stressmeters, tiltmeters, magnetometers, seismometers, etc...) should be installed in all areas where disturbances are to be expected. A good test area would be Greece and Turkey. But all these instruments should be automatic and the information send to a data reduction center through a space data retrieval system.

2. Surface studies program (Ocean, ice, gravimetry and vertical motions determination).

The general goal of this program is to provide global informations on ocean surface phenomena. In particular, it has the following objectives :

- To study the general dynamics of the oceans.
- To determine the location of the oceanic tidal dissipation.
- To acquire an improved knowledge of the general oceanic circulation.
- To provide information on the interaction between sea and atmosphere.
- To measure the bulk change of ice caps.

The determination of ocean topography necessitates the determination of a precise (10 cm accuracy) reference surface which has to be the geoid. This is, therefore also a major goal of the program which involves, like the first one, three parallel actions (see fig.2).

A. Determination of a Precise Geoid. It is not possible to know, at present, what technique will be the most suitable to achieve a 10 cm precision for a short wavelenght (200 km or so) description of the geoid. It is therefore necessary to start technological developments and to test the methods during the 7 years to come. This may be a low-low satellite to satellite tracking or gradiometer. These studies should lead to the definition and the launch at the end of the 1980's of a geoid satellite.

It is also to be noted that for the operation of such a satellite, it is also necessary to know with high accuracy the motion of the pole and the rotation of the Earth. Therefore, the first action of the solid Earth program, that is the establishment of a polar motion and Earth rotation service, is also a part of the surface studies program.

B. Oceanographic and ice satellite. Such a satellite may be launched before the geoid satellite since there is no major technical difficulty to overcome. The european participation in the SEA SAT experiments (SURGE) is a fundamental preparation step and will unable an optimum definition of the proposed satellite. The launch around 1985 would permit to obtain with a better precision and resolving power than SEA SAT, many oceanographic parameters. But one would have to wait the launch of the geoid satellite in order to determine the absolute ocean topography.

C. Ground based segment of the Mission. The calibration of the satellite implies a good knowlegde of the real parameters of the sea surface. This implies important campaigns on ocean and ice fields.

Furthermore, the geoid satellite will imply an intensive and very accurate tracking system.

3. Other projects

The SONG workshop has also selected three smaller projects that could support the accomplishment of the two programs just described as well as other ESA missions.

- Monitoring of changes in the magnetic field of the Earth using a low orbiting satellite carrying a 3 component magnetometer.

- Study of the global radiative balance of the Earth for climatology using a spherical homogeneous satellite equipped with a micro-accelerometer.

- Development and testing of navigation systems.

CONCLUSIONS

It is important to stress that the programs described above are not approved projects and it is difficult to say what will really occur. The important point is the recognition of the field by ESA. Actually, several preliminary steps have already been taken, among which :

- A general study of a low-low satellite to satellite tracking system.
- The endorsement of SURGE.
- A phase A study of SIRIO II-LASSO experiment for a possible launch on a test flight of ARIANE.
- A mission definition study of an european space supported VLBI system.

Among the other steps that are not yet taken, but are now specifically requested by european scientists, one may quote an extension with ESA support of the MEDOC experiment, a technical feasability study of low cost mobile laser ranging systems and some technological studies for an oceanographic satellite.

So, there are good reasons to hope that in continuation of the actions in which european laser stations are now engaged , there will be new and exciting european programs in geodynamics, oceanography and ice dynamics requesting a strong support of the european and probably other laser ranging systems.

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FIG.1

Ⓐ **SOLID EARTH PROGRAMME**
(Tectonics Research and Positioning System)

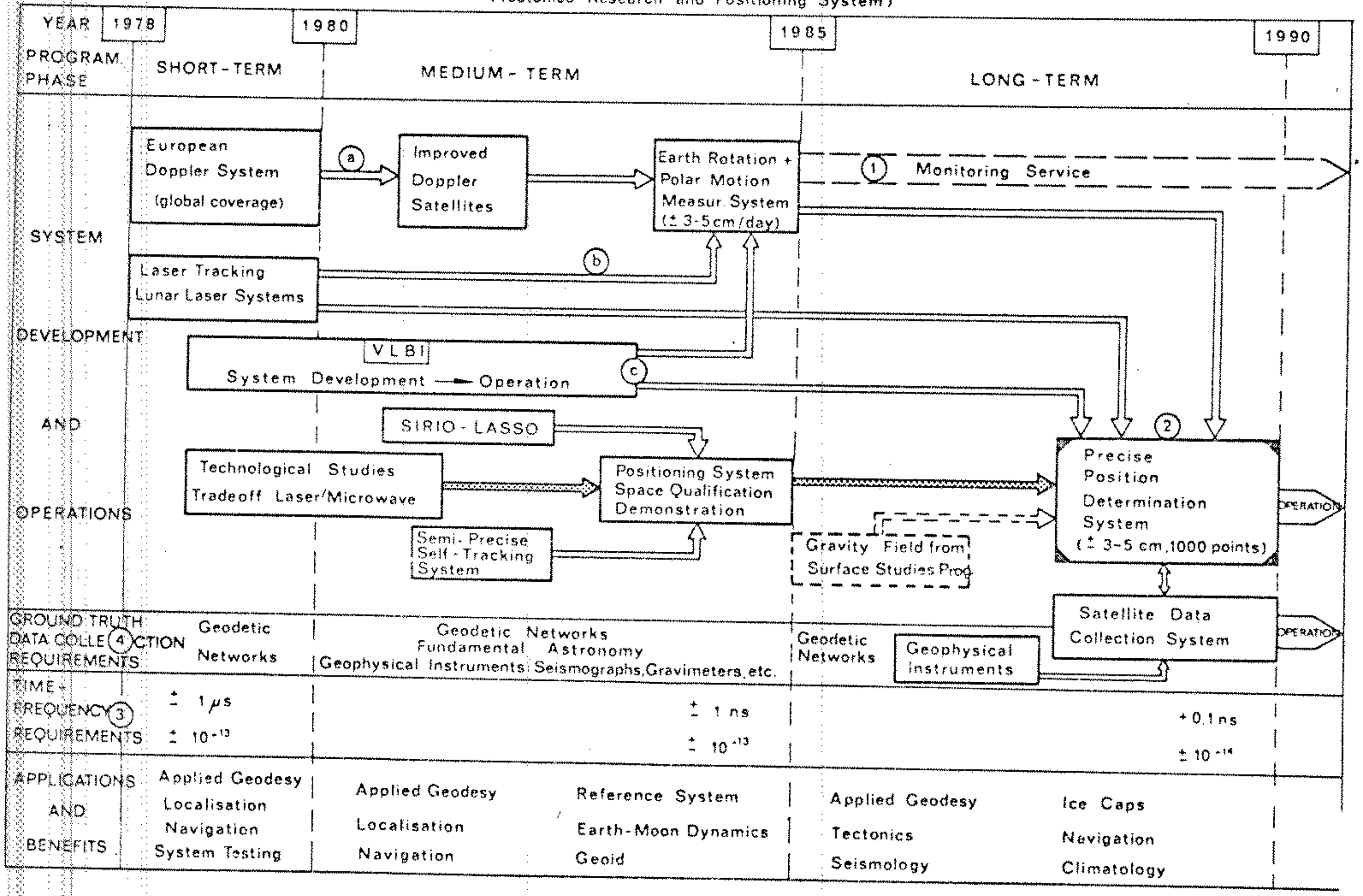
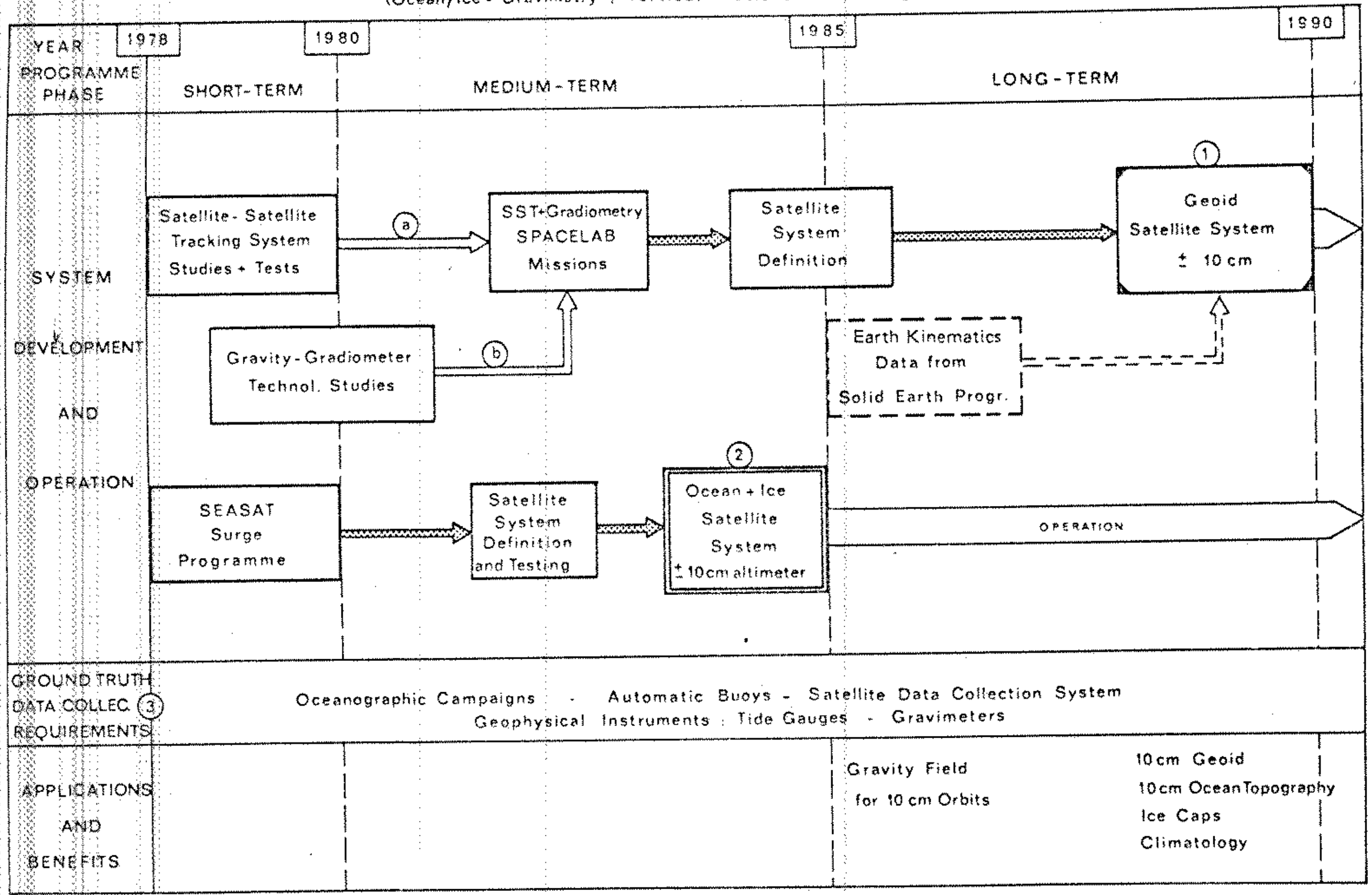


FIG. 2

(B) SURFACE STUDIES PROGRAMME
(Ocean/Ice - Gravimetry , Vertical Motions Monitoring)



SCIENTIFIC GOALS OF LUNAR LASER RANGING

J. Derral Mulholland
University of Texas at Austin, U.S.A.

and

Odile Calame
Centre d'Etudes et de Recherches Géodynamiques
et Astronomiques, Grasse, France

INTRODUCTION

The first direct distance measurement to an extraterrestrial target was accomplished in 1946, when a radar echo was reflected from the Moon; it required six months of data processing to separate the signal from the noise, and the result was probably not better than could have been achieved with classical indirect methods. There was no direct scientific exploitation. Two decades later, the problem of locating landed spacecraft led to exploitation of radar tracking of points on the lunar surface, but scientific applications were of secondary priority.

The Moon was also the target in 1962, when the first laser echos were obtained from an extraterrestrial body. Scientific exploitation soon became the main focus of this technique, with an early suggestion that reflectors be placed on the Moon to provide targets that could be localized with extreme precision. The first reflector was set down by the first man on the Moon, on 20 July 1969. Four additional arrays have been carried aboard Luna 17, Apollo 14, Apollo 15 and Luna 21. Since 1969, the near-daily observing program at McDonald Observatory has permitted a number of important scientific results. Several others remain to be achieved, either because they require data from multiple stations, or covering a longer time span, or of a higher accuracy. A comprehensive statement of the scientific goals of lunar laser ranging (LLR) is to be found in the proceedings of the SALUR symposium[1], where many of the applications summarized here are elaborated, with experimental results as of early 1976.

GRAVITATIONAL THEORY AND THE LUNAR ORBIT

The largest part of the topocentric motion of the reflector is the orbital motion of the Moon. It began by being the least accurately known aspect of the problem, and thus it is where some of the most spectacular improvements were made early in the LLR program. Over the past decade, the absolute accuracy of the numerical lunar ephemeris has been improved by 2-3 orders of magnitude (e.g. Williams[1]), although there are some uncertainties as to whether the means for accomplishing this truly represents improved understanding of the physics; there is much more to be done.

One of the most vexing problems is more procedural than physical: how does one assure that the ephemeris adequately represents the physical situation? The necessary precision is easier to obtain with numerical integration, but one must beware of the possible effects of finite difference approximations to differential equations. The numerical and analytic methods share the problem of including all significant influences in the acceleration model. The use of LLR has led to the inclusion of several effects never before used in the construction of a lunar ephemeris, for example the influence on the orbit of the lunar physical libration. It is far from certain that all such effects have been identified, and LLR can play a major role here.[2]

The 18.6-year precession of the lunar ascending node along the ecliptic (combined with other motions) provides LLR data with a sensitivity to the Earth's obliquity and dynamical equinox. This gives a direct tie to, and capability of improving the celestial inertial coordinate system, an advantage not shared by artificial satellite techniques.

It is an observed fact that angular momentum is not conserved in the lunar orbit, but we still insist that it must be conserved in the Earth-Moon system. As the Moon is observed to gain orbital angular momentum, the Earth is observed to lose it in its rotational motion; the global change is supposed to be zero. How does one observe this change in the lunar orbit? The relative change of the specific orbital angular momentum is, to first order

$$\delta h/h = \delta n/n + 2\ \delta a/a \qquad (1)$$

where n is the orbital mean motion and a the mean distance; a change in h will be exhibited by a change either in n or in a. In fact, both change, as required by Kepler's 3rd law. The secular change in n, referred to as the *tidal acceleration in the lunar mean longitude*, has been studied by several methods; a first determination from LLR data has recently been published[3], but one expects further refinement in the future.

After three centuries, the lunar orbit continues to provide critical tests of gravitational theories. There are at least two ways in which relativity theories can be tested with LLR. A test of the equivalence principle has resulted in a confirmation of Einstein at the *1/2%* level, by showing that the Brans-Dicke scalar field is negligible.[4] An unresolved problem is the existence of a time-variation in the gravitational constant, which would violate Einstein's theory. As can be seen from differentiation of Kepler's 3rd law

$$\delta G/G = 2\ \delta n/n + 3\ \delta a/a - \delta M/M \tag{2}$$

this also involves secular variations in the mean motion and mean distance, but the functional relation between these two parameters is different than for tidal friction.

At present, the only reliable way to determine a current value for dG/dt appears to be to use observations that permit simultaneous solutions for both dn/dt and da/dt. An attempt has been made, but it appears that a considerably longer time span of LLR data is required.[3] In any case, the tidal and cosmological components of the observed dn/dt and da/dt will not be separable without additional independent information, either the formal expression of $G(t)$ or a tidal determination unmixed with the cosmological component; the former might come from astrophysical data, while the latter might come from solar system ephemeris studies. This is the most delicate possible application of LLR, and the possible existence of orbit model errors could easily give invalid results.

LUNAR ROTATION AND MODELS OF THE LUNAR INTERIOR

Cassini's Laws for the lunar rotation are modified by both forced and free librations, due to external phenomena. The forced oscillation is due to the gravitational couples exerted by Earth, Sun and planets on the nonspherical figure. This results in periodic displacements of surface points of about 1 km from the Cassini position, so an accurate knowledge is necessary for locating the reflectors. LLR has already given significant improvements in the theory of the librations. In addition, the problem can be inverted to study the gravity field. New values are already obtained for the 2nd degree and some 3rd degree harmonics (e.g. Williams[1]), and one expects further improvements. Even some of the 4th degree terms produce periodic motions of a few cms, and eventually even these may be resolved.

The free libration is an unforced oscillation resulting from meteorite impacts. These may occur at three frequencies, corresponding to the homogeneous solutions of the differential equations; the periods are about 3, 24, and 75 years. The amplitudes, and even the existence, are controversial. We believe that the 3-year mode has been unambiguously determined from LLR data (Calame[1]), with a tangential amplitude of about 14 m, with less certain determinations of the other modes. Still, the periods are so long that these results are certain to be improved with more data.

The librations are strongly influenced by the structure of the lunar interior. The moment of inertia ratios appear explicitly in the equations of motion, and were among the first parameters to be improved. These can be used (with other data) to determine the principle moment of inertia, a function of the density profile. As LLR data accumulated, it became evident that the density is larger towards the center; the current LLR value is $C/Mr^2=0.392$ (Williams[1]), consistent with a core. If the uncertainty can be reduced further, this will place important constraints on models of the interior.

Internal dissipation will influence both the forced and free librations, which can thus be used to study the elastic properties of the interior. The dissipation function Q will produce a phase lag in the forced librations.[5] The higher-degree gravity harmonics will also introduce phase lag in some of the same frequencies, which presents a difficult parameter separation problem. The first LLR attempt to measure dissipation[6] directly has given the result $Q=10$. We find this unbelievable, because it is about the same value as the tidal Q for Earth, which is due to the liquid oceans. More work is needed here.

Dissipation acts on the free librations to attenuate the amplitudes; essentially Q represents the e-folding time in cycles. If $Q=10$, then there should be no free librations during most of history; they would be damped rapidly compared to the meteorite influx. In the absence of large recent events, Calame's result for the free libration implies a Q of around 5000, which seems consistent with the seismic data. Kovalevsky[1] noted that this result might be evidence of a recent major impact. Hartung[7] has hypothesized a specific event only 800 years ago, and we have found that this is dynamically plausible, but unprovable.[8] Even this event, however, does not permit Yoder's value of 10, which would have damped this specific impact in less than 800 years. The results obtained by studies of the forced and free librations are in violent contradiction.

Another elastic effect that may be accessible to LLR is the solid tide raised by the gravity of Earth, as the Moon moves around its eccentric orbit. If it can be observed, constraints can be imposed on the density profile in the outer layers of the Moon, possibly eliminating some currently-viable models.[9]

Finally, in the distant future, the LLR reflectors should provide high-precision benchmarks for selenodetic control systems.

GEOSCIENCES

LLR is capable of studying the several phenomena that affect the space motion of a point fixed on the Earth's surface. Several sensitivity studies (e.g. [10]) indicate that a network's nominal coordinates can be established with an accuracy comparable to the accuracy of the observations. Thus, one could use the LLR stations as an intercontinental system of geodetic baselines; one such baseline has been determined.[11] Most of the interest, however, arises from the fact that the Earth is not rigid.

We have already mentioned the transfer of angular momentum from Earth to Moon, which arises from frictional losses in the oceans, resulting in a deceleration of the Earth's rotation, corresponding to increasing the length of the day by about 2 msec/cy, with a current uncertainty of 5%.[12] This is very small, and it seems unlikely that LLR will contribute to its improvement for many years to come. There is some evidence (Calame[1]) for unexplained long-periodic fluctuations in the rotation, but it is not yet clear if these are in Universal time, nutation, or some other phenomenon.

Even at short period, the Earth's crust is not fixed relative to the rotation pole, nor is the rotation rate constant. A single station will experience fluctuations in the apparent Universal Time and the apparent latitude, due to processes in the interior of the Earth. Neither the origin nor the mechanism of these processes is understood, and there are random (i.e. unpredictable) components in the motion. A network of several LLR stations is capable of measuring the three components of Earth rotation with an accuracy better than that with which the distance to the Moon is observed (Stolz & Larden[1]). An observing campaign (EROLD) has been organized to demonstrate this, but most of the stations are not yet in full operation. If this can be made to work, LLR has one important advantage over some of the other new methods, in that the data can be fit to a continuous and dynamical-consistent orbit over the entire data span, without the discontinuities inherent in orbit rectification. This is important, because it is widely believed that the Chandler motion of the pole is driven by seismic energy. If this be true, then massive earthquakes will produce discontinuities in the path of the pole; such correlations appear to exist (e.g. Smylie[1]). Orbit rectification may mimic or mask this effect.

Finally, the high geodetic accuracy attainable presents the possibility of studying the relative motion of the stations. Tectonic drift should be readily detectable with LLR systems of 3-cm accuracy.

NINE YEARS AFTER APOLLO 11

We have summarized in the following table the physical parameters that can be studied by lunar ranging, noting whether improved values are already available, or whether this remains for the future. It seems appropriate to end with a few words on the present status. Observations have been attempted from nine sites in five countries, and all nine have reported the acquisition of echos; four of those stations are now dead, but two additional stations have not yet fired at the Moon. Hopefully, both will during 1978. About 2500 high-quality observations now exist, with the addition of about 20-30 new ones per month. In principle, this is adequate for the lunar objectives, although higher accuracy would be desirable. The geophysical goals require that several more of the seven present potential stations produce observations regularly and frequently. We urge that every effort be made in the immediate future to accomplish this.

ACKNOWLEDGEMENTS

Preparation of this paper was partially supported by the U.S. National Aeronautics and Space Administration, under grant NGR 44-012-165, the other part by the Centre d'Etudes et de Recherches Géodynamiques et Astronomiques, Grasse, France.

TABLE 1: PARAMETERS AND PHENOMENA DETERMINABLE FROM LUNAR LASER RANGING

	ATTEMPTED	IMPROVED	FUTURE
Observatory Coordinates and Baselines		X	
Reflector Coordinates and Baselines		X	
Mass of Earth-Moon System		X	
Lunar Orbit Model and Initial Conditions		X	
"Tidal" Acceleration in Orbital Mean Longitude		X	
Relativistic Equivalence Principle (Nordvedt Effect)		X	
Time-Variation of Gravitation	X		
Dynamical Equinox and Obliquity Of Ecliptic	X		
Lunar Libration Model		X	
Lunar Moment of Inertia Ratios		X	
Lunar Gravity Harmonic Coefficients	(X)	(X)	X
Lunar Dissipation Function Q	X		
Free Libration Amplitudes and Phases	X	(X)	
Long-Period Terms in Earth Rotation		(X)	X
UTO and Variation of Latitude	X	(X)	
Universal Time (UT1) and Polar Coordinates			X
Continental Drift			X

Parentheses indicate only a subset of the possible parameters are intended.

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session 2 3A operating satellite laser systems

chairman L. Aardoom /co-chairman H. Seeger

Aardoom

Gaignebet

Gaignebet

Wilson /Nottarp /Seeger

Wilson

McGunigal

Hamal

Pearlman /Lanham /Wohn /Thorp /Imbier /Young

Aardoom /Zeeman

Fischer /Neubert

Johnson /Veis

Cugusi

Bauersima /Beutler /Gurtner /Klockler /Schurer

Halme /Paunonen /Sharma /Kakkuri /Kalliomaki

Yumi /Kakuta

Aardoom

reports from NASA, SAO, Wettzell, Kootwijk, Cagliari
Zimmerwald, Metsahovi, Helwan, Crimea, Dodaira

OPERATING SATELLITE RANGING SYSTEMS; INTRODUCTORY REMARKS

L. Aardoom
Delft University of Technology, Delft (The Netherlands)

Laser ranging is potentially the most precise of the currently operational techniques for tracking artificial satellites from the Earth's surface. This feature is due basically to the high precision of modelling ratios of ranges in terms of ratios of propagation times of light through the refracting atmosphere. On the other hand meteorological conditions can seriously hamper the application of laser ranging. Therefore satellite laser ranging in a global context is a compromise between precision and orbital coverage, the latter as limited by weather conditions. Nevertheless, because of the potential precision, the development of laser ranging equipment and the deployment of such equipment has over the years been an integral part of planning solid Earth and ocean physics studies by means of space techniques. This emphasis on satellite laser ranging is in fact the very reason for holding a sequence of workshops on laser ranging instrumentation.

Initiated to create an international forum for discussing mainly technical items on the level of construction, operation and development it now seems appropriate that these discussions, at least partly, take place against the backgrounds of scientific requirements and the development of complimentary or competing techniques. It is therefore fortunate that the satellite tracking requirements from a scientific point of view will be specified in the first session (1) of this workshop. The issues of that session should be guiding arguments for the work in the present session (2/3A) and in session 3B on lunar ranging systems.

As concerns session 2/3A, first of all the present state of development together with the trends foreseen should be reviewed in broad outline. This then would indicate where the satellite ranging work stands and how it is foreseen to proceed. The issues of session 1 should then be used to control further work as to meet the specified requirements put in a near-, medium and long-term time frame. If sufficiently specific these requirements may be interpreted in terms of concluding issues which then may be adopted to guide the discussions in subsequent sessions. The other way around users of satellite laser data should tune in there requirements to the realistic potentials and planned development of laser ranging and to the intended deployment of equipment.

To promote this dialogue between the users of laser ranging data and those responsible for the construction, operation and development of laser ranging equipment, probably is the main task to be performed in session 2/3A. Such feed-backing dialogue most likely takes place within the larger groups operating a regional or global network of laser stations. Smaller groups eager to contribute to regional or global work, in particular those newly entering the field of laser ranging and those about to make major decisions concerning further development, may however need this dialogue to base their policy on. This in turn is of importance to the entire satellite laser ranging community because a global deployment of facilities is needed in a joint activity to best meet scientific requirements.

Such requirements may be stated in a variety of terms, varying from a vague indication to a specific data request. The requirements will probably concern:
- precision and other data characteristics;
- orbital coverage;
- data formats, in particular as regards information provided;
- deployment of equipment, where and when?

In part these will have to be interpreted in terms of design goals or technical specifications for individual instrumental items, in terms of operation plans and procedures. The deliberations in session 2/3A will have to be structured as to assist in this interpretation where needed.

Without being exclusive, questions which could and possibly should be addressed are:
- what is, practically speaking, the ultimate precision to be achieved by pulsed laser ranging to artificial satellites?
- when is this practical limit supposed to be reached?

- what are the least demanding specifications under which a weather-restricted laser ranging system could, with reasonable scientific prospects, be developed in the next few years?
- noting the advent of precise all-weather satellite observing techniques, what will be the design goals for laser ranging systems by 1980 and by 1985, say?
- what will the critical system components and development steps be?
- which scientific programmes foreseen up till 1985 and eventually thereafter draw on satellite laser ranging?
- which retro-reflecting satellites are planned for launch up till 1985 and thereafter?
- is there a future for immobile laser ranging systems?
- what will be the availability of laser systems, grouped according to criteria of precision, mobility etc, by 1980 and 1985?
- how will such systems most likely be deployed?

The answers to questions like these may be critical as starting points for further planning of satellite laser ranging activities and scientific programmes to be supported by those.

THE CNES SATELLITE RANGING LASER SYSTEMS

Gaignebet J.
GRGS/CERGA
Obs. du Calern - 06460 St Vallier de Thiey

INTRODUCTION

Two systems are working. One, since a long time, is a modified first generation and works in San Fernando, Spain.

The second one "Second Generation" now fixed at Observatoire du Calern near of Grasse, France. This station is under tests.

FIRST GENERATION MODIFIED

- Mount automatic Alt-Az mount open loop encoding
  Resolution 13" of arc
  Accuracy 20" of arc
  Speed 40°/s maximum
  The mount is computer driven with an option of joystick or punch tape.
- Laser: The Laser has been modified by use of a dye cell to have a pulse width of 12ns FWHA , 1J , 1Hz .
- Receiver optic: 36cm Cassegrain telescope gold plated
- Detection: the 56 TVP PMT is used only for day tracking and an RCA 3103A is used by night connected with a 40 db amplifier and a 3 Å, 40% filter
- Tracking scope: we replaced the edge piece by a TV Camera/Nocticon Thomson tube/coupled with a monitor.
  A 12th to 13th magnitude is seen in a nonintegrating mode. Field 1°
- Electronics: 1ns resolution counter. Stop channel is controlled by an automatic gate.

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

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

-Performances: 75cm RMS

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

The expected accuracy should be better than 40cm RMS.

SECOND GENERATION

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

-Laser: Ruby Single mode diffraction limited Laser with the following performances:
2 J per ns pulse width
4 J, 2ns to 15 J, 10ns
repetition rate 0.25 Hz
0.75 J per ns pulse width
1.5, 2ns to 7.5 J, 10ns
repetition rate 0.5 Hz

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

-Receiver optics: 1m Cassegrain telescope Al plated

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

-Tracking scope: 18cm refractor associated with a TV camera/Nocticon Thomson CSF tube/
Field 1°,12 magnitude possibilities on a non-integrating mode

-Electronics: 100 ps resolution counter. Stop channel gated

-<u>Computer</u>: Télémécanique T1600 computer working in a two pass way.
Orbital elements to position and interpolation
A digitizer is used. Thomson System adaptable on a Tektronix 7903 scope.

STATION DE TELEMETRIE LASER

2ème GENERATION

J. Gaignebet
CERGA, 8 bd Emile Zola
Grasse, France

CRITERES DE CHOIX DES SOUS-ENSEMBLES

Les caractéristiques de : portée
précision
conditions de tir

ont déterminé les sous-ensembles suivants :

- laser et son optique associée
- télescope de réception
- tourelle
- ensemble télémétrie (intervalomètre et circuits associés)
- horloge de datation
- calculateur
- optique de reprise
- lunette de visée

le niveau des caractéristiques a été choisi comme suit :

I. PORTEE

Les projets ou lancements de satellites de différentes classes c'est à dire : bas, de faible surface coopérative "Starlette"
hauts, mais plus importants "Lageos"
geostationnaires

nous ont amené à définir une portée opérationnelle égale à 40 M_m sur des satellites du type Geos A.

II. PRECISION

Cette précision est définie comme un écart type soit la moyenne quadratique des résidus par rapport à une trajectoire, théorique, ajustée pour passer au mieux, par la méthode des moindres carrés, parmi les mesures effectuées.

Un progrès important par rapport aux stations dites de 1ère génération (σ = 1,5m) est nécessaire pour rester au niveau des meilleures réalisations étrangères.

Une première étape avec une précision de 15cm a été choisie, la possibilité d'une meilleure précision est prévue mais nécessite un développement ultérieur de la méthode de traitement du signal retour.

III. CONDITIONS DE TIR

Les trois configurations suivantes sont nécessaires pour assurer d'une part, une bonne couverture, d'autre part, une acquisition aisée en début de campagne.

III.1. Tir de nuit sur satellite viable avec une poursuite manuelle

III.2. Tir de nuit en automatique avec une poursuite programmée sur éphémérides.

III.3. Tir de jour en automatique.

Evaluons maintenant l'influence de ces caractéristiques sur les sous-ensembles.

I. PORTEE

La portée est limitée par la possibilité de détecter un signal au milieu des bruits.

I.1. Bilan de Liaison

Le bilan de liaison permet de calculer, pour chaque niveau du signal détecté, la portée de la station. On peut l'exprimer de plusieurs façons dont la plus simple est l'adaptation de la formule de portée des radars faite par Mr. PlotKin.

Soit : W_r l'énergie reçue sur la photocathode du détecteur en photons

W_e l'énergie émise par le laser en photons

θ_e le diamètre angulaire du cône d'émission en radians

αS la surface efficace des réflecteurs en m^2

T_A le coefficient de transmission atmosphérique

T_o le coefficient de transmission de l'ensemble optique de réception

S_r la surface de collection du télescope en m^2

θ_r le diamètre angulaire du faisceau réfléchi par les réflecteurs en rad.

D la distance station satellite en m

la formule de Mr. Plotkin s'écrit

$$W_r = W_e \frac{4 \alpha S}{\pi D^2 \theta_e^2} \cdot \frac{4 S_r}{\pi D^2 \theta_r^2} \cdot T_o T_A^2$$

avec $W_e = 3{,}2\ 10^{18}$ photons par joule pour la longueur d'onde du laser utilisé (Rubis λ = 6943 A°)

Une seconde formule développée par Mr. Fournet utilise un terme d'efficacité du panneau réflecteur tenant compte de plusieurs facteurs :

- angle d'incidence du faisceau sur les n différents réflecteurs
- défauts des trièdres réflecteurs
- diffraction des trièdres réflecteurs
- aberration de vitesse

Ce facteur d'efficacité tient compte de l'attitude du satellite par rapport à la station et varie donc tout au long du passage. On peut en établir une valeur moyenne pour chaque satellite et pour la portée maximale envisagée sur ce satellite. A partir de cet indice $\sum_1^n f\,(G_i)$ il est possible de calculer un α S équivalent

$$\alpha S\,(m^2) = 0{,}24\,(10^4 \theta_r)^2 \sum_1^n f(G_i)$$

Nos possibilités de validation des échos nous conduit à définir un W_r égal soit à 2 photoélectrons , soit à 4 (voir § I_3 protection aux bruits).

I.2. Choix des élements

Au moment de la conception et des premiers appels d'offre de la station, le développement de photocathodes dopées à l'arsenure de Gallium ($A_s\ G_a$) permet de mettre sur le marché des photomultiplicateurs ayant un rendement quantique de 13a 15%, (λ = 6943 A°). Ce progrès considérable (2-3% → 13-15%) compose pratiquement le choix d'un laser Rubis comme émetteur.

Pour pouvoir continuer l'exposé, nous allons partir d'un certain nombres d'hypothèses. Par la suite nous analyserons le pourquoi de ces choix.

les paramètres éclairés sont :

W_r = 16 photons en tirs de nuit
32 photons en tirs de jour
W_e = 3 à 15 joules
θ_e = $2\,10^{-4}$ rad.

α_S = 3,6 $10^{-3}m^2$ (satellite type Diadème) 3.6 $10^{-2}m^2$ (satellite type Geos A)

T_A = 0,7

T_o = 0,4

S_r = 7,8 10^{-1} m^2

θ_r = 5 10^{-5} rad. a 10^{-5} rad.

Nous pouvons calculer la portée minimale obtenue

$$D^4 = \frac{3 \times 3,2\ 10^{18}}{32} \times \frac{4 \times 3,6\ 10^{-3}}{\pi \times (2\ 10^{-4})^2} \times \frac{4 \times 7,8\ 10^{-1}}{\pi \times (5\ 10^{-5})^2} \times 0,4 \times (0,7)^2$$

Soit $D^4 \simeq 2,676\ 10^{30}$

$D \simeq 40\ M_m$

Sur satellite type D_1 en tir de jour

Sur satellite Geostationnaire la portée est obtenue avec le facteur multiplicatif

$$K = \left(\frac{3,6\ 10^{-2}}{3,6\ 10^{-3}} \times 5^2 \right)^{1/4} \simeq 4$$

Soit une portée voisine de 160 M_m

En pratique la portée calculée est optimiste. Le rapport entre cette portée calculée et la portée opérationnelle est en pratique de 3 (valeur déduite de l'expérience de la 1ère génération).

On en déduit des portées efficaces de jour égales à

$D \simeq 13\ M_m$ sur satellites type D1.C ou Starlette

$D \simeq 50\ M_m$ sur satellite Geostationnaire

Ces parties sont obtenues avec W_e = 3j en fait nous avons prévu 3 à 15j à l'émissions. Il semblerait que ces énergies importantes soient surabondantes. Cette surpuissance permettra, par un traitement de la forme de l'écho, d'augmenter ultérieurement la précision.

I.2. Bruits

La portée calculée ci-dessus n'est possible que si le signal reçu peut être discriminé du bruit de fond à la réception.

Deux catégories de bruits se distinguent

bruits internes à la station

bruits externes à la station

I.2.1 Bruits internes . Dans notre cas, la source très nettement prépondérante de bruits est le photomultiplicateur (PM).

Néanmoins, cette source de bruit (10^2 à 10^4 photoélectrons par seconde) est en général négligeable devant les bruits externes. Il n'est pas nécessaire de refroidir le PM et seule une climatisation (18 à 20°) l'empêche de se détiorer si la température externe devient trop élevée (30 à 45°).

I.2.2 Bruits externes. Ces bruits sont dus à la lumière collectée par le télescope en dehors de la réflexion de l'impulsion Laser.

Le tableau suivant fournit un ordre de grandeur des bruits avec les paramètres suivants :

Télescope de ϕ = 1m
Champ objet du télescope 2.10^{-4} rad.
Bande passante SA° centrée sur λ = 6943 A°
$T_o = 0.4$
Rendement quantique du PM = 0,13

Photoélectrons Bruits en seconde	Source de bruit
$1.7\ 10^2$	Ciel nocturne sans lune
$5\ 10^2$	Ciel nocturne à 20° de la pleine lune
$2.5\ 10^3$	Ciel nocturne à 10° de la pleine lune
$1.7\ 10^2$	Satellite D1.C éclairé
$5\ 10^7$	Lune éclairé dans le champ
$1.7\ 10^8$	Ciel diurne
$2.5\ 10^3$-10^4	Fluorescence du laser 5nS après l'émission
$6\ 10^3$	Etoile polaire dans le champ

Il faut noter que dans le cas d'un photomultiplicateur rapide où l'impulsion d'un photoélectron unique présente une largeur à mi-hauteur, égale à 3nS la fréquence limite où l'on peut considérer le bruit comme une succession d'impulsions discrètes est : $f \simeq (3\ 10^{-9})^{-1} \simeq 3\ 10^{8}$ Hz ce qui est assez voisin des valeurs obtenues de jour ou sur la lune éclairée.

Il est évident que, puisque le temps d'aller et retour de la lumière est de l'ordre de 10^{-2}s pour un satellite proche il est nécessaire de disposer de dispositifs pour éliminer le plus possible les arrêts du compteur sur le bruit.

Les moyens à notre disposition pour éliminer ces "faux échos" sont de deux origines :

I.2.2.1 <u>Optique</u>

- réduction du champ objet du récepteur
- réduction de la bande passante du filtre interférentiel

I.2.2.2 <u>Electronique</u>

- génération d'une porte encadrant le moment prévu de l'écho
- déclenchement de niveau
- déclenchement par un système de coïncidence

Traitons sucessivement ces différents moyens

I.2.2.1.a Réduction du champ de récepteur (1)

Il est difficile d'adapter un champ inférieur à 2.10^{-4} rad. Néanmoins toute amélioration du télescope, du système de poursuite, des éphémérides et qui permettent de réduire le champ , sont directement rentables car le bruit croît comme le carré de ce champ.

I.2.2.1.b Réduction de la bande passante du filtre

Un filtre interférentiel étroit (1,5 à 5 A°) est interposé sur le trajet du faisceau lumineux entre le télescope et le photodétecteur.

Cette valeur a déjà été choisie en fonction des possibilités de la technologie au moment de l'achat des filtres. Il est difficile de descendre audessous avec des filtres classiques.

Une étude est en cours au CERGA pour essayer de réaliser des filtres avec une bande passante de 0,6 à 0,2 A°. Ceci permettrait une réduction du bruit d'un facteur 3 à 10.

I.2.2.2.a Génération d'une porte

Les éphémérides nous fournissent les éléments de position du satellite par rapport à la station et en particulier la distance.

Il est donc possible de calculer le temps τ mis par l'impulsion pour son trajet aller et retour, donc l'instant $T + \tau$ ou le retour doit se produire.

Un système de porte n'autorise l'arrêt du compteur, après un tir laser, que pendant une durée centrée autour du temps $T + \tau$

(1) une note annexe traite du problème plus spécifiquement

A l'heure actuelle, les incertitudes sur la position du satellite ne permettent pas de réduire cette porte au-dessous de $10 \mu s$; exceptionnellement, et dans les cas difficiles on pourra essayer $5 \mu s$.

Le tableau suivant fournit les probalités de "faux échos" dans les conditions précédentes

Bruits internes $10^3 \times 10^{-5}$	10^{-2}
Ciel nocturne sans lune $1,7\ 10^2\ .\ 10^{-5}$	$1.7\ 10^{-3}$
Ciel nocturne à 20° de la pleine lune $5.10^2.10^{-5}$	$5\ 10^{-3}$
Ciel nocturne à 10° de la pleine lune $2.5\ 10^3.\ 10^{-5}$	$2.5\ 10^{-2}$
Satellite D_1 éclairé $1,7\ 10^2.\ 10^{-5}$	$1.7\ 10^{-3}$
Lune éclairée dans le champ $5.10^7.\ 10^{-5}$	$5\ 10^{-2}$
Ciel diurne $1.7\ 10^8 \times 10^{-5}$	$1.7\ 10^{-3}$
Fluorescence du laser 5nS après l'émission $10^4.\ 0$	0
Etoile polaire dans le champ $6 10^3.\ 10^{-5}$	$6\ 10^{-2}$

Ces différents bruits étant indépendants, il faut additionner les probabilités de "faux échos" dans chaque condition de tir. Cette porte est donc en principe suffisante dans de bonnes conditions de tir (nuit assez loin de la lune), et avec des éphémérides précises. C'est effectivement le procédé employé par beaucoup de stations.

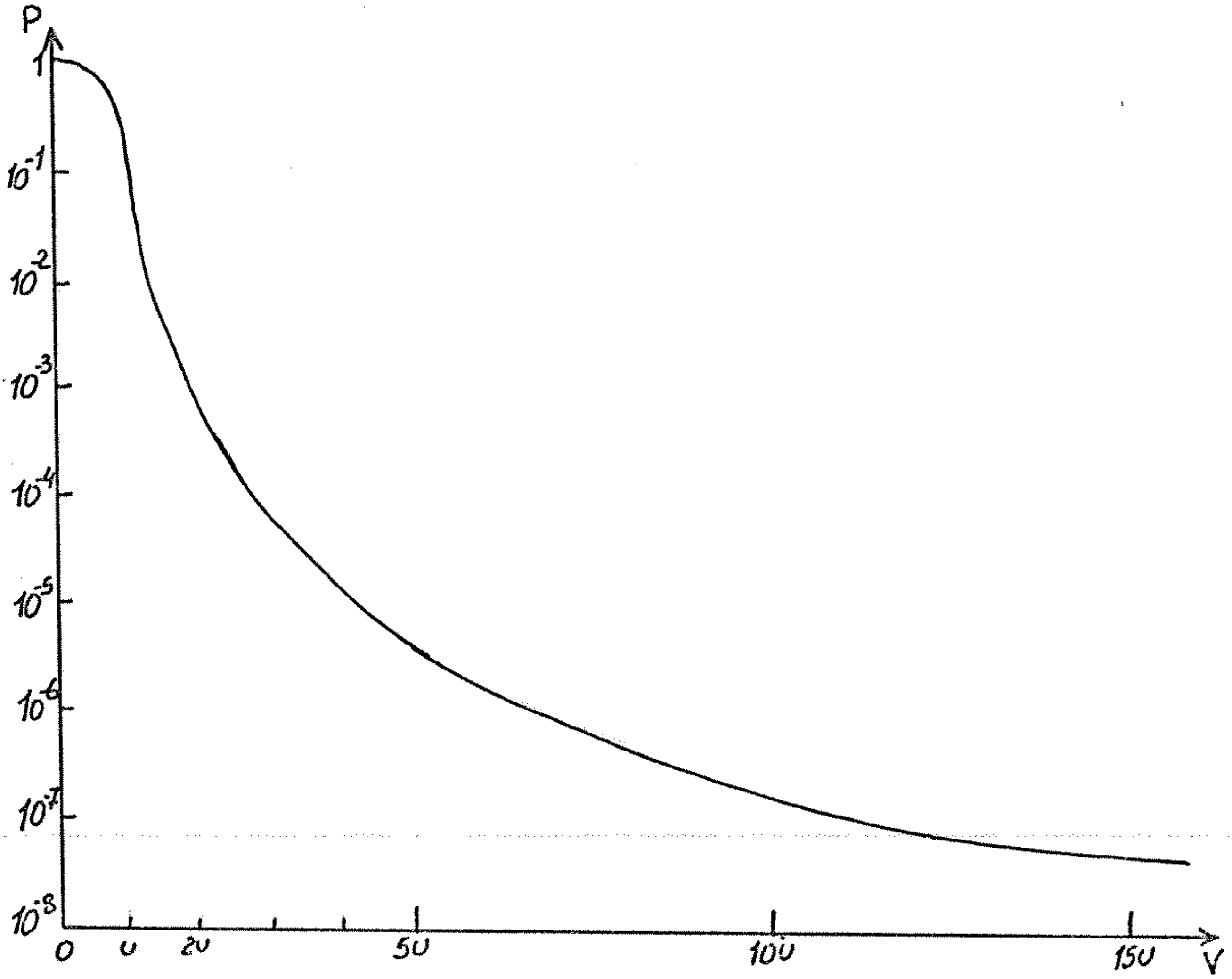
I.2.2.2.b Détection de niveau

Ce procédé classique revient à réduire le gain de l'ensemble de la collection et de la détection.

On diminue l'amplitude de l'ensemble du signal bruité et l'on fixe un seuil qui sélectionne statistiquement le signal seul.

La courbe ci-dessous représente la probalité de répartition des photoélectrons de bruit en fonction de leur niveau.

Si U représente cette moyenne, on voit par exemple que la probabilités pour avoir des impulsions de bruit de niveau V = 2 U est de 10^{-2}



P probalité pour qu'une impulsion de niveau donne V apparaisse
U niveau moyen des impulsions de bruit

Si nous appelons : p la probalité désirée de faux écho
t le temps d'ouverture de la porte
P la probalité pour qu'une impulsion de bruit dépasse le niveau V
M la fréquence moyenne d'apparition des impulsions de bruit

Nous avons la relation

$$MtP = p \quad \text{ou} \quad P = \frac{p}{Mt}$$

Si par exemple nous prenons

$p = 10^{-2}$ $t = 100 \mu s$ $M = 10^4$ photoélectrons s^{-1}

$$P = \frac{10^{-2}}{10^4 \times 10^{-4}} = 10^{-2}$$

Sur la courbe nous obtenons V = 2 U

Pour avoir V = 2 U il faut qu'il y ait au moins deux photoélectrons superposés pendant le temps de retour de l'impulsion laser.

Cette impulsion est au moins égale à la largeur de l'impulsion laser émise qui est elle-même beaucoup plus large, en général, que les impulsions de bruit du photodétecteur.

Ceci signifie que dans le meilleur des cas (impulsion émise très courte ($\leqslant$ 1nS) et fonction de transfert du satellite très étroite) il faut deux fois plus de photons de retour que dans une détection simple. En général, pour des impulsions laser plus longues et (ou) une mauvaise fonction de transfert du satellite le facteur multiplicatif est beaucoup plus important (un traitement mathématique voisin de celui développé pour les coïncidences peut être fait. Il faut noter que si le signal reçu est très puissant, c'est à dire si les photoélectrons ne sont pas séparés, le rapport est effectivement égal à 2. Comme nous allons le voir, à réduction de portée égale ou inférieure, le bruit admissible par une coïncidence à 2 photoélectrons est beaucoup plus important que celui admis par une détection de niveau de rapport 2.

I.2.2.2.C Auto déclenchement d'une porte par l'impulsion de retour

Nous grouperons dans cette rubrique plusieurs procédés :

- système de coïncidence temporelle
- système de coïncidence spatiale
- système de coïncidence mixte spatio-temporelle

Ces méthodes mettent à profit la très grande concentration temporelle de l'émission d'un laser déclenché.

I.2.2.2.C.a. Coïncidence temporelle

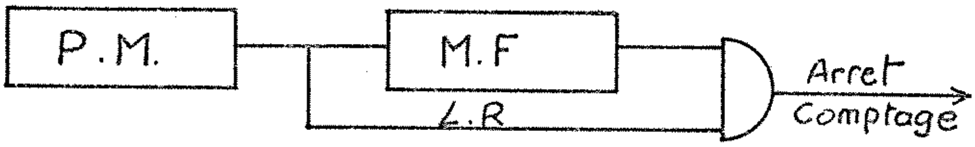
Le principe est de n'accepter un signal que s'il présente la caractéristique de comporter au moins n photoélectrons pendant une durée égale ou très légèrement supérieure à celle de l'impulsion de retour.

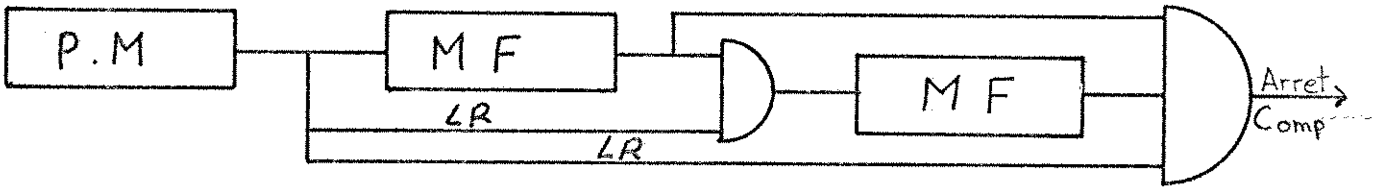
Le signal issu du photodétecteur est divisé en deux. Une des voie attaque un circuit de mise en forme qui fournit une impulsion de sortie normalisée à une largeur légèrement supérieure à la durée de l'impulsion de retour prévue.

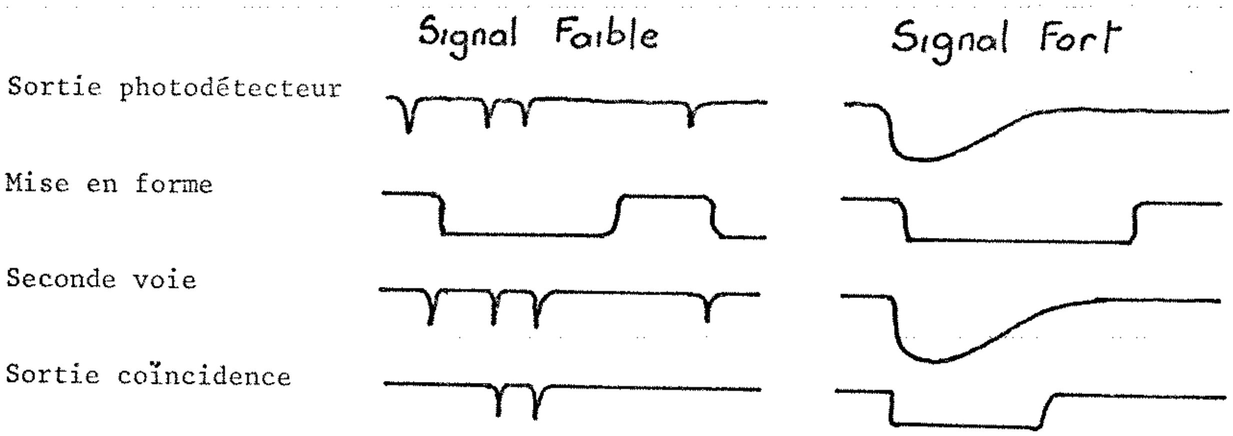
La seconde voie après passage dans une ligne à retard attaque une porte commandée par le signal mis en forme.

L'impulsion de la seconde voie doit se présenter à l'entrée de la porte juste avant celle venant de la première voie, de sorte qu'il n'y ait d'impulsion en sortie que si l'impulsion du photodétecteur est, soit : plus large que celle de bruit, soit multiple dans le temps d'ouverture

Schémas







Si nous admettons que l'émission du photodétecteur est un processus de Poisson.

Le nombre q d'électrons émis dans l'intervalle Θ a pour moyenne $M\Theta = p$ (M bruit moyen du photodétecteur en impulsions s^{-1}) et pour probalité d'apparition $\pi(q) = e^{-p} \frac{p^q}{q!}$

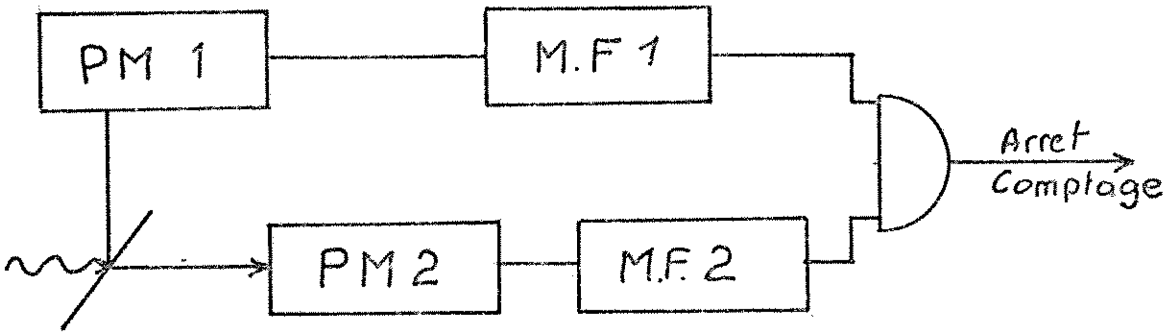
La probalité de fausse alarme dans un intervalle est donc

$$P_\Theta (q \geq n) = \sum_{q=n}^{q=\infty} \pi = \sum_{q=n}^{q=\infty} e^{-p} \frac{p^q}{q!}$$

Si on admet que dans le temps d'ouverture t il y a $\frac{t}{\Theta}$ intervalles élémentaires indépendants, la probalité globale de faux écho est :

$$P_\Theta = \frac{t}{\Theta} e^{-p} \frac{p^n}{n!} \quad \text{ou} \quad p = M\Theta$$

I.2.2.2.C.b Coïncidence spatiale



le faisceau de retour est distribué sur deux photodétecteurs. Les signaux issus de chacun d'eux sont mis en forme puis attaquent une coïncidence à 2 voies.

Il est possible par ce procédé d'effectuer des coïncidences sur plus de 2 photoélectrons en répartissant le faisceau sur plus de 2 photodétecteurs. On notera que chaque photodétecteur ne reçoit plus que la moitié du flux collecté, ce qui permet de doubler la fréquence de bruit sans saturer le photodétecteur tant du point de vue électronique (impulsions de bruit discrètes), que du point de vue électrique (dissipation maximum).

Si nous supposons, comme précédemment, que l'émission des électrons suive une loi de Poisson et que tout électron émis soit détecté. Si le signal reçu comporte P électrons et si le détecteur nécessite n électrons, le possibilité de manquer le signal :

$$P'_n = \sum_{K=0}^{K=n-1} e^{-p} \frac{p^K}{K!}$$

Si l'on divise ce signal en deux pour attaquer deux détecteurs fixés à n/2 électrons (n pair), et dont on exige que les deux se déclenchent, la probabilité de manquer le signal devient :

$$P''n = 1 \; (1-e^{-p/2} \Sigma)^2 \quad \text{avec} \quad \Sigma = \sum_{p=0}^{n/2-1} \frac{\left(\frac{p}{2}\right)^K}{K!}$$

$$P''n = 2e^{-p/2} \Sigma - e^{-p} \Sigma^2$$

Soit, dans le cas où n=2

$$P'_2 = e^{-p} (1+p) \qquad P''_2 = 2e^{-p/2} - e^{-p}$$

$$\frac{P''_2}{P'_2} = \frac{2e^{p/2-1}}{1+p} \quad \text{toujours supérieur à 1}$$

En particulier, en limite de portée où P est égal à 2

$$P'_2 = 3 \; e^{-2} \simeq 0,4$$

$$P''_2 = 2 \; e^{-1} \simeq 0,6$$

Nous n'effectuerons pas le calcul pour un système où la division est supérieure à 2 (équivalent de la détection sur coïncidences temporelles $n > 2$) car le montage devient assez complexe et le rapport de sensibilité décroît encore.

Par contre, un système à coïncidence spatiale présente aux bruits une protection plus efficace car les émissions de deux photomultiplicateurs ne sont pas absolument pas corrélées. En effet, l'émission électronique d'une photocathode n'obéit pas parfaitement à une loi de Poisson, il y a au contraire une émission de "rafales d'électrons".

I.2.2.2.C.c Coïncidence spatio temporelle

Dans le schéma de la coïncidence spatiale précédent on impose à chaque photodétecteur de fournir au moins une impulsion de signal durant l'intervalle Θ.

Si An représente le $n^{ème}$ signal issu du 1er photodétecteur pendant un intervalle Θ.

Si Bn représente le $n^{ème}$ signal issu du $2^{ème}$ photodétecteur, le signal d'arrêt du chronomètre C peut être représenté dans l'intervalle Θ par :

$$C = (A_1 + A_2 \ldots\ldots + A_l \ldots\ldots) \quad . \quad (B_1 + B_2 + B_3 \ldots\ldots B_n \ldots)$$

En limite de portée, le minimum imposé est :

$C = A_1 \, . \, B_1$ (coïncidence spatiale à 2 voies)

On peut revenir à la sensibilité de la coïncidence temporelle à 2 photoélectrons en représentant le signal d'arrêt C par

$$C = A_1 \, . \, B_1 + A_1 \, . \, A_2 + B_1 \, B_2$$

C'est à dire que l'arrêt ait lieu

Soit si la coïncidence spatiale fonctionne

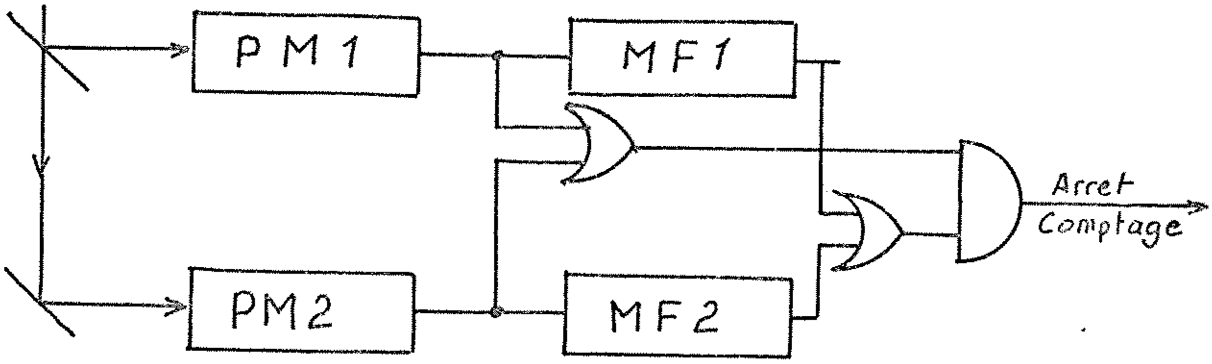
$$C = A_1 \cdot B_1$$

Soit si une coïncidence temporelle sur un des 2 photodétecteurs fonctionne

$$C = A_1 \cdot A_2$$

$$C = B_1 \cdot B_2$$

Le schéma suivant est un exemple possible de réalisation de ce circuit



Cette méthode combine en grande partie les avantages des deux procédés et peut être généralisée à plus de 2 photoélectrons.

L'optique de reprise est mécaniquement prévue pour réaliser un système à deux voies et permet donc l'adaptation de coïncidences :

soit, temporelle sur 2 ou 3 photoélectrons
soit, spatiale sur 2 photoélectrons
soit, spatio temporelle sur 2 à 6 photoélectrons

II. DETERMINATION DE LA PRECISION

On peut séparer les erreurs en deux groupes :

II.1. Erreurs Systématiques

II.2. Erreurs Aléatoires

II.1. Erreurs Systématiques

II.1.1. Erreur sur la vitesse de la lumière

Les résultats obtenus sont en secondes-lumière, la conversion en unités métriques s'obtient avec une erreur de l'ordre de 10^{-8} actuellement.

II.1.2. Fréquence de l'oscillateur local

Cet oscillateur pilote tant la chronométrie que la garde temps de la station horaire. Sa stabilité est de l'ordre de 10^{-13} (Cesium). L'erreur de chronométrie qui en résulte sur satellite est extrêmement faible $\ll$ à 1mm.

II.1.3. Définition de la grandeur mesurée

Ni la station, ni le satellite ne sont ponctuels, pour le satellite on portera une correction moyenne, en tenant compte de la position des réflecteurs par rapport au centre de gravité.

Des satellites tels que STARLETTE ou LAGEOS ont été étudiés pour minimiser cet effet et l'incertitude est réduite à des valeurs aussi faibles que quelques mm. Ce sont ces satellites qui doivent permettre l'évaluation de la précision de la station.

D'autre part, le point de référence fixe de la station est choisi à la croisée des deux axes. Ce point a un mouvement par rapport à l'embase de la tourelle très inférieur au mm.

II.1.4. Synchronisation horaire

Il est évident que la datation de l'heure de tir est extrêmement importante.

La solution actuelle est de se synchroniser sur un étalon connu.

Les moyens actuels permettent de synchroniser l'heure station sur le Temps Atomique à une valeur inférieure à 1 μs dans les pays développés (Europe, Amérique du Nord) par les méthodes de synchronisation télévision ou par le réseau Loran C.

La vitesse radiale des satellites étant au maximum de 5km s^{-1} ceci introduit une erreur externe à la station de télémétrie, égale à 0.5 cm. Dans les pays ayant un support technique horaire moins développé, un oscillateur "Cesium" associé à une synchronisation VLF et à des transports d'heure relativement fréquents (1/mois) doit permettre de déterminer l'heure des tirs par rapports au TUC avec un écart inférieur à 2 μ s (soit un ΔD $<$ 1 cm).

II.1.5. Réfraction troposphérique

Il serait illusoire de concevoir des stations de télémétrie laser ayant une précision de quelques décimètres, à fortiori de quelques centimètres, si les perturbations inconnues introduites par la réfraction troposphérique étaient plus importantes.

Un certain nombre d'études ont été entreprises à ce sujet, en particulier par H.S. Hopfield. Les résultats suivants sont tirés de ses hypothèses et résultats.

Le passage de l'impulsion optique à travers la troposphère, introduit un accroissement de la durée du trajet. La connaissance de l'indice de réfraction le long du chemin optique fournit la correction à apporter sur la distance mesurée. L'étude de H.S.Hopfield permet de déterminer cette correction en fonction des conditions météorologiques locales.

Soit N l'indice de réfraction de la troposphère en un point. Nous le diviserons en deux composantes Nd et Nw, composante sèche et humide de cet indice local.

$$N = Nd + Nw$$

$$\text{ou} \quad Nd = \frac{77{,}6}{T} P$$

$$Nw = 3{,}73.10^5 \frac{e}{T^2}$$

avec P : pression totale en millibars.

e : pression partielle de la vapeur d'eau en millibars.

T : température absolue en °K.

Si nous admettons une décroissance linéaire de la température en fonction de l'altitude, la fraction sèche de l'indice de réfraction s'exprimera par la formule :

$$Nd = N_o d \left[\frac{\frac{T_o}{\alpha} - H}{\frac{T_o}{\alpha}} \right]^{\mu}$$

$$\text{où } \mu = \frac{9}{R\alpha} - 1$$

$N_o d$ et T_o : indice de réfraction et température de la surface au niveau 0 (niveau de la mer).

α : le coefficient de crécroissance de la température

R : constante de gaz : PV = RT

avec $\alpha = 6{,}8°C/Km$ et $\mu = 4$

$$Nd = \frac{N_s d}{(hd-hs)} (hd-h)^4 \qquad h \leqslant hd$$

de la même façon

$$Nw = \frac{N_s w}{(h_N-hs)} (hw-h)^4 \qquad h \leqslant hw$$

où les indices s correspondent aux conditions au sol qui peuvent être différentes de celles du niveau de la mer. hd et hw les altitudes équivalentes pour lesquelles Nd et Nw deviennent respectivement nuls.

On déduit de ces formules les temps de trajet :

$$\int_{hs}^{hd} Nd \; dh = \int_{hs}^{hd} \frac{N_s d \; (hd-hs)}{5}$$

$$\int_{hs}^{hd} Nw \; dh = \int_{hs}^{hd} \frac{N_s w \; (hw-hs)}{5}$$

Les facteurs hd et hw de ces équations théoriques sont ajustées en utilisant la méthode des moindres carrés de façon à rendre compte des résultats expérimentaux avec la meilleure approximation possible.

Les valeurs trouvées sont de la forme :

$hd = h_o + a_d$ TC où $h_o d$ est la valeur de hd quand la température au sol est de 0°C

ad est le coefficient de température de hd TC en °C

Les valeurs numériques sont les suivantes :

hd = 40,082 Km

ad = 0,14898 Km/°C

de même

$hw = h_o w + a_w$ TC

avec

$$h_ow = 13,268 \text{ km}$$

$$a_w = -0,09796 \text{ km/°C}$$

Ceci fournit la valeur zénithale du temps de trajet à travers la troposphère avec une précision de quelques mm sur la composante sèche $\int Nd\, dh$ de quelques cm sur la composante humide $\int N_w dh$ l'ensemble $\int N\, dh$ étant déterminé à 1% sur une valeur zénithale de l'ordre de 2,5 m.

Depuis cette étude d'autres ont été réalisées, tenant compte non seulement des conditions locales au niveau de la station, mais aussi des conditions au sol autour de cette dernière (10 à 50 km), ce qui permet d'établir un modèle d'atmosphère anisotopique. La correction de réfraction peut alors être calculée avec une précision de quelques millimètres.

II.1.5. Constante d'étalonnage

Un certain nombre de retards électroniques existent dans la station et se compensent plus ou moins. La somme de ces retards fournit la constante d'étalonnage ou décalage fixe de la grandeur mesurée.

L'étude de la précision d'appareillage de la station se fait en négligeant tous ces facteurs qui déforment l'orbite d'un satellite de plusieurs façons :

- soit, par une homotélie par rapport à la station dans le cas d'erreur sur la vitesse de la lumière ou d'écart de fréquence de l'oscillateur local.

- soit, par un biais constant lors d'erreur de définition de la grandeur mesurée et de la constante d'étalonnage.

- soit, par un décalage des noeuds ascendants de l'orbite dans le cas d'erreur de datation

II.2. Erreurs Aléatoires

La mesure est le temps entre le centre de l'impulsion de départ et celui de l'impulsion de retour.

Si nous prenons $e^{-P} = 1$ ($M\Theta \ll 1$) et limitons le développement au premier terme

$$P(q \geq n) = \frac{p^q}{q!} \quad \text{donc}$$

$$P_t = \frac{t}{\Theta} \frac{p^n}{n!} = \frac{t}{\Theta} \frac{(M\Theta)^n}{n!}$$

Calculons la limite de bruit admissible dans les mêmes conditions que la détection de niveau étudiée au paragraphe $I.2.2.2._b$ soit :

$t = 100 \mu s$ $\quad P = 10^{-2}$ $\quad n = 2$ $\quad$ et pour deux intervalles élémentaires Θ = 4nS et Θ = 12nS (Θ est la durée de la porte autodéclenchée)

$$M = \sqrt[n]{\frac{n!\,P}{\Theta^{n-1}\,t}}$$

$t = 100 \mu s$ $\quad P = 10^{-2}$ $\quad n = 2$ $\quad$ = nS $\longrightarrow$ $M = 2.2\ 10^5$

$t = 100 \mu s$ $\quad P = 10^{-2}$ $\quad n = 2$ $\quad$ = 12nS $\longrightarrow$ $M = 1.3\ 10^5$

(l'hypothèse $M\Theta \ll 1$) est bien vérifiée)

Les bruits admissibles sont donc beaucoup plus élevés que pour une détection de niveau qui, dans pratiquement tous les cas, amène une perte de portée de loin supérieure.

Si nous adoptons les valeurs limites pratiques suivantes :

$t = 100 \mu s$ $\quad P = 10^{-2}$ $\quad n = 3$ $\quad$ = 3ns

On en déduit $\quad$ M maximal égal à 4.10^6

$t = 10 \mu s$ $\quad P = 10^{-2}$ $\quad n = 3$ $\quad$ = 3ns

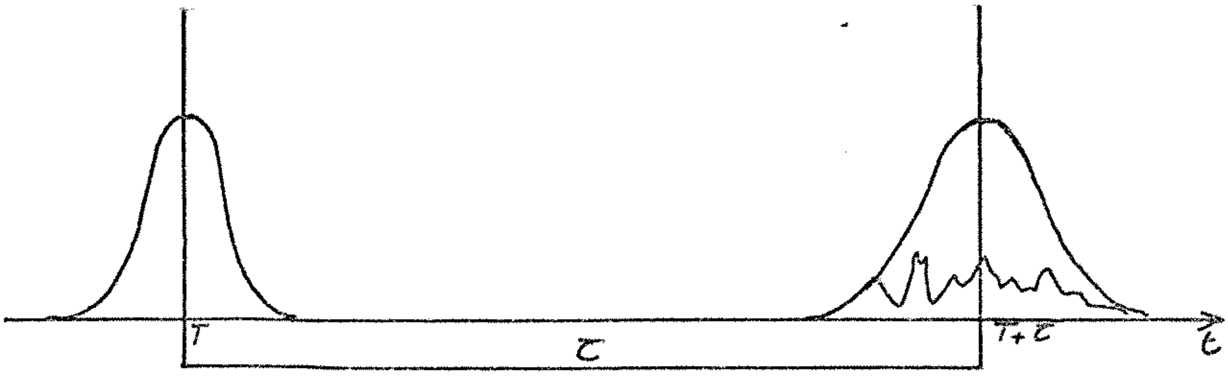
M devient voisin de 10^7

donc, sauf en tir de jour ou avec la lune éclairée dans le champ la probabilité de faux écho est très faible.

En réalité, le raisonnement ci-dessus néglige le fait que les intervalles Θ divisant t sont juxtaposés alors que l'instant initial d'un intervalle Θ susceptible de comprendre plus de n photoélectrons est en fait quelconque. Le calcul exact donne :

$$P_t = \frac{t}{\Theta} \frac{p^n}{(n-1)!}$$

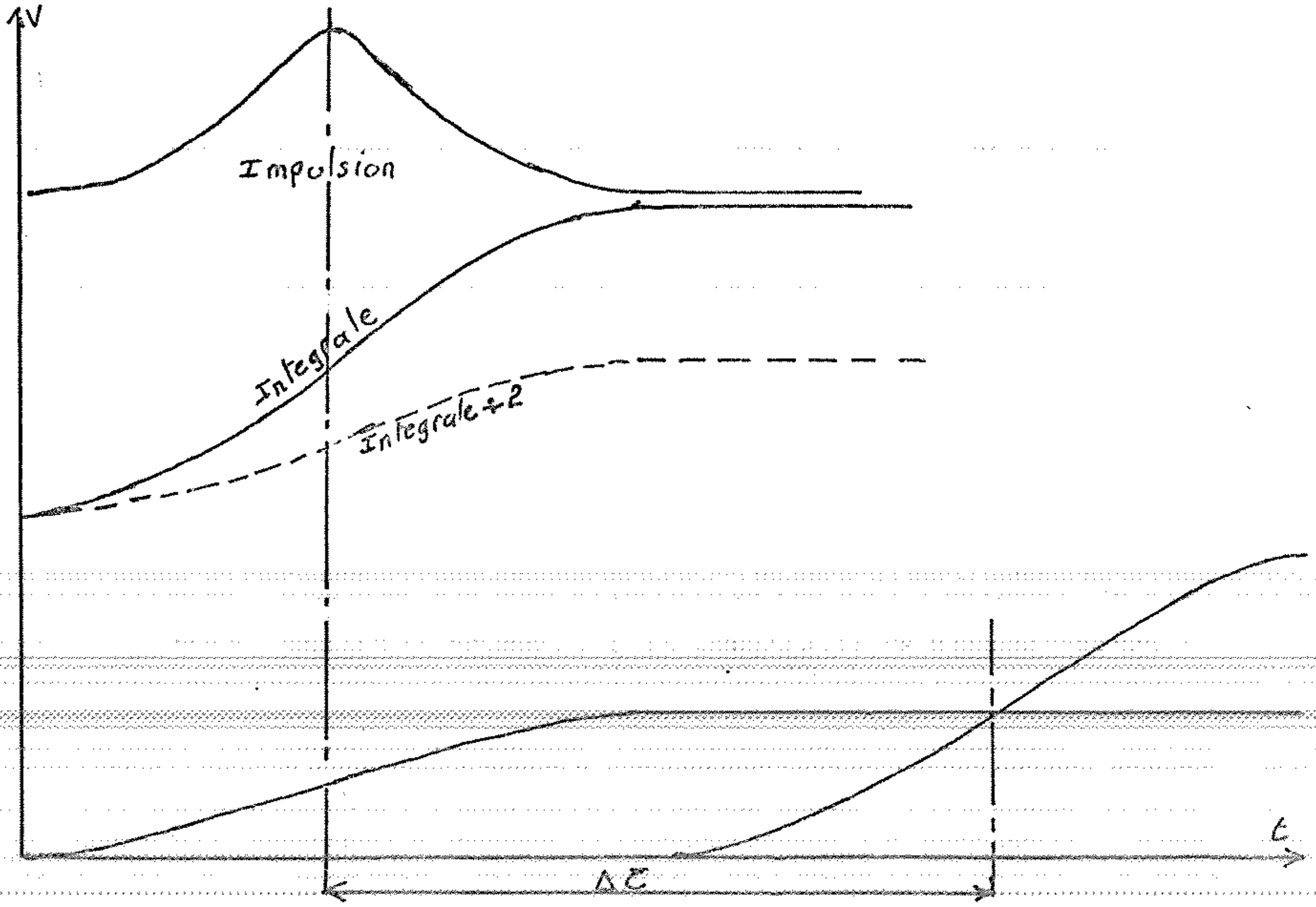
Ce calcul simplifié fournit donc un calcul optimiste d'un facteur égal au nombre de photoélectrons choisi dans la coïncidence.



Si nous supposons qu'aucun phénomène aléatoire n'intervient, la forme de l'écho est celle de départ convaluée par la fonction de transfert du satellite cible. Si nous admettons que les deux sont des phénomènes Gaussiens, le temps de mesure est le temps pris entre les deux centres des courbes. Ces deux datations sont tributaires de variations aléatoires.

II.2.1. Déclenchement de la chronométrie

Nous avons adopté un système de détection centroïde. Pour cela, nous intégrons l'impulsion qui est ensuite distribuée sur 2 voies de rapport de tension 1 à 2. La voie de niveau le plus haut est retardée d'une durée au moins égale à celle de l'impulsion. Un comparateur rapide génère une impulsion au croisement des deux signaux



quel que soit le niveau de l'impulsion le moment daté est le centre de gravité de l'impulsion.

Les premiers essais du système réalisé à l'heure actuelle définissent un écart type sur $\Delta\tau$ de l'ordre de 50 PS pour des énergies laser variant de 2 à 15 j et des largeurs d'impulsion θ variant de 2 à 10 nS

II.2.2. Arrêt de la chronométrie

L'amplitude et la forme de l'impulsion de retour sont aléatoires. En cas d'échos faibles, cette forme peut même être représentée par des impulsions de photoélectrons uniques disjointes.

Dans le cas de fonctionnement sur des coïncidences, le déclenchement se produit sur le second photoélectron.

On peut estimer qu'en cas d'écho fait, on a un déclenchement avant le sommet avec un décalage moyen de $\frac{\theta}{3}$ et un écart type égal à $\frac{\theta}{10}$ en cas d'écho faible, le déclenchement se produit après le sommet avec un décalage moyen de + $\frac{\theta}{3}$ et un écart type égal à $\frac{\theta}{3}$

II.2.3. Erreur due à la résolution du compteur

Dans notre cas, le compteur a une résolution de 100 PS. Ceci signifie que l'on compte un nombre entier d'incréments de 100 PS. Si τ est un multiple de 100 PS nombre compté peut être la partie entière de ou cette quantité plus une unité. La répartition de l'erreur x (en PS) a pour densité de probabilité P (x) = 1-x et pour variance $\frac{1}{6}$ (écart type 17PS).

Le tableau suivant fournit donc les erreurs aléatoires calculées, suivant les conditions de tir. Pour réaliser ce tableau nous avons ajouté les variances des erreurs aléatoires, ce qui n'est pas vigoureusement valable.

	θ = 2nS	θ = 6nS	θ = 10 nS
impulsions fortes	3 cm	9 cm	15 cm
impulsions faibles	9 cm	30 cm	45 cm

Il doit être possible de diviser ces chiffres par un facteur 2 à 10 avec une analyse de l'écho de retour. Le facteur de division sera d'autant plus important que la quantité d'information donc le nombre de photons sera plus important.

Retour sur l'étalonnage

La détermination de la constante d'étalonnage peut être réalisée de trois façons différentes :

- mesure des retards électroniques et optiques dont la somme fournit la constante d'étalonnage.
- tirs sur cibles à distances connues en affaiblissant le signal suffisamment au retour pour simuler un écho sur satellite. La différence entre la valeur vraie de la distance et sa mesure par la station fournit la constante d'étalonnage.
- Réinjection par un appareillage optique (équerre optique, fibre de verre) d'une partie de l'énergie émise dans le télescope de réception. Ceci doit permettre un étalonnage interne et éventuellement une calibration à chaque tir.

III. CONDITIONS DE TIR

Nous avons défini trois conditions de tir :

III.1. Tir de nuit sur satellite visible en poursuite manuelle

Du point de vue télémétrie, cette condition est extrêmement facile à remplir. On peut déjà fonctionner avec un fitre relativement étroit (1,5 A°) et une simple détection.

Un système à coïncidence temporelle sur deux photoélectrons permet de travailler avec une porte large (plusieurs nS) et une très faible probabilité de faux échos facilitant grandement la validation des résultats et le traitement ultérieur.

La poursuite sera réalisée grâce à un "manche à balai" commandant la tourelle et à une visée optique à l'aide d'une lunette couplée à une caméra de télévision (Noticon) qui permettra, en limite de visibilité, de poursuivre un satellite de faible magnitude comme STARLETTE (12 à 13 cm).

II.2. Tir de nuit sur éphémérides

Les bruits étant les mêmes que précédemment il en est de même des résultats.

III.3. Tir de jour en automatique

Cette condition de tir n'est pas encore mise au point.

Néanmoins, en fonction de ce que nous avons analysé lors de l'étude des bruits il est possible de la remplir en adoptant un ou plusieurs des moyens suivants :

- réduction de la bande parasite du filtre interférentiel (étude et réalisation CERGA en cours)
- mise en service d'une coïncidence spatio-temporelle sur 3, 4, 5 ou 6 photoélectrons.
- détection de niveau en sortie des deux photomultiplicateurs.

La préférence est, bien sûr, donnée aux moyens qui réduisent peu la portée c'est à dire dans l'ordre où nous les avons classés ci-dessus.

CONCLUSION

Cette étude, non exhaustive, du choix des éléments de la station de télémétrie laser 2ème Génération, permet de mettre en évidence la définition des sous ensembles pour satisfaire aux exigences exposées au début de l'étude.

Ce choix ne limite pas la station à sa configuration minimale de départ et permet, sans interrompre son exploitation :

1er) d'augmenter sa précision par une étude de la forme de l'écho de retour

2ème) d'étendre la couverture, par une extension de périodes de tir (tir de jour) et par une réduction des domaines interdits (lune, voisinage du soleil).

THE SHORT-PULSE LASER-RANGING SYSTEM INSTALLED IN WETTZELL

P. Wilson, K. Nottarp, H. Seeger
Institut für Angewandte Geodäsie (Abtlg.II, DGFI), Frankfurt and
Sonderforschungsbereich 78, Satellitengeodäsie, der TU München
Fed. Rep. of Germany

HARDWARE DESCRIPTION

1. INTRODUCTION

In December 1974 the Institut für Angewandte Geodäsie, Frankfurt a.M., acting together with, and on behalf of the Sonderforschungsbereich Satellite Geodesy of the Technical University Munich, (SFB 78) placed an order with GTE-Sylvania, Mountain View, California, for an advanced laser ranging system. The contract was financed jointly by the Bundesministerium des Innern (Ministry of the Interior) and the Deutsche Forschungsgemeinschaft (German Research Council) through the Sonderforschungsbereich 78 and the system has been installed in Wettzell in a new building provided by the Institut für Angewandte Geodäsie, the stationary components being maintained in a climatically controlled environment.
The system characteristics are summarised in Tables 1 - 5.

2. PRESENT SITUATION

Following the difficulties experienced during the installation (see later discussions during the other sessions) the system is now being used daily for ranging to near-earth satellites such as GEOS-2 etc. No recent ranging results have been completely analysed, but first results obtained in Wettzell from Starlette (2 passes observed in June 1977) indicate a 5 cm noise level. A later pass observed to GEOS-A gave indications of discrete ranging with three distinct ranging intervals. These and other results will be presented during the symposium.

3. THE PROBLEM-AREAS ENCOUNTERED

The following summarises the main design problems which came to light during the first year of experience with the new system. These topics will be discussed in more detail during the subsequent sessions:

a) problems have been experienced with the laser power supply e.g. due to inadequate precautions against over-heating of the transformers in going from 60 Hz to 50 Hz operation;

b) the adjustment stability of the laser had to be upgraded;

c) problems are still being encountered with the surface loading on the optical components in the Coudé path;

d) an unsatisfactory coupling design gave rise to encoder damage;

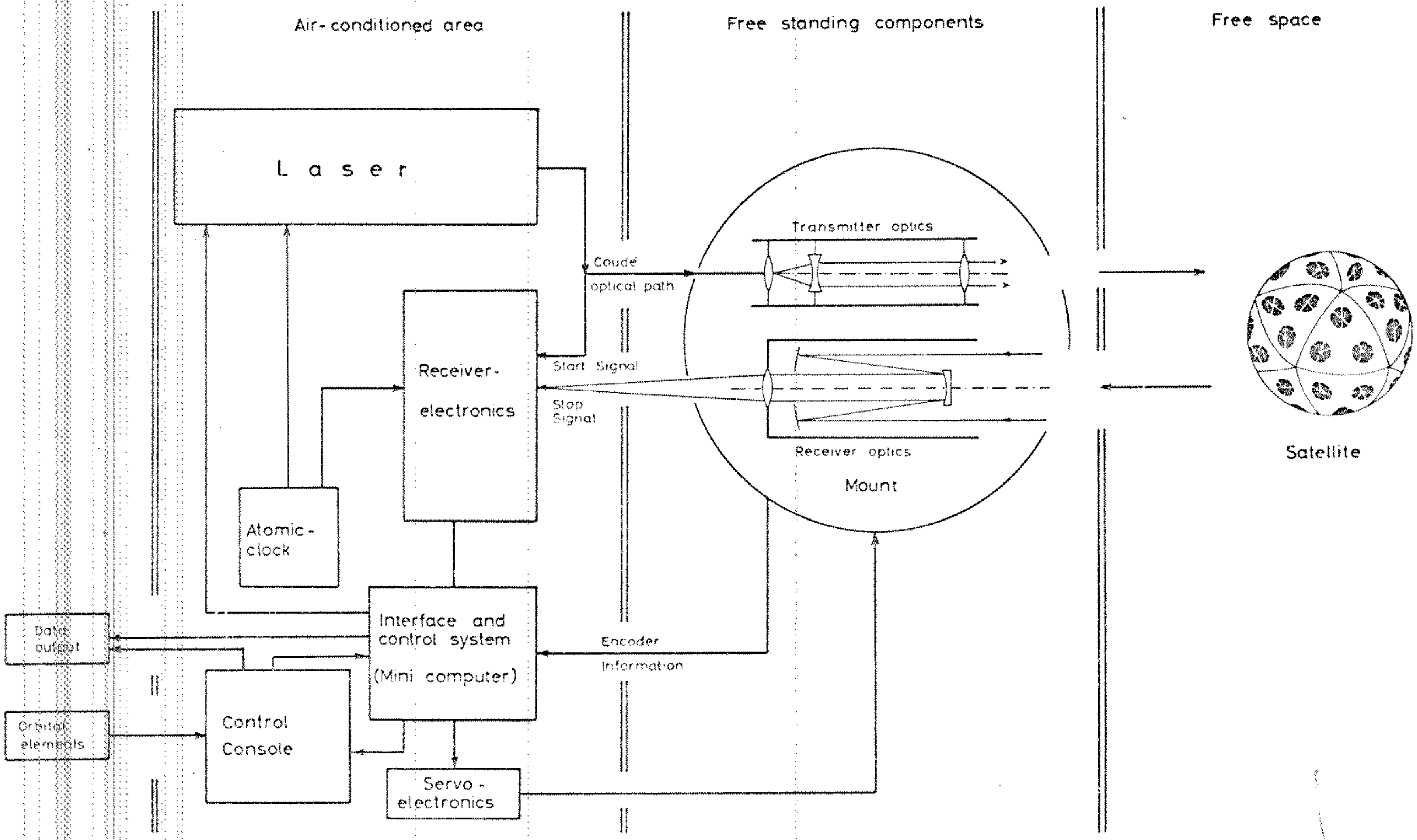
e) the cable wrap proved to be poorly finished.

Apart from these design defects, the most significant time losses were suffered from

f) damage to the heat-exchanger, which occurred during transport from San Francisco to Frankfurt;

g) the search for a fault in the receiver electronics which prevented the recording of data for about five months.

Although we have been disappointed in the quantity of data delivered to date, we are optimistic for the future and look forward to making a significant contribution to future tracking campaigns.



BLOCK DIAGRAM OF THE LASER-RANGER

Table 1. Summary of Specifications for Laser Ranging System

Original Specification	Original Proposal	Acceptance Tested
General		
Range 350 to 20 000 km	350 - 20 000 km	900 - 9000 km
Data recovery rate up to 1 range/sec	3 ranges/sec	up to 5 ranges/sec
Operating staff / 2 persons	2 persons	1 person
Mount		
Configuration alt-az. or x - y with Coudé axes	alt-az. with Coudé	alt-az. with Coudé
Angular travel - elevation 110° - azimuth 540°	190° 540°	190° 540°
Tracking		
Continuous from -10° through zenith to -10° under control of computer	Continuous from -10° to within 2° of zenith to -10° under computer control	Continuous from -10° to within 2° of zenith to -10° under computer control
Tracking rates from 1°/min to 1°/sec in plane of orbit	1°/min to 1°/sec	1°/min to 1°/sec
Orthogonality of rotational axes/±2"	±2"	1"
18 bit encoders	18 bit	18/20 bit
Transmitting Optics		
Effective beam divergence 0.1 to 5.0 mrad	0.1 to 5.0 mrad	0.025 to 2.0 mrad
Receiving Optics		
Cassegrain	Cassegrain	Cassegrain
Diameter 60 to 90 cm	61 cm	61 cm
FOV 1 to 15 arc	0.05 to 2.3 mrad	0.05 to 2.3 mrad
Laser		
Ruby or Nd-YAG	Ruby or Nd-YAG	Nd-YAG
Pulse transmission mode or mode-locked operation	PTM or mode-locked	mode-locked
Halfenergy pulse width/100 psec to 5 nsec	200 psec to 5 nsec	200 psec
Peakpower 1 to 2 GW	1 GW or 1.25 GW	1.25 GW
Natural divergence 1 mrad	1.2 to 6 mrad dependent on rep.rate, or 1 mrad	0.3 mrad
Spectral region - green or red, 694 nm or 532 nm	694 or 532 nm	532 nm
Pulse repetition rate/1pps or better	3 pps	4 pps
Receiver		
Electrostatic	Electrostatic	crossed-field
Rise time better than 2 nsec	≤ 2 nsec or 0.5 nsec	0.5 nsec
Pulse Analysis	if required	not required
Computer		
Data Storage on mag.- tape and/or disk	disk with 1.2 mio word capacity	disk
Imput-output-teletype, mag.-tape, punched tape	all three	mag.-tape, punched tape, printer
Memory - at least 16 K 16-bit words	16 K expandable to 127K	32 K

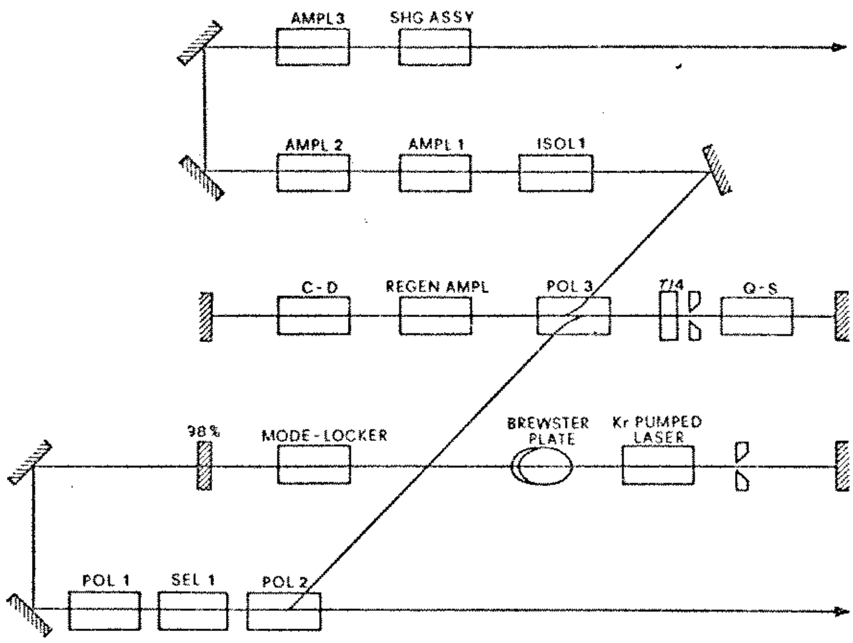


Figure 2. Block Diagram of the Optical Lay-Out of the GTE Sylvania Nd-YAG Laser

Table 2. Characteristics of the Frequency Doubled Nd-YAG Laser

Peak power output:	1.25×10^9 watts at 0.53 µm
Energy output:	0.25 joules per pulse at 0.53 µm
Output stability:	± 5 °/o
Pulsewidth:	Less than 0.2 nanoseconds
Repetition rate:	4 pulses per second
Beam divergende: (full angular-field containing 90 °/o of the energy)	Less than 10 times the diffraction limit from the final amplifier assembly
Beam diameter:	12 mm
Spectral linewidth:	Less than 2 nanometer
Spectral line stability:	Better than 0.1 nanometer
Spectral line position:	Repeatable to better than 0.1 nanometer from one operational cycle to another

Table 3. Specifications for the Positioning Mount

Rotational freedom in elevation in azimuth	- 10° to + 190° ± 270°
Orthogonality of rotation axes	± 2 arc sec
Wobble on each axis	± 1 arc sec
Tracking velocity in elevation in azimuth	0.5°/min to 2°/sec 0.5°/min to 32°/sec
Acceleration in elevation travel in azimuth travel	$2°/sec^2$ $10°/sec^2$
Payload	500 kg
Static pointing accuracy	Better than 10 arc sec
Levelling and alignment in azimuth	Better than 1 arc sec
Prime power	220/380 V
Operating temperatures	- 20° C to + 50° C
Humidity	0 - 100 °/o without damage

Table 4. Specifications of the Optical Subsystems

Transmitting optics	
Configuration	Galilean
Magnification	12 x
Input diameter	16 mm
Output diameter	200 mm
Focus (divergence)	0.025 to 2.0 mrad
Alignment stability	10 % of divergence
Correction wavelengths	532, 643, 1064 nm
Peak power input	2 GW/cm^2
Optical coatings - maximum loss	0.25 % / surface
Receiver optics	
Configuration	Catadioptric Cassegrain
Aperture diameter	60 cm
Focal length	440 cm
Correction wavelength	532 nm
Alignment stability	10 arc sec over $\pm$ 20° C
Field of view	0.05 to 2.3 mrad
Sighting telescope	
Configuration	Maksutov - Cassegrain
Aperture	90 mm
Focal length	1 300 mm
Magnification	50 x
Field of view	55 arc min
Resolution	1.5 arc sec

Table 5. Specifications for the Varian 153A Static Crossed-Field Photomultiplier

Photocathode / window material	S-20/Sapphire
Cathode diameter	5 mm
Cathode quantum efficiency	10% typical at 530 nm
Gain	10^5 typical, 5×10^4 min.
number of stages	6
Dynode material	BeCu Alloy
Anode dark current	3×10^{-9} typical at 20°C
Output current	250 µA max. continuous
Bandwidth, 0 to -3 dB	DC to 2.5 GHz
Anode rise time (10 % to 90 %)	150 picoseconds

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

Peter Wilson
Institut für Angewandte Geodäsie (Abtlg.II, DGFI), Frankfurt and
Sonderforschungsbereich 78, Satellitengeodäsie, der TU München
Fed. Rep. of Germany

HARDWARE

1. 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.

2. 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 stars, from the observers telescope position;
- reduction of the laser firing jitter from currently 125 msec to approx 150 μsec;
- upgrading of the photomultiplier by introduction of the newest Varian static crossed field unit, with 25 °/o guaranteed minimum quantum efficiency (35 °/o typical);
- introduction of a thermostatically controlled 10 Å narrow-band filter to replace the current 25 Å 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 visualise the computation of the lunar ephemerides, system calibration, ranging execution, preliminary data processing 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.

LASER RANGING WORK AT THE GODDARD SPACE FLIGHT CENTER - AN UPDATE -

Thomas E. McGunigal
NASA/Goddard Space Flight Center
Code 723
Greenbelt, MD 20771

INTRODUCTION

A paper[1] which described the Goddard laser ranging systems was included in the Proceedings of the 2nd Workshop on Laser Ranging Instrumentation which was held in Prague in 1975. The purpose of this paper is to describe the current status of the laser ranging work at Goddard. There are two main thrusts to this work; 1) the development and operation of the network systems to meet operational requirements, and 2) advanced systems development and system improvement. Within the Goddard organization the network engineering and operations work is being done by the Networks Directorate and the advanced development is being done by the Engineering Directorate. The work being done in both directorates will be briefly summarized in this paper.

THE LASER TRACKING SUBNET

For the last several years the network activity has been in a period of dynamic growth. In 1975, one fixed and two mobile stations were in operation and by the end of 1978 the network will consist of one fixed and eight mobile stations. Although the systems are not identical, the fundamentals of system operation and the performance goals are the same as those described in the 1975 paper. The characteristics of the various systems are summarized in Table 1. The first three mobile systems were designed and integrated in-house at Goddard. The newest systems, Moblas 4-8, are two trailer systems consisting of the Mobile Optical Mount System (MOMS) developed for Goddard by Contraves Goerz Corporation, and the Electronics Van designed by Goddard's Networks Directorate. Systems integration and test are being done at Goddard with the Bendix Field Engineering Corporation as integration contractor.

Moblas 4-8 Characteristics

A. The Mobile Optical Mount System. The Mobile Optical Mount System has been described in detail by Economou et al[2]. Briefly, it consists of a trailer housing a two axis tracking mount including an 0.75 meter receiver telescope and a coude type transmit optical system with a 10cm clear aperature. The trailer also includes a transmitter compartment which is a class 10,000 clean room and additional space for laser power supplies and electronics racks. The mount compartment has a retractible roof and walls which deploy to form a working platform around the mount. The specified performance characteristics are summarized in Table II[2].

B. Laser Subsystem. The laser for the Moblas 4-8 systems is a frequency doubled Nd:YAG laser which was manufactured by General Photonics, Inc. It is a Q-switched laser with a 6 nanosecond pulsewidth and an output energy of 0.25 Joules at a wavelength of 532 nanometers. It has been designed to operate in any orientation and over a wide temperature range so that it can be mounted on the elevation axis of the telescope. A collimator is an integral part of the laser resulting in a beam divergence of 0.2 milliradians.

C.. Receiver Subsystem. The receiver subsystem is essentiallythe same as the earlier systems. It uses an Amperex 56TVP photomultiplier tube and a fixed threshold pulse discriminator in conjunction with a waveform digitizer for pulse position measurements. The waveform digitizer is a Tektronix 7912 system rather than the previously employed LeCroy WD-2000. The time interval unit is a Hewlett Packard 5360A computing counter.

D. Computer Subsystem. The Moblas 4-8 system's use a Mod Comp II computer unit with 16-bit word length and 64K BYTES of memory. The software package is being extensively revised to accomodate the new computer and to conform to Network standards for data format and satellite predictions. It is not complete at this writing so that no details are available.

E. System Status. The Moblas 4-8 systems are now in the process of final integration. System testing is presently scheduled for the Summer of 1978 with operational deployment planned to begin in the Fall.

ADVANCED SYSTEMS DEVELOPMENT

Advanced systems development at Goddard is being done by the Electro-Optics Branch in the Engineering Directorate. Facilities are available for both laboratory and field test work.

I. Field Facilities

The centerpiece of the advanced development activity is the 1.2 meter telescope located at the Goddard Optical Research Facility - four miles away from the central complex at Goddard. This telescope is illustrated in Figure 1.

The telescope employs a coude optical system with a 1.2 meter aperture, a focal ratio of f 26.3 and an equivalent focal length of 32 meters. The mirrors have polished aluminum surfaces on fused silica substrates. An indexable mirror within the pier at the couderoom level permits the light bundle to be quickly redirected through any one of eight ports to eight possible experiments. It is possible to reconfigure the telescope to a Cassegrain system to meet special requirements. Also,machined surfaces are provided on the elevation axis for mouting equipment directly to the telescope. Electrical connections to these areas are provided by a cable wrap and sliprings. The entire moveable structure rides on an azimuth axis air bearing. Precision roller bearings are used for the elevation axis. Each axis is equipped with a directly coupled torque motor, tachometer and 22-bit digital shaft angle encoder.

The system is controlled from an operator's console in the computer/control room or from an observer's position on the azimuth axis. A Honeywell 716 computer is interfaced to the telescope and to the operator's console and controls telescope pointing. This computer has a 16-bit word length and 48 thousand BYTES of memory. In addition to its realtime interfaces, it has two magnetic tapes, a line printer, card reader, typewriter and paper tape equipment. For satellite tracking the 716 computer generates telescope pointing commands in realtime from polynominals describing the satellites position.

Another function of the 716 is to model the structural and alignment errors of the telescope. Typical errors include a lock of orthogonality between the azimuth and elevation axes, sagas which vary with elevation angle, encoder offsets, coude mirror misalignments, etc. These errors are determined by observations of a well distributed series of 40 to 50 stars. A regression analysis is then performed to determine the coefficients of all the error terms in a mathematical model of the telescope. The model equations are evaluated during satellite tracking to correct the telescope pointing.

An Interdata 8/32 computer has been interfaced to the Honeywell 716. This machine has a word length of 32 bits and 384 thousand bytes of memory plus a 10 megabyte disc. A software system has been written which allows the two machines to exchange data and makes the line printer, card reader and magnetic tapes available to the 8/32. The 8/32 was added to provide more mathematical computing power. It will be used in realtime to correct the predicted satellite state vector on the basis of the actual range measurements in order to improve orbit prediction accuracy. In non-real time it will be used to analyze the ranging system measurement data.

In addition to software directly related to satellite ranging, the software system includes capabilities for solar, lunar, planetary and star tracking.

Two experiments which have an immediate bearing on the improvement of future laser ranging systems are currently in progress at this facility. The first of these is a more or less conventional ranging system using a 5 nanosecond pulsewidth cavity dump Nd:YAG laser producing 75 millijoules of energy at 532 nanometers. The receiver uses a static crossfield photomultiplier tube with a risetime of 200 picoseconds and a high performance constant fraction discriminator developed by Branko Leskovar and C.C. Lo at Lawrence Berkeley Laboratories[3]. The time interval unit is a Hewlett Packward 5370A with 20 picosecond resolution which was recently introduced. The purpose of this work is to test on a continuing basis under actual field conditions new ranging system components or concepts which might be of value to the network systems.

The second experiment is being conducted with NASA and Navy funding by Prof. Carroll Alley and others of the University of Maryland. The purpose of this work is to demonstrate the feasiblity of using single photoelectron ranging techniques for satellite ranging. He is using a 200 picosecond pulsewidth Nd:YAG laser which operates at 30pps and with less than a millijoule of energy per pulse at 532 nanometers.

2. Laboratory Facilities

Extensive laser laboratory facilities are available at Goddard but the precision ranging laboratory is uniquely equipped to perform state-of-the-art measurements of system or subsystem performances. This laboratory is shown schematically in Figure 2 . A wide range of laser sources, optical detectors, and ranging electronics are available. Single retroreflectors are mounted on water tanks and towers at nominal distances of 500 meters, 5KM meters and 22 KM permitting measurements through variable length atmospheric paths.

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TABLE I

PARAMETER	STALAS	MOBLAS I-III	MOBLAS IV-VIII
WAVELENGTH (Å)	5300	6943	5300
ENERGY/PULSE (J)	0.25	0.75	0.25
PULSE WIDTH (Ns)	0.2	5	5
RECEIVER APERTURE (M)	0.5	0.5	0.75
DIVERGENCE (Mr)	0.1	0.1	0.2
QUANTUM EFFICIENCY (%)	12	2.5	12
SYSTEM EFFICIENCY (%)	15	15	20

Table II
Summary of Mount Operational Parameters

Receive Optics:	30-inch clear aperture f/5 Cassegrain telescope f/1.5 primary mirror 15% optical loss 10% obscuration loss 80% of energy in 5 arc second blur over 5 milliradian field
Transmit Optics:	Five identical but independently adjustable mirrors allowing a 10 centimeter diameter transmission path from a stationary point off mount. Mirrors: $\lambda/10$ @ 532 nm 99.8% reflectivity at 532 nm 70% reflectivity between 450 and 650 nm 1.25 gigawatt energy and handling
Servo Performance:	20°/sec. azimuth axis velocity 5°/sec. elevation axis velocity 0.001°/sec. minimum velocity, both axes $5^{\circ}/sec.^2$ azimuth axis acceleration $3^{\circ}/sec.^2$ elevation axis acceleration
Readout:	21-bit natural binary
Physical Measurements:	110 inches maximum height (telescope pointed to Zenith) 82 inches of height to elevation axis 9500 pounds of weight 45-inch azimuth swing radius 34-inch elevation swing radius 50 Hertz resonance (legs)
Pointing Accuracy:	Transmit optical system 12 arc seconds 3

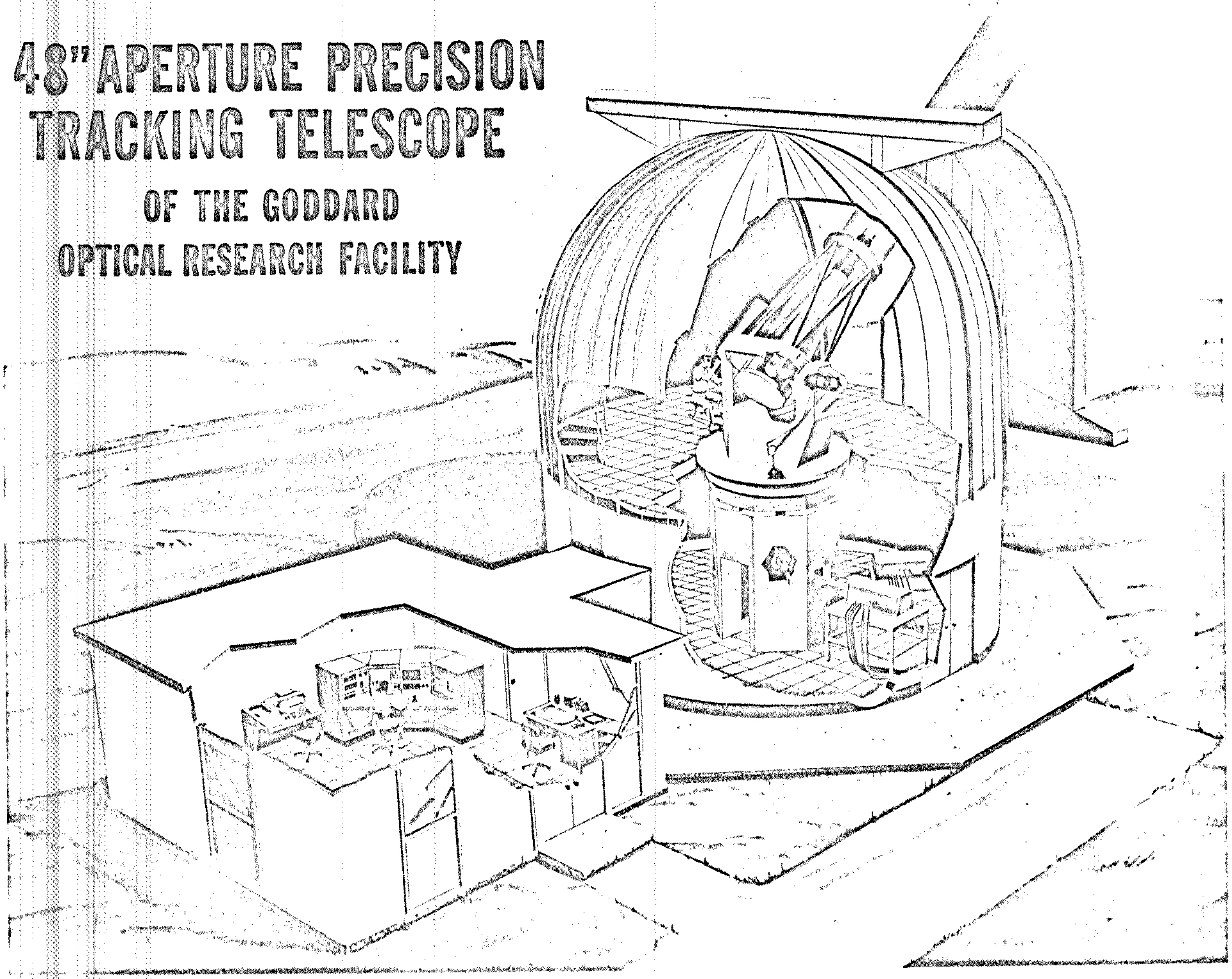
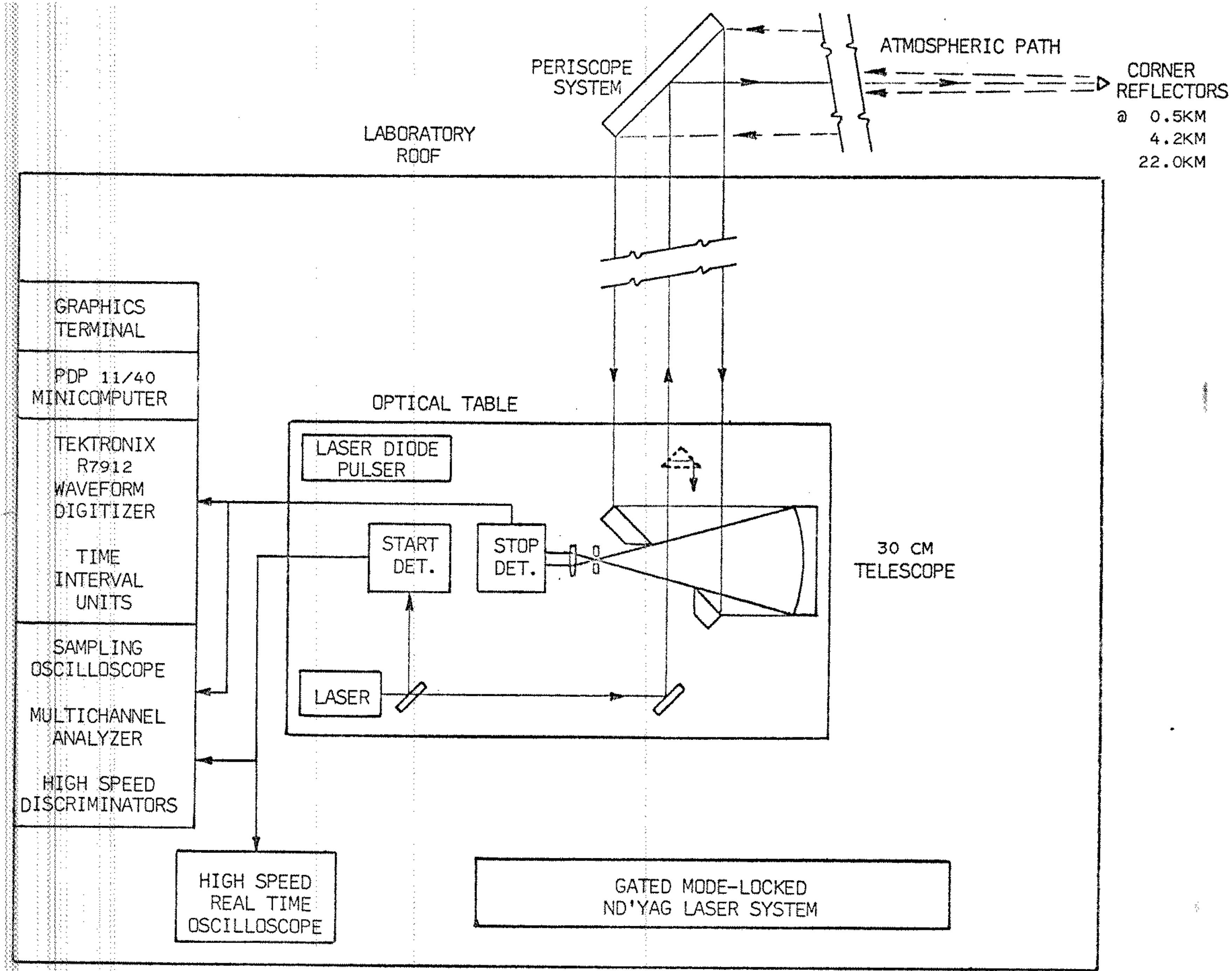

48" APERTURE PRECISION
TRACKING TELESCOPE
OF THE GODDARD
OPTICAL RESEARCH FACILITY

FIGURE 1



ADVANCED RANGING RECEIVER LABORATORY

FIGURE 2

INTERKOSMOS LASER RADAR NETWORK

K.Hamal
Faculty of Nuclear Science and Physical Engineering
Brehova 7,Prague 1,Czechoslovakia

To fulfil the requirements of the Interkosmos program related to the projects of Long Arc Arctic Antarctic and the Long arc East West,the international Laser Radar Working Group and the Interkosmos Laser Radar Network has been built |1,2|.The accuracy ± 1.5 m and ranges up to 3000 km has been expected.

Twelve stations of the first generations have been build in the cooperation of CSSR,GDR,PRH,PRP,USSR,Cuba and have been operating together with ISRO in India,HIAG in Egypt,UMSA in Bolivia. One station is kept in Prague for training purposes.

The main performances are summarized in Fig.1.The expected retrosignal is shown.However,the measured signal was 10 times lower.The explanation is possible to find in the saturation efect of a PMT due to the scattering,especially when high humidity.The efect was examined and confirmed at Crimean observatory (station No.4) |3|.PMT was covered when the beam passes through the atmosphere.The description of the typical station is in |2|.The block scheme is on Fig.2.There are certain differences especially ref. to the mount,data output and time base.See Tab.1.Station No.2 is equiped by HP 30 desk top calculator |4|.The stations No.8 and 11 are equiped by SBG 2 mount.The station No.6 is equiped by a special mount.The upgraded station No.2 is described in |5|.The transportability aspect are desribed in |6|.The time interval measuring technique including the calibration is decribed in |7|.

Long arc fit using |8| SAO Differential Orbital Improvement Program with abbruated gravited field,residuals and the internal coherence are shown in Tab.2.

The photograph of the stationary station No.9 in Kavalure in India is on Fig.4.

The Interkosmos satellite laser network is shown on Fig.3.

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Figure Capture

Fig.1. (a) The calculated retrosignal based on radar equation.
(b) Characteristics of the Interkosmos stations.

Fig.2. Block scheme of the station No.10.

Fig.3. Interkosmos Laser Radar Network May 1978.

Fig.4. The photograph of the station No.9.

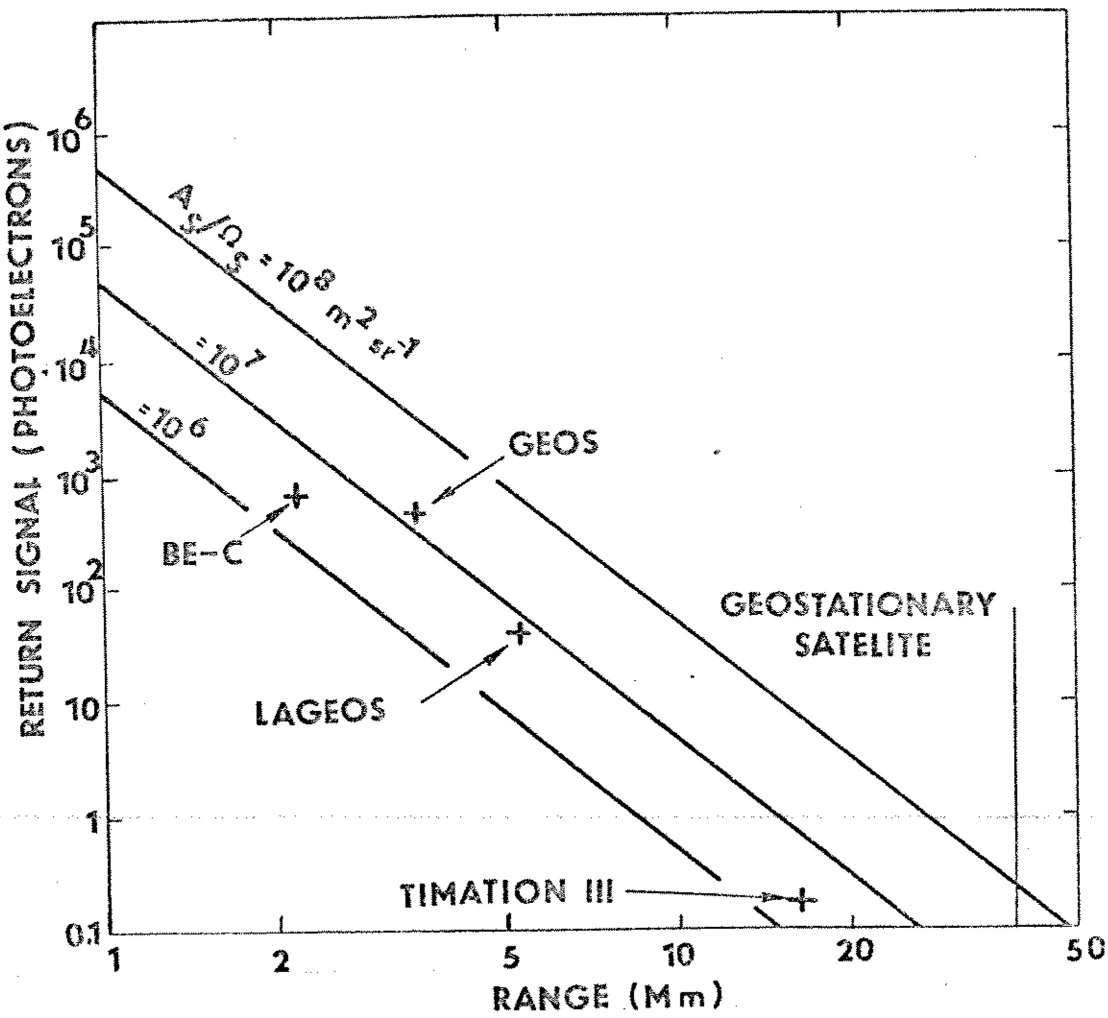
Tab.1. INTERKOSMOS LASER RADAR NETWORK MAY 1978

No.	Type	Operation	Location	RMS	Calibr.	Time base	Safety
1	Stationary	1972	Poland,Borowce	1 meter	Permanent target	VHF	
2	Mobile	1973	Egypt,Helwan	-"-	-"-	Loran C	
3	Air transp.	1975	Bolivia,Patacamaya	-"-	-"-	VHF	
4	Stationary	1975	USSR,Crimea	-"-	-"-	Loran C Rubidium clock	
5	Stationary	1976	USSR,Zvenigorod			TV	
6	Stationary	1975	CSSR,Hradec Kralove	-"-	-"-	TV	
7	Air transp.	(1975)	CSSR,Prague			Cesium clock TV	
8	Stationary	1976	USSR,Crimea			TV	
9	Stationary	1976	India,Kavalure	-"-	-"-	Cesium clock Transit	
10	Stationary	1977	Cuba,Santiago de Cuba	-"-	-"-	Loran C	
11	Stationary	1977	Hungary,Penc	-"-	-"-	Transit	

Tab.2. Long Arc fit using |8| SAO Diferencial Orbital Improvement Program with abbruated gravity field. Residuals. System errors. (Adaptive threshold).

Station Helwan Year 1977, Month October

SAO day	No. of range obser.	Observ. reject by SAO	Range residuals /meter/	Standard deviation /meter/	Note
42339	21	1	from 382 to 297	0,63	Residual systematic Possibly timing problem
42340	61	9	from 375 to 184	0,35	atto
42341	15	1	-10.7 - 1.6	0.72	Data looks good
42342	14	0	-10.7 -12	1.01	atto
42342	52	4	-6.8 -9.7	0.46	atto
42343	25	1	-20 -15	0.54	atto
42344	91	15	-11 - 7	0.46	excellent
42346	50	5	0.2 13	0.42	nice pass



Characteristic of system	INTERKOSMOS laser radar
η_T, optical efficiency of the transmitting telescope	90%
E , laser energy	1 J
A_R, aperture area of the receiving telescope	0.07 m²
Θ_R, transmitter beam divergence	0.3 miliradians
T , one way atmospheric transmittance at 694 nm	58%
η_R, conversion efficiency of receiver incl.losses	1.5%
hν, energy of one photon at 694 nm	$2.86 \cdot 10^{-19}$ J

Fig.1

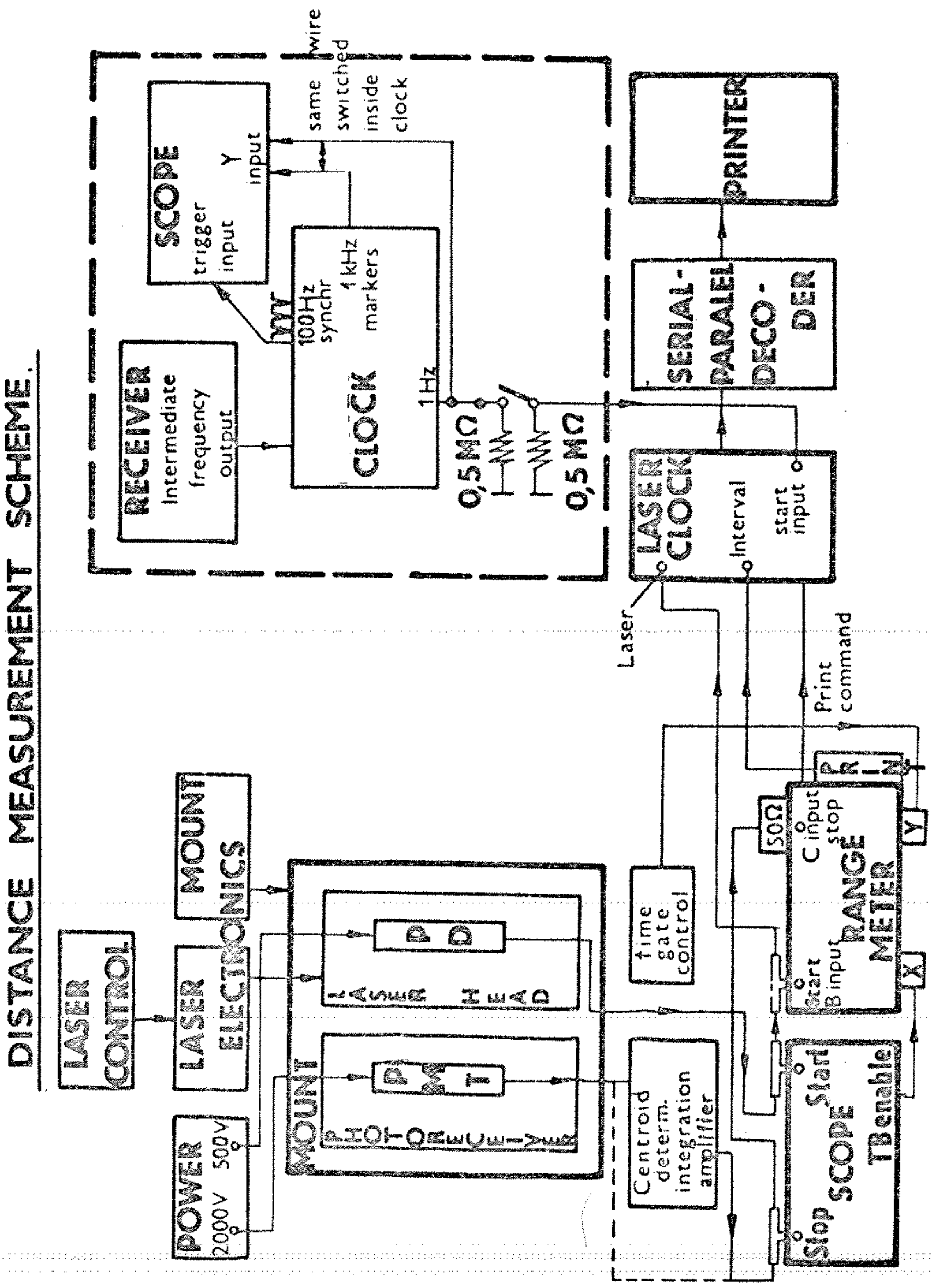

DISTANCE MEASUREMENT SCHEME.
LASER CONTROL
LASER ELECTRONICS
MOUNT ELECTRONICS
POWER
2000V
500V
MOUNT
PHOTORECEIVER
PMT
LASER HEAD
PD
RECEIVER
Intermediate frequency output
CLOCK
100Hz synchr
1kHz markers
1Hz
SCOPE
trigger input
Y input
same wire switched inside clock
0,5 MΩ
0,5 MΩ
PRINTER
SERIAL-PARALEL DECO-DER
LASER CLOCK
Interval
start input
Laser
Print command
time gate control
Centroid determ. integration amplifier
RANGE METER
C input stop
B input start
50Ω
X
Y
PRIN
SCOPE
Stop
Start
TB enable

Fig.2


INTERKOSMOS LASER RADAR NETWORK.
ZVENIGOROD
POLAND
USSR
CSSR
CRIMEA
HUNGARY
SANTIAGO
CUBA
CAIRO
EGYPT
KAVALUR
INDIA
LA PAZ
BOLIVIA

Fig.3

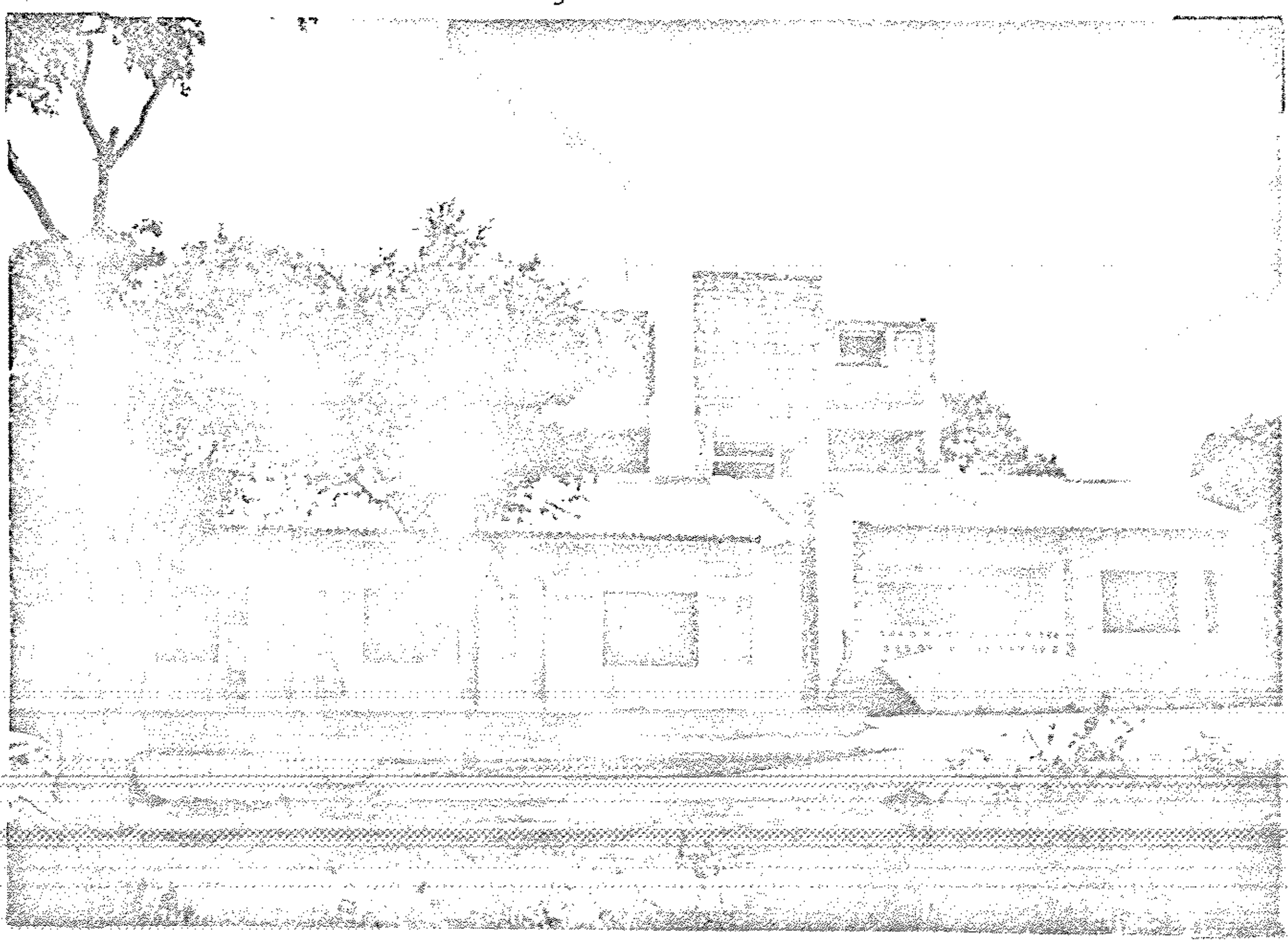


Fig.4

THE SMITHSONIAN ASTROPHYSICAL OBSERVATORY
SATELLITE RANGING HARDWARE

M. R. Pearlman, N. W. Lanham, J. Wohn, J. M. Thorp,
E. Imbier, and F. D. Young

Smithsonian Astrophysical Observatory
Cambridge, MA

INTRODUCTION

The Smithsonian Astrophysical Observatory (SAO) operates four satellite ranging laser systems to support research in geodesy and geophysics. The systems — in Natal, Brazil; Arequipa, Peru; Orroral Valley, Australia; and Mt. Hopkins, Arizona — have been in routine operation for 8 years. During the last 3 years, the lasers have been equipped with pulse-processing systems and minicomputer control and data-processing systems. Work has also been under way to install pulse choppers in the systems to reduce the laser pulse width.

The SAO laser ranging system shown in Figure 1 has a static pointing mount that is aimed by means of computed predictions of satellite azimuth and altitude. The predictions are computed and fed to the mount by minicomputer, which also collects and preprocesses the laser data on line. The system operates in both day and night conditions.

LASER TRANSMITTER

The laser, a ruby system built in an oscillator-amplifier configuration, generates an output of 5 to 7 joules in a 25-nsec pulse (half-power, full width). The system uses a Pockels cell and a Brewster stack for a Q-switch and operates at 8 pulses per minute. Both the 0.95-cm (3/8-inch) diameter oscillator ruby rod and the 1.6-cm (5/8-inch) diameter amplifier ruby rod are mounted in 15.2-cm (6-inch) double elliptical cavities, each containing two linear flashlamps. The optical cavity of the oscillator is formed by a flat rear mirror, with a reflectivity of 99.9%, and the uncoated front of the oscillator rod.

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

The oscillator output of 1 to 2 joules is coupled into the amplifier through a beam-expanding telescope. The amplifier has a single-pass gain of about 5. Both ends of the amplifier rod are antireflective-coated. The amplifier output is expanded to a diameter of 7 cm and passes through the 12.7-cm (5-inch) objective lens of a Galilean telescope. The diameter of the output-beam divergence can be adjusted from 0.5 to 5.0 mrad. Mounted at the output of the laser, photodiodes pick up atmospherically scattered light from the outgoing pulse and send an electrical start signal to the ranging system electronics. This basic laser transmitter has been in use in our network since 1969. Additional details on these lasers are given in Pearlman et al. (1973, 1975).

During the past 3 years, SAO has made several attempts to improve range accuracy by reducing the laser output pulse width with a chopper. The early versions of this system, based on a laser-triggered spark gap, proved to be too sensitive for our operational environment and could not be made to operate in a routine, reliable manner. To overcome this problem, SAO and Lasermetrics, of Teaneck, New Jersey, have designed an electronically triggered system that is now being tested at Mt. Hopkins. Additional units are being built for the other three stations. A diagram of the chopper is shown in Figure 2.

The chopper is basically a krytron-activated Pockels cell with appropriate polarizers for the necessary transmissions and isolation. A Blumlein circuit provides the proper high-voltage pulse to operate the Pockels cell, and a PIN diode and avalanche transistor circuit to trigger the system. The Blumlein is essentially a delay-line structure, in which delays and reflections are used to produce a high-voltage rectangular pulse of desired width from a voltage step provided by the krytron. The pulse width is adjustable by the length of the Blumlein. The present configuration utilizes a ceramic Blumlein with a length of 15 cm, a width of 1.75 cm, and a dielectric constant E = 30; this system produces a 6-nsec-wide output pulse with a 1-nsec risetime.

The optical assembly of the chopper has been designed to fit between the present laser oscillator and amplifier sections, thus minimizing installation impact in the field. The assembly consists of a thin-film dielectric polarizer sharpener and analyzer, a K$\overset{*}{D}$P 50Ω Pockels cell, and a half-wave plate to match optical polarization to the laser amplifier. The Pockels cell is operated in a pulse-on for transmission mode. The pulse chopper timing is controlled in a gross sense by optical attenuation in front of the PIN diode; fine tuning is made by threshold adjustments to the preamplifier.

The laser can be readily switched electronically from the Q-switched mode to the chopper mode. The laser produces about 1 joule in the 6-nsec chopper mode. In routine operation, the chopper will be used with most of the low orbiting satellites, while the Q-switched mode will be used with Lageos, NTS-2, and possibly some of the lower satellites with small effective cross sections.

RANGING SYSTEM ELECTRONICS

The ranging system electronics consist of a clock, a firing control, a range-gate control, a processing system for the start and stop (return) pulses, a time-interval unit, and a data-handling system, which feeds an on-line minicomputer. The clock, synchronized to within 1μ sec of each station's master clock, controls the firing rate and the time of the laser firing and provides the epoch of observation. Both the firing rate and the time of the laser firing can be controlled by the laser control unit. The firing time can be shifted manually by multiples of 0.001 sec, with a maximum of 3 sec, to account for the early or late arrival of a satellite at a predicted point in its orbit. The range-gate control unit, which provides a gate to the counter and the pulse-processing system, is normally operated with a 20-μsec window. The time-interval unit, with a resolution of 0.1 nsec, is triggered on and off by outputs from the pulse-processing system.

The pulse-processing system records the width and area of the outgoing laser pulses and the pulse shape of the returns. The range measurements are referred to pulse centers to avoid random and systematic errors due to pulse irregularities. The pulse processor is divided into two sections, the start and stop channels. The start channel is based on dual discriminators and pulse integrators to measure pulse width and area. The stop channel, which records return-pulse waveforms is basically a commercially available waveform digitizer and a time-interval unit. The digitizer has 20 sampling channels with spacing adjustable from 1 to 25 nsec. Q-switched operation uses 5-nsec spacing, while the chopper mode employs 1-nsec spacing. The pulse-processing system is discussed in more detail in Pearlman et al. (1975). A diagram of the system is shown in Fig. 3.

In operation, the laser output wave shape is recorded before each pass and then used in a cross-correlation analysis to determine the pulse centers. This requires, of course, that great care be taken to ensure that laser operating conditions (pulse shape) do not change appreciably during a pass.

MOUNT AND PHOTORECEIVER

The azimuth-altitude static-pointing mount has a pointing accuracy of better than ±30 arcsec. The system is driven by stepping motors in an open-loop mode, with the stepping-motor drive-system gears allowing for slewing speeds of 2°/sec and positioning increments of 0°001. The mount has goniometers graduated to 0°001 for reference and verification. Predictions, including pointing angles and range-gate settings, are entered in the system on a point-by-point real-time basis from the on-line minicomputers.

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

The photodetector, an RCA 7265, was chosen for its quantum efficiency of 4% at 6943 Å. The PMT has a gain of 5×10^7 and a risetime of approximately 3 nsec as operated in the SAO system.

MINICOMPUTER AND CONTROL SYSTEM

The SAO laser stations have Data General Nova 1200 minicomputers for data processing and system control. Each minicomputer has 32K words of 16-bit core memory and a floating-point processor. Its peripherals include three block-addressable magnetic-tape units, alphanumeric CRT display units, a high-speed paper-tape reader and punch, and thermal printers with keyboards.

The minicomputers were originally installed at the laser sites for stand-alone operation in 1975. The direct connection with the lasers was undertaken over the past year. In connecting the minicomputers to the lasers, we looked for a scheme that would have minimum impact on the laser operation and existing hardware and software. We decided to build an interface that made the minicomputer emulate the original paper-tape input-output equipment in terms of electronic interaction and communication. To do this, the control pulses originally used to start the paper-tape reader and punch were adapted to cause hardware interrupts in the minicomputer. The interface was designed to distinguish between the interrupts (input or output) and to enable the software to perform the appropriate action, i.e., either put data on the laser systems by input lines or take data off by output lines. With the appropriate interrupt-driven software, this relatively simple system has fulfilled our needs for both interface and display. A diagram of the minicomputer system and interface is shown in Figure 4.

The minicomputer generates pointing predictions from orbital elements provided by Headquarters and feeds them to the laser in real time for pointing and range-gate adjustment. The minicomputer receives all incoming data on line from the laser system in real time and performs most of the preprocessing, including centroid determination, start-channel correction, and calibration. A second pass through the machine prepares the quick-look data message for transmission to SAO. The minicomputer provides detailed analysis of hardware (start and stop channel) and target calibrations as well as a review and summary of satellite and associated prepass and postpass calibration data on a pass-by-pass basis.

During ranging operations, the operator has a real-time display of point and pass parameters, including return-pulse shape, output-pulse parameters, range residuals to predictions, and data and hardware error diagnostics.

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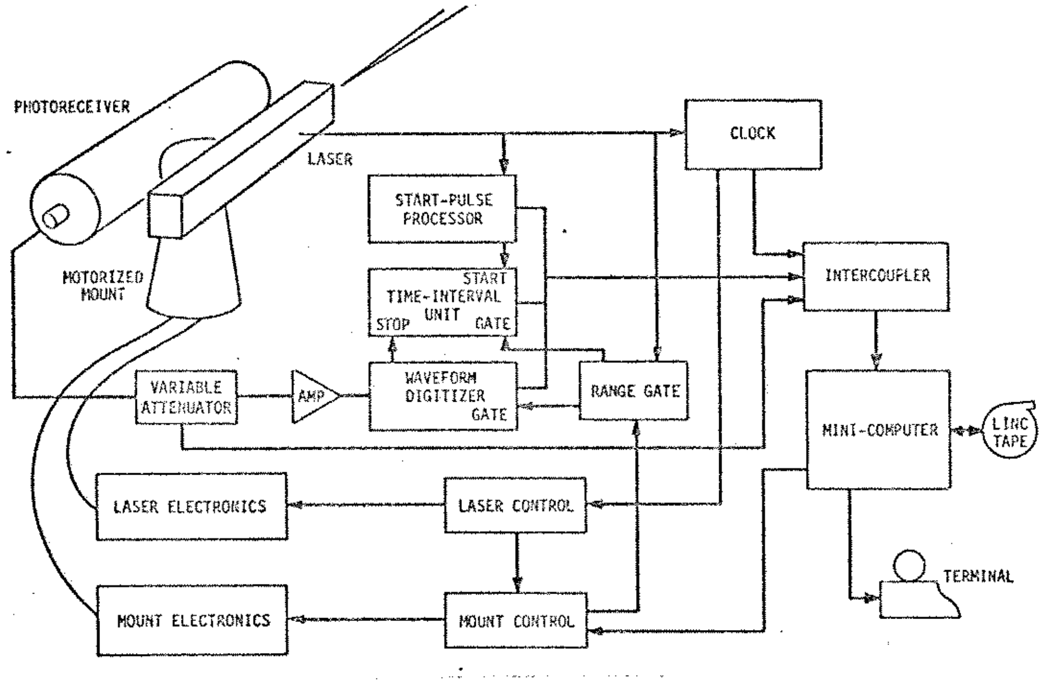


Figure 1. Block diagram of the laser system.

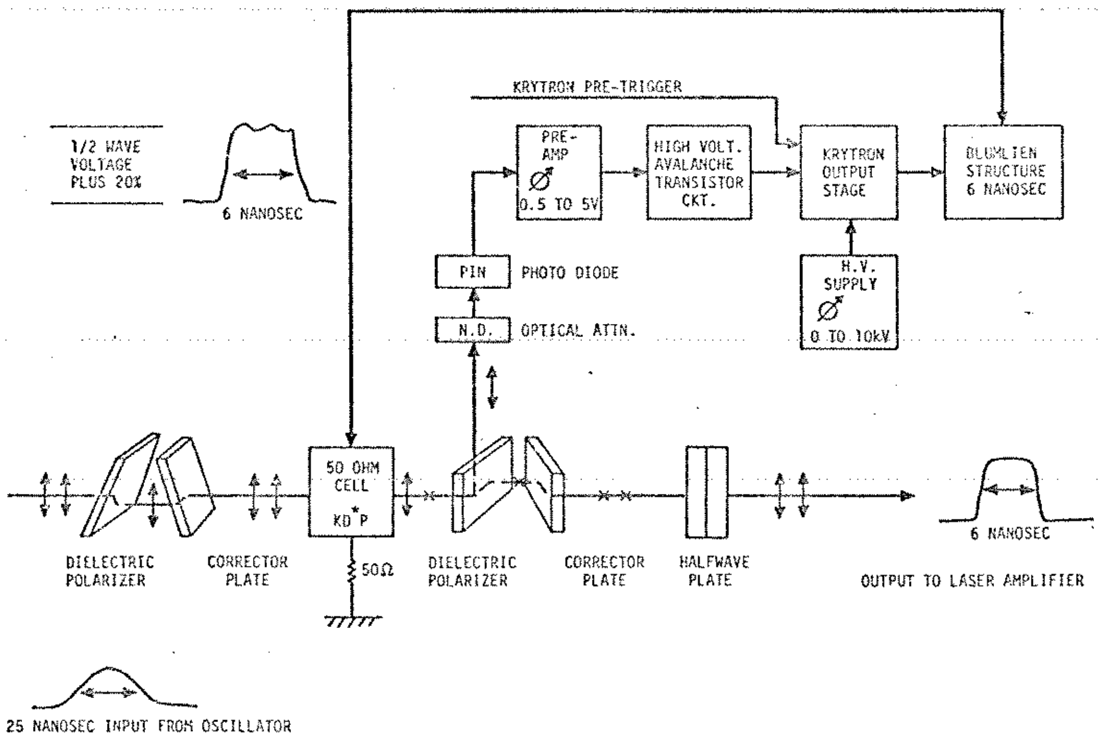


Figure 2. Krytron activated pulse-shaping system.

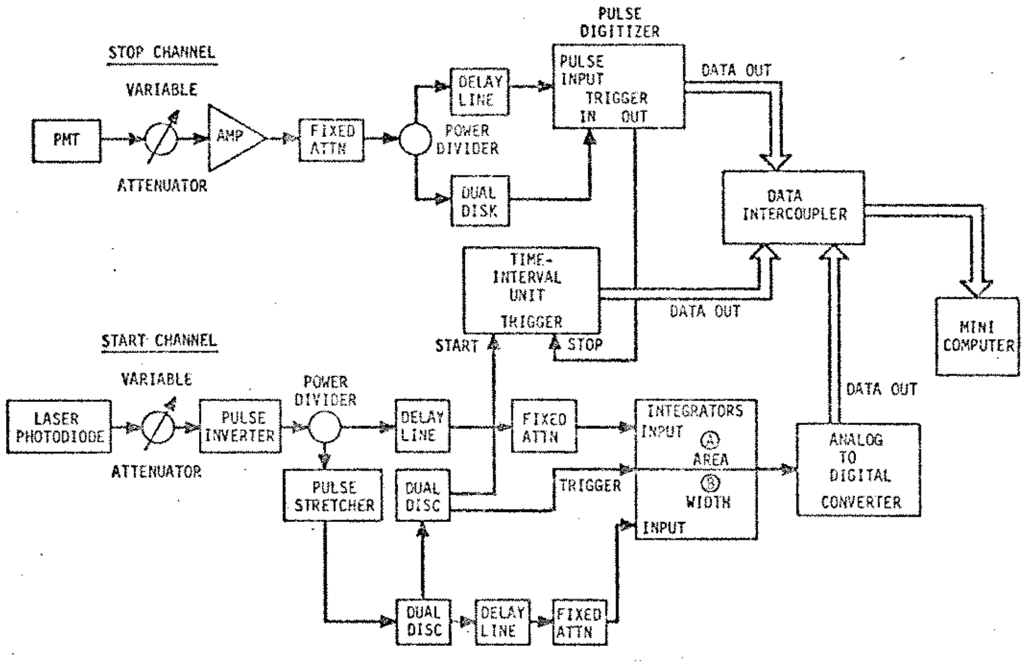


Figure 3. Pulse-processing system.

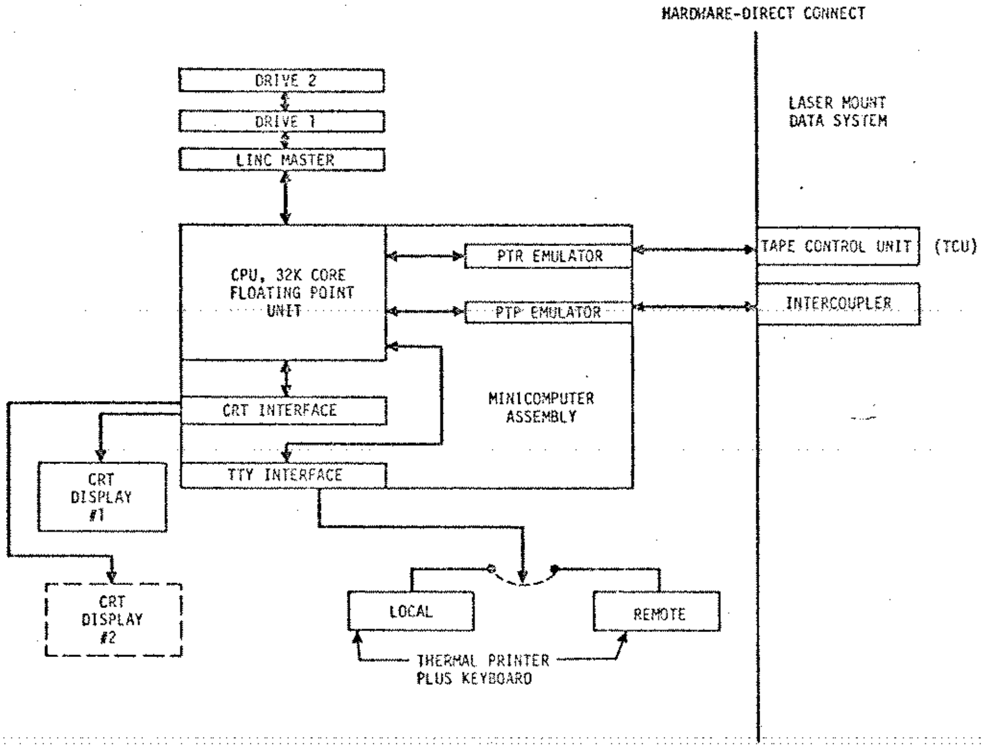


Figure 4. Minicomputer control system.

THE SATELLITE RANGING SYSTEM AT KOOTWIJK

L.Aardoom , F.W.Zeeman
Delft University of Technology, Delft (The Netherlands)

INTRODUCTION

At the observatory for satellite geodesy near Kootwijk - lat. 52° 10' N long. 5° 48' E - the Geodetic Institute of the Delft University of Technology operates a laser ranging system since August 1976.
Routine day and night operation is possible on all cooperative geodetic satellites presently in orbit, with the exception of daytime operation on LAGEOS. Modification of the system in order to decrease the minimum signal-to-noise ratio for daytime tracking is in preparation.
The measurements so far show an accuracy level of 15 - 30 cm (r.m.s.) in satellite ranging and 3 - 6 cm on ground targets up till 1 km.
Accuracy will be improved using waveform analysis.

LASER SYSTEM

The ruby pulse laser system consists of a multi-mode Q-switched oscillator, a spark-gap activated pulse chopper and two amplifier stages. It can produce 4 ns wide pulses at a maximum rate of 15 ppm. The output energy in routine operation is 1 - 2 Joule (3 Joule max.). A sketch of the configuration of the oscillator, the pulse chopper and the alignment optics is given in figure 1.
The laser has been installed on an optical bench in an air-conditioned room to avoid any problems with moisture, dust and stability of alignment.

TRANSMITTING AND RECEIVING TELESCOPE

The transmitting telescope is of a refractive coudé design and the receiving telescope is of a partial coudé design (optical path passes through the elevation axis only) 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. By doing so the size of the complete optical system has been significantly

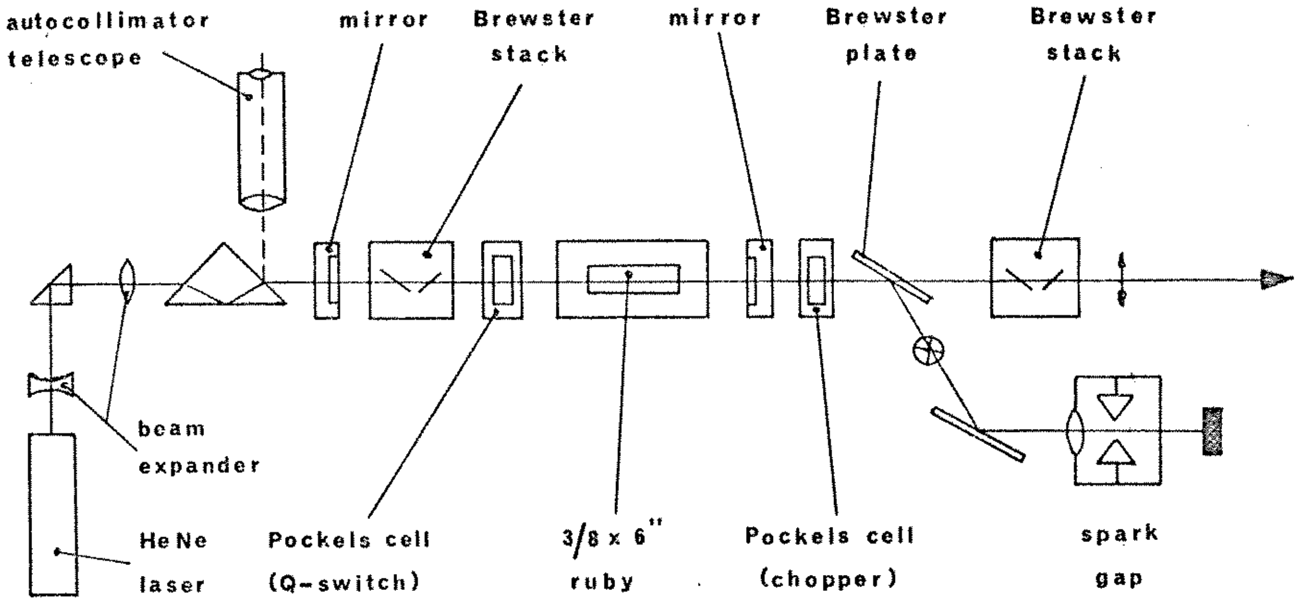


Figure 1

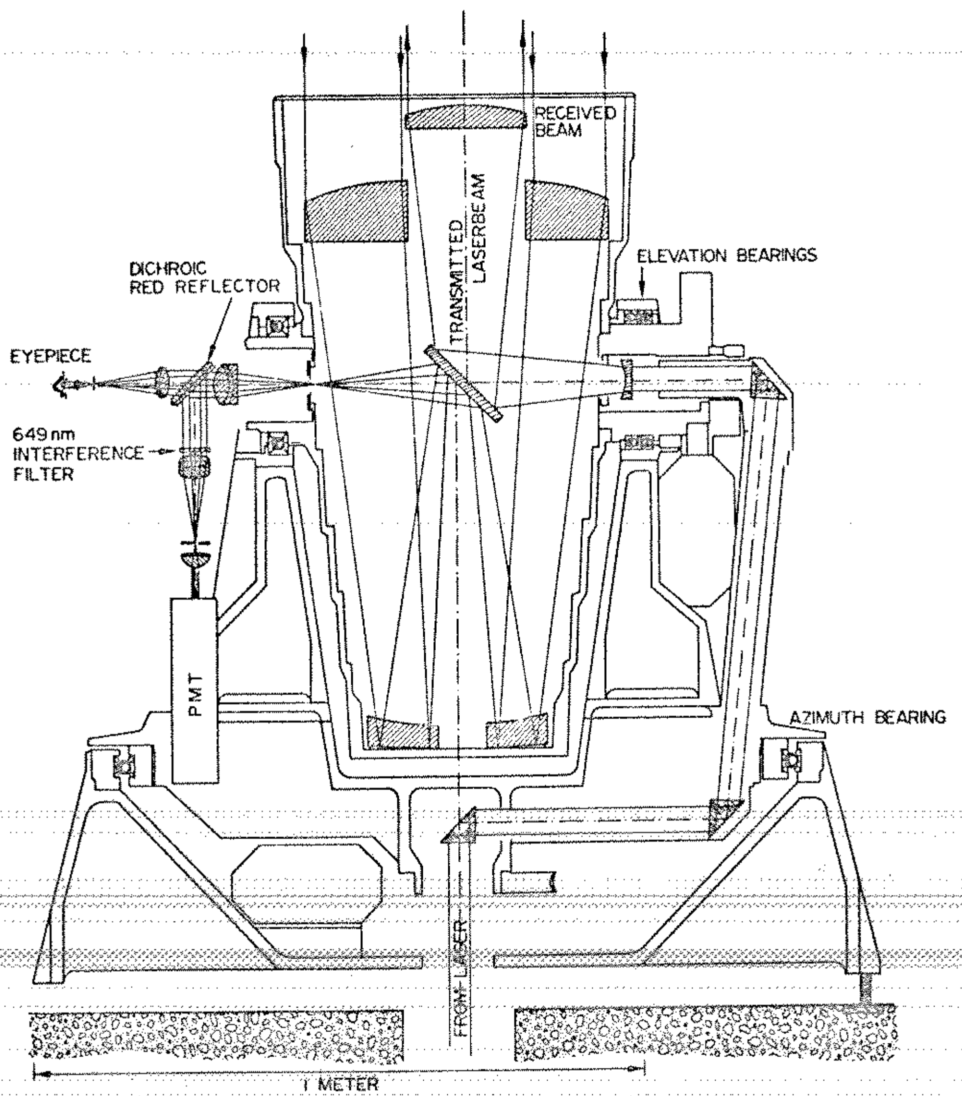


Fig. 2. Coudé telescope.

reduced (figure 2.).
The transmitted laser beam has a diameter of 19 cm and the divergence is adjustable from 1 to 20 arcminutes.
The aperture of the receiving telescope is 50 cm and the field of view is adjustable from 1 to 20 arcminutes.
The mount's angular position is read out using fine and coarse absolute optical shaft encoders. The mount control unit then compares the actual position with the desired position. The error signal generated is used to drive the DC servo motors. The absolute pointing error of the mount is less than 20 arcseconds. The total positioning range of the elevation axis is $0 - 180^{\circ}$; the range of the azimuth axis is $0 - 720^{\circ}$.
By means of a dichroic red reflector the received light is split into wavelengths > 6500 Å which are directed to the photomultiplier and wavelengths < 6500 Å going to an eyepiece. In this way the operator can see sunlit satellites to a visual magnitude of + 13. This feature has shown to be extremely useful in acquiring poorly predicted satellites with a narrow beam.
The reflection of the transmitted laser beam on the second prism has been directed via a secondary optical path (not shown in figure 2) and an adjustable attenuator to the photodetector. In this way it is possible to perform system calibrations without an external target.

MEASURING SYSTEM

The detection circuitry and time interval meter is composed of the following principal equipment:

- photomultiplier: RCA model 8852
- interference filters: bandwidths 3 Å and 10 Å
- preamplifier: Hewlett Packard model 10855A, ampl. 24 dB, 1300 Mhz, noise figure 8 dB
- xx - preamplifier: Trontech W 500 B, ampl. 31 dB, 500 MHz, noise fig. 1.5 dB
- progr. attenuator: Texcan PA - 51 , atten. 0 - 63 dB
- amplifier: Avantek AV - 9T , ampl. 30 dB, risetime 0.8 ns
- xx - amplifier: Trontech W 500 C, ampl. 40 dB, 500 MHz
- range gate generator: SAO design, window 1 - 99 µs, range 1 - 999999 µs
- time interval counter: Hewlett Packard 5360A , H01 - 5379A , resolution 0.1 ns , discrimination technique: fixed level, leading edge
- start pulse detector: ITT F-4000 biplanar photodiode, risetime 0.5 ns

xx - <u>discriminator start pulse</u>: Ortec 473A constant fraction discriminator

xx - <u>discriminator stop pulse</u>: EG & G T 105/ N leading edge discriminator

- <u>waveform digitizer</u>: Tektronix R 7912 transient digitizer, package WP 2003, to be linked to a Hewlett Packard 21 MX-E minicomputer (second half 1978)
- <u>epoch clock</u>: SAO design, resolution 1 μs

The xx marked instruments have been integrated in the system recently (May 1978).

CALIBRATION PROCEDURE

Before and after each satellite pass a minimum of 10 calibration measurements are carried out, using the internal short circuit light path. This light path has been measured with an AGA 700 laser geodimeter to a preliminary accuracy of 3 cm.

During the measurements the transmitted beam is attenuated by a factor of about 10^6. On the photomultiplier side an optical attenuation is introduced in order to equalize the calibration return signal with the average return signal from the satellite.

STATION TIMING

Standard frequency and station time is derived from a rubidium standard. The principal synchronisation technique is time comparison against the Netherlands national time standard UTC_{vsl} in The Hague using television broadcast synchronisation pulses.

Present overall timing accuracy: 1 microsecond UTC.

LASER SAFETY

The following safety measures have been taken:

- personal protection: safety goggles, warning signs, optical and electrical shielding, etc.
- careful control system design, including strict operating procedures
- attenuation of the laser beam when performing tests and calibration measurements
- airtraffic protection: an optical airplane detection system with automatic laser inhibiting.

PREPROCESSING

All satellite observations are subjected to an adjustment with respect to a best fitting elliptical orbit, in order to have a first insight into the number of likely succesful returns. After rejecting probable outliers each residual is individually tested statistically with respect to an a priori estimated single shot precision of 1.5 ns (round travel time). Figure 3 gives an example of the residuals of a typical LAGEOS pass.
As mentioned already pre- and post-pass calibrations are carried out routinely. These measurements are used to update the value of the system delay with respect to the reference point at the intersection of the two telescope axes.

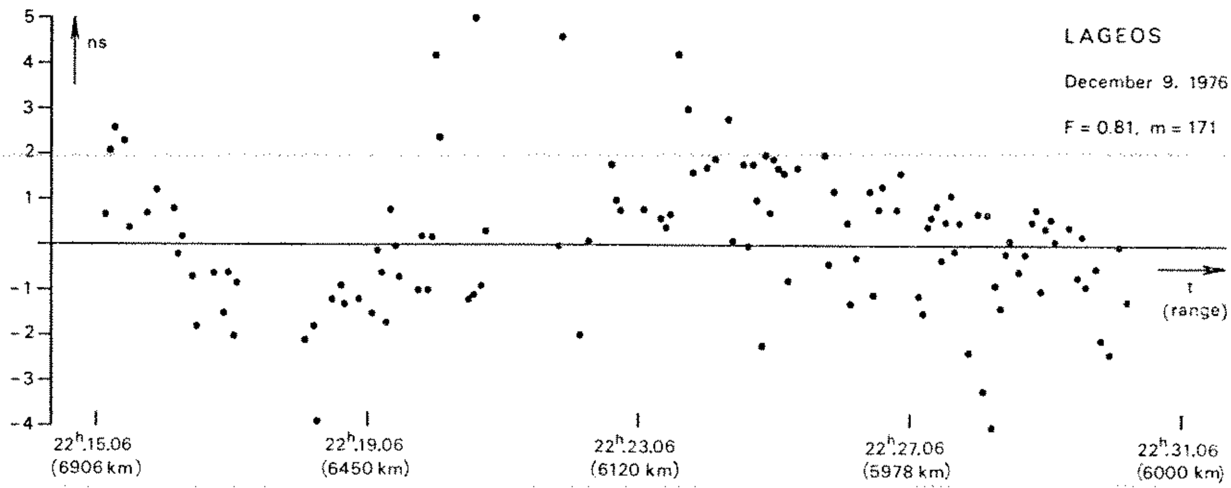
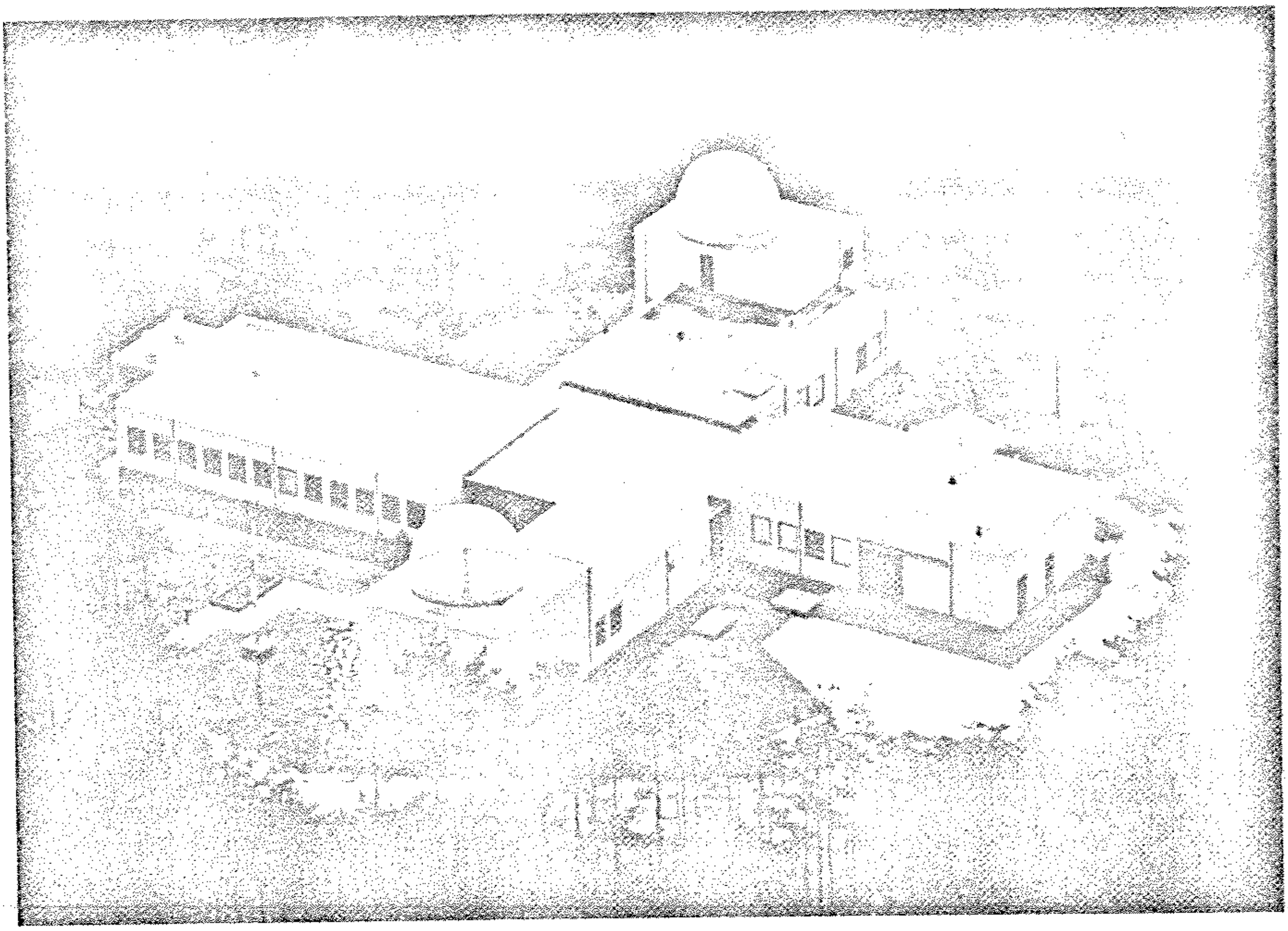
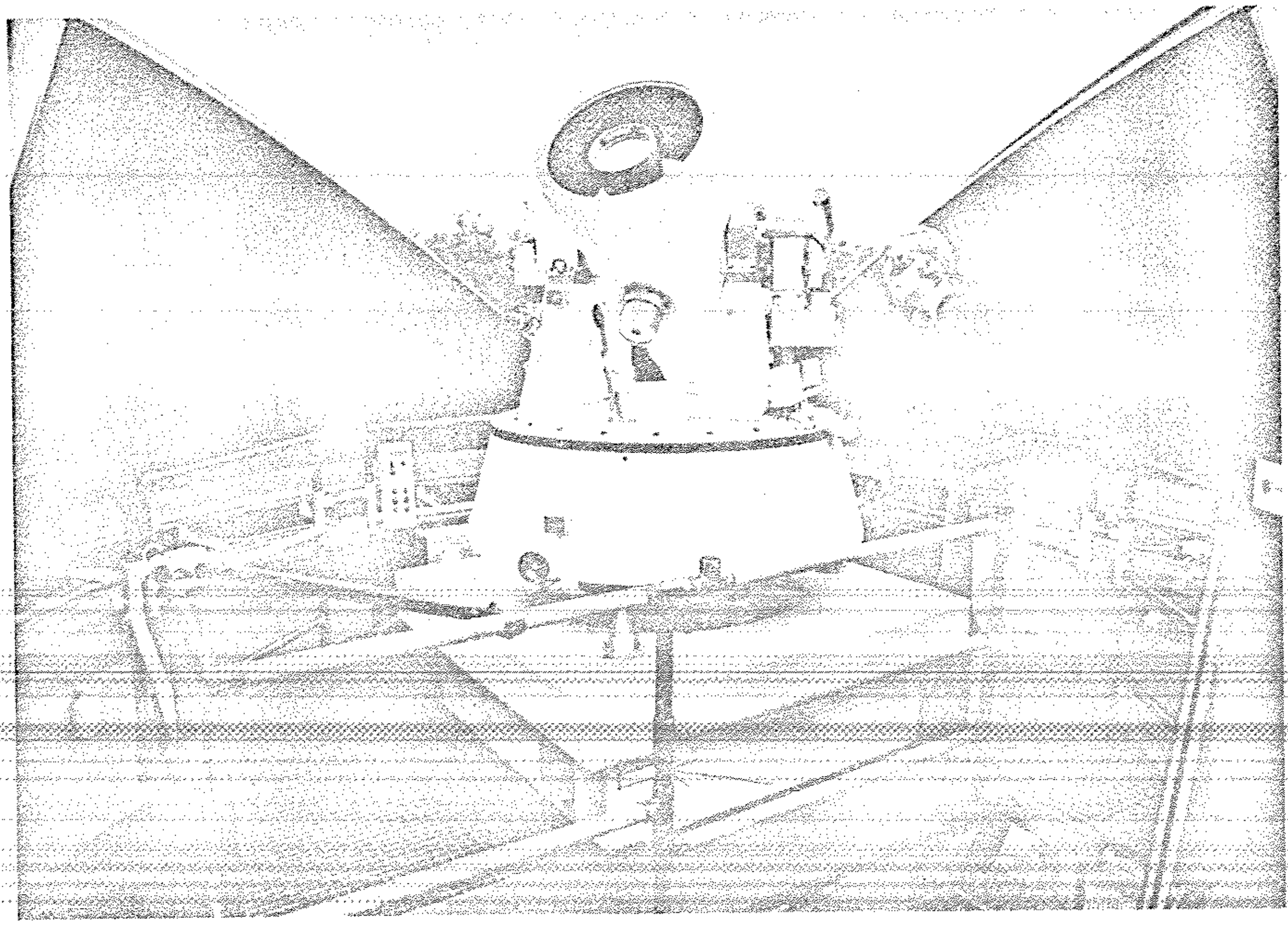


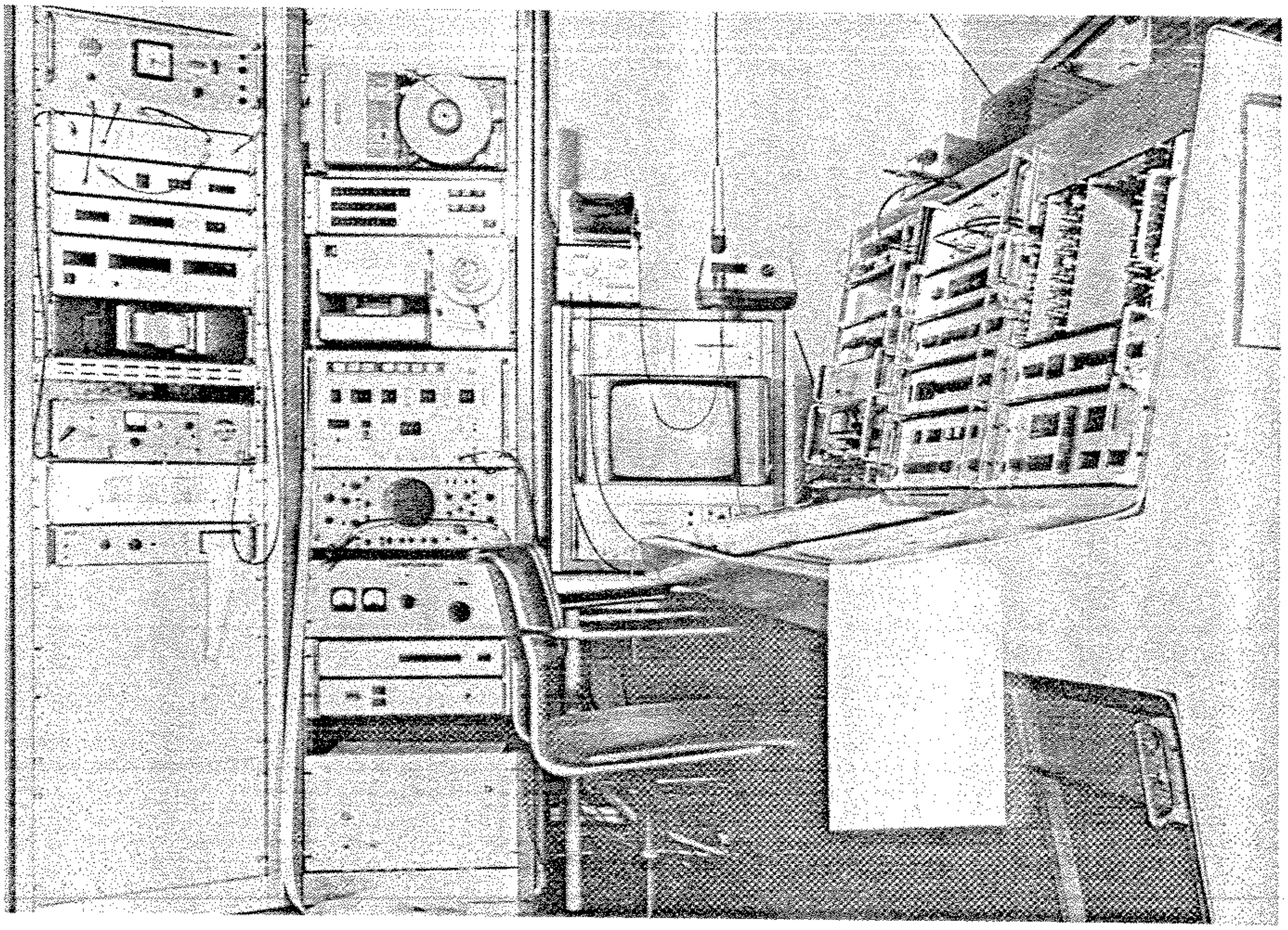
fig. 3



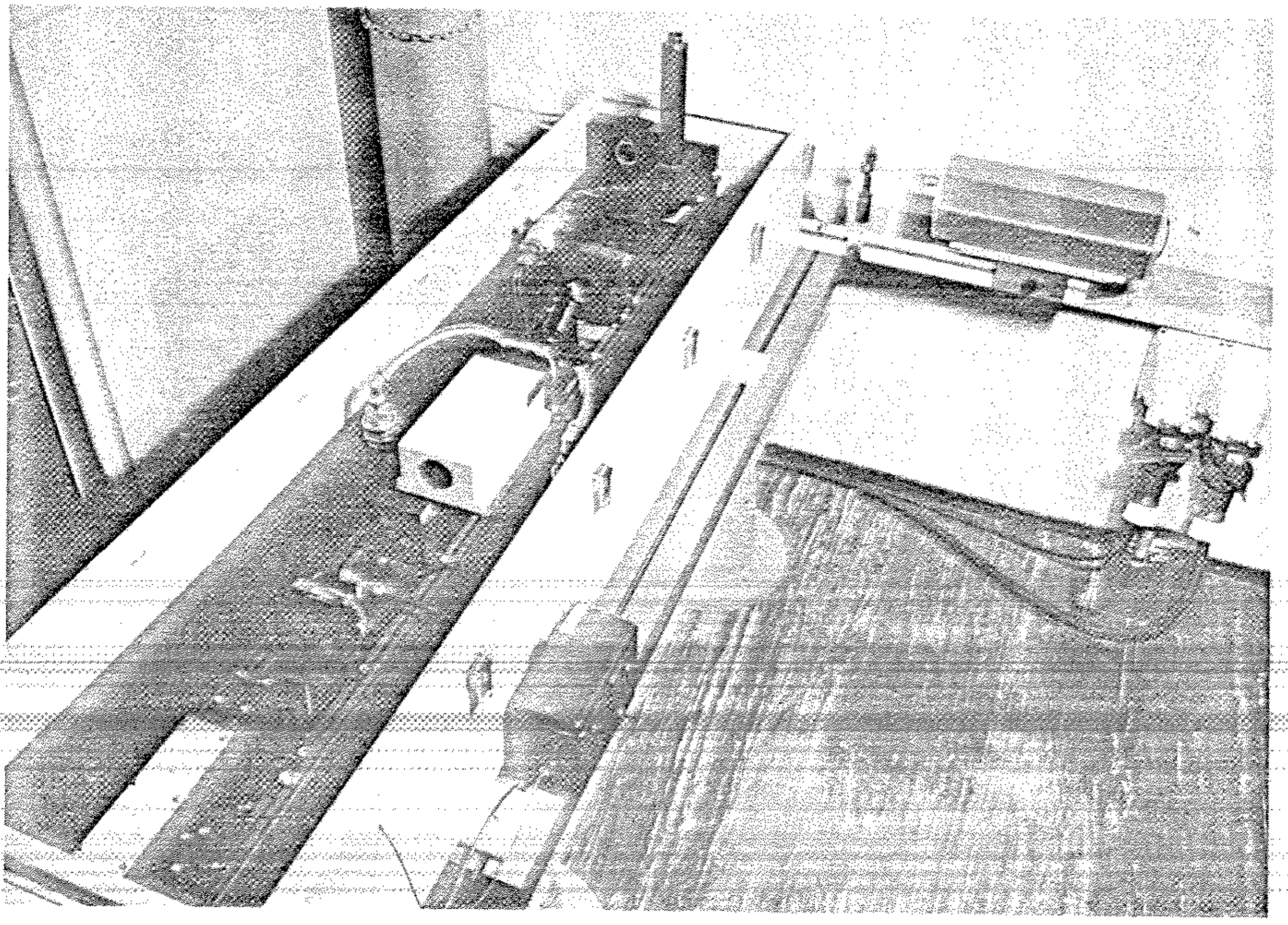
KOOTWIJK OBSERVATORY



COUDÉ MOUNT



CONTROL ROOM



LASER OSCILLATOR

SUMMARY STATISTICS STATION: 7833 KOTWIK PERIOD: 1976-1978 (DATE: 780516 CODE: 01)

	CALIBRAT. (0000000)		BEACON-C (6503201)		GEOS-1 (6508901)		GEOS-2 (6800201)		STARLETTE (7501001)		GEOS-3 (7502701)		LAGEOS (7603901)		TOTAL	
	OBS	PAS	OBS	PAS	OBS	PAS	OBS	PAS	OBS	PAS	OBS	PAS	OBS	PAS	OBS	PAS
JAN	0	0	0	0	0	0	0	0	53	6	167	7	439	7	659	20
FEB	0	0	0	0	0	0	0	0	0	5	35	13	21	6	56	24
MAR	0	0	0	1	1132	21	0	0	165	21	252	18	560	13	2109	74
APR	0	0	0	0	690	11	0	0	848	42	710	31	1359	15	3607	99
MAY	0	0	85	3	285	9	0	0	287	21	378	20	1138	7	2173	60
JUN	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
JUL	0	1	0	0	0	0	70	1	0	0	145	3	0	0	215	5
AUG	0	0	0	0	841	7	167	3	91	17	446	27	83	1	1628	55
SEP	0	0	0	0	358	4	144	3	659	42	787	30	153	9	2101	88
OCT	0	0	0	0	48	1	52	1	222	25	375	38	399	12	1096	77
NOV	0	0	0	0	0	0	101	1	466	40	533	26	884	17	1984	84
DEC	0	0	0	0	236	5	0	0	289	13	241	10	861	10	1627	38
TOT	0	1	85	4	3590	58	534	9	3080	232	4069	223	5897	97	17255	624

SATELLITE LASER RANGING INSTRUMENTATION AT THE POTSDAM STATION [1)]

Harald Fischer and Reinhart Neubert
Zentralinstitut für Physik der Erde
Potsdam, DDR

INTRODUCTION

The Potsdam laser ranging instrument is based on the satellite camera SBG made by Zeiss Jena, which was already in operation at the beginning of our laser work. The modification of the camera was done in such a way, that both photographic and laser observations are possible with quick switchover between the two modes of operation.

Tab. 1.: Specifications

Transmitter	
Laser energy:	1 ... 2 J
Pulse width:	15 ... 25 ns
Beam divergence:	1 ... 10 min of arc
Receiver	
Effective aperture:	320 mm dia
Field of view	1 ... 10 min of arc
Filter passband:	1 nm, T > 50 %
Photomultiplier type:	RCA C 31034 A
Resolution of time interval counter:	10 ns

According to the main data (see Tab. 1.) the instrument belongs to the first generation characterised by accuracies of about 1 m. The laser modification was put into experimental operation at the beginning of 1974.

1) Paper read by K. Hamal Additional information is contained in unread papers distributed to participants of the workshop.

Since that time more than 1000 points have been collected mainly from GEOS-satellites, but some from STARLET and LAGEOS too. The number of measurements may be increased by operating the instrument more routinely and by the planned modification for daylight tracking. In the following we give a short description of the instrument.

SYSTEM DESCRIPTION

The Potsdam laser ranging system is of almost conventional design and the diagrams of figure 1 and 2 are thought to be quite self-explanatory. We note here that both the start and stop channel contain constant fraction discriminators of identical characteristics. The epoch timer is initiated from the same pulse which starts the range counter. This is necessary to eliminate the time jitter of the passive Q-switched laser. To protect the sensitive GaAs-cathode photomultiplier, pulsed supply voltage is used. The output data are printed and punched on paper tape.

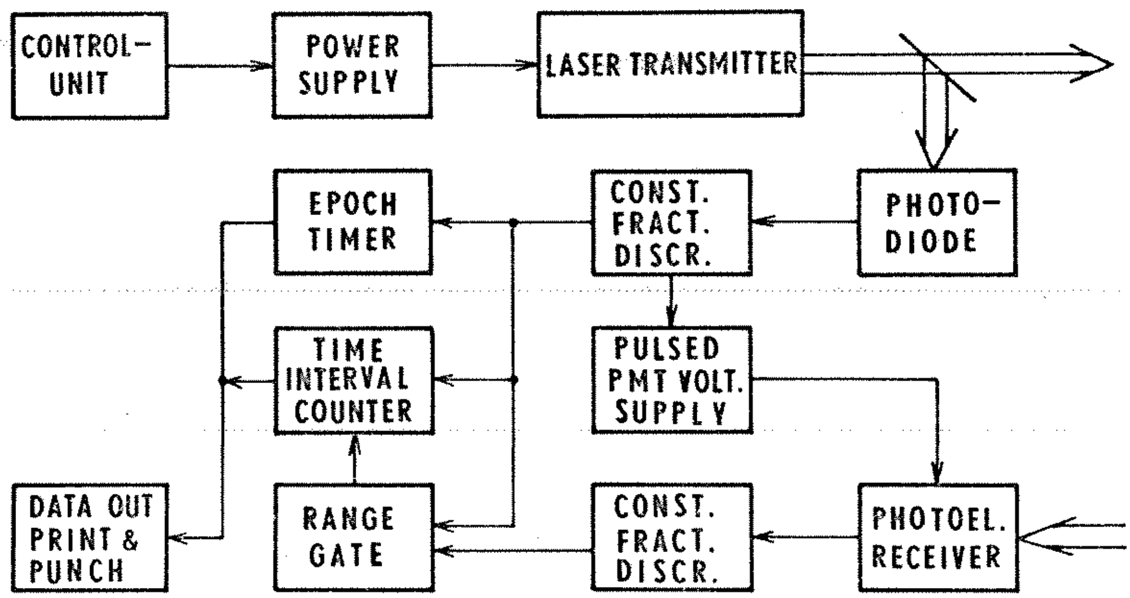


Fig. 1.: Block Diagram of the Laser Ranging System

1. Laser Transmitter

The laser used is a two-stage ruby system, which was constructed in our laboratory. The oscillator is Q-switched by the simple saturable dye method, giving pulses of 15 to 25 nanoseconds duration and energies of 0.3 to 0.5 Joule. After passing through the amplifier rod, the pulses have an energy of about 2 J. Both ruby rods are pumped by two linear flash-lamps in diffuse reflection cavities. The repetition frequency is determined by the power supplies to 0.2 cps maximum. Using high stability charging units for the condenser batteries the reproducibility of the laser pulses has been found to be quite satisfactory. The Q-switching solution has to be exchanged after about 1000 shots.

2. Mount and Receiver Optics

The SBG-camera has a 4-axis mount which is well suited to visual tracking but the original tracking system is not sufficiently accurate for automatic operation. We have attached to the mount a theodolite for exact setting of the inclination of the 3^{rd} axis and digital encoders to the 3^{rd} and 4^{th} axis. This way an absolute pointing accuracy of better than 1 min of arc has been reached as checked by reference stars /1/. The Schmidt telescope of the SBG has been equpped with a hinged Cassegrain mirror which may be swept into the ray path in front of the photoplate assembly (figure 2). The switchover between photographic and ranging mode takes about one second. The photoelectric receiver package is placed behind the main mirror. It consists of the iris field stop, the temperature controlled filter unit, the photomultiplier and two bending mirrors. In 1976, the first bending mirror has been replaced by a dichroic one so that by an additional eyepiece the main telescope may be used as a guide too. this low cost improvement enabled us to track STARLET and LAGEOS visually.

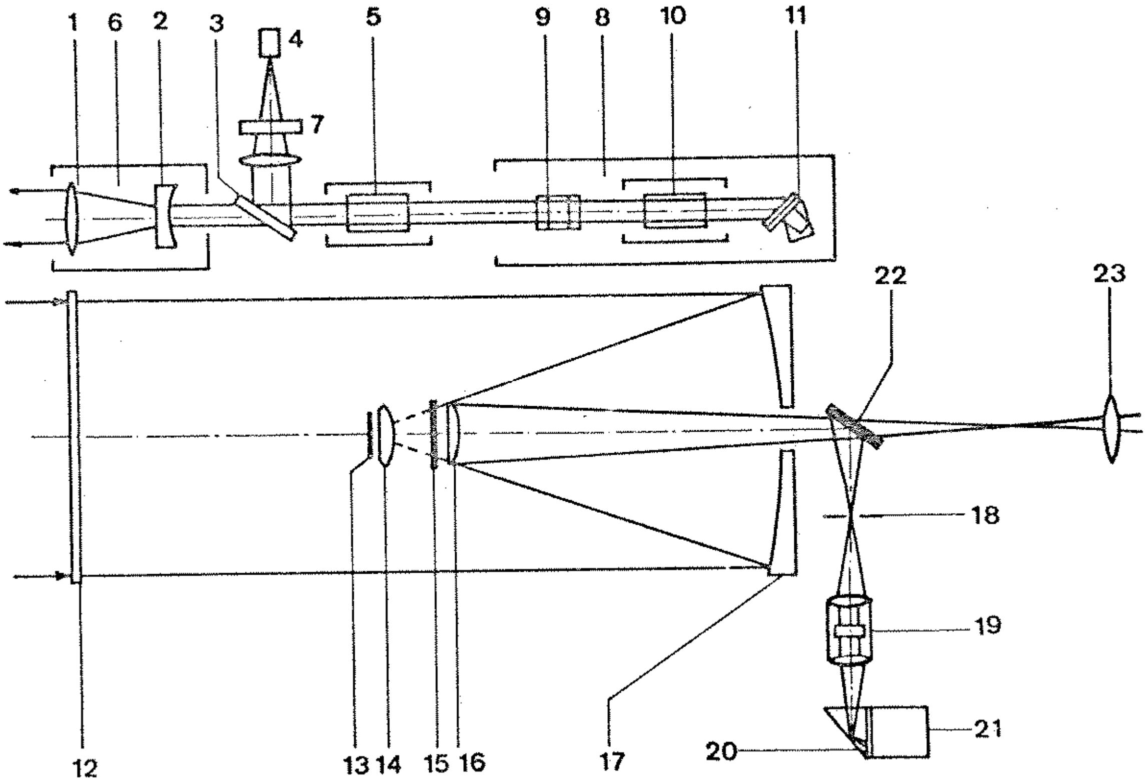


Fig. 2.: Optical Diagram of the Transmitter and Receiver System

1 = Objective Lens, 2 = Negative Lens, 3 = Parallel Plate, 4 = Silicon Photodiode, 5 = Amplifier Ruby, 6 = Beam Expander, 7 = Neutral Density Filter, 8 = Oscillator Stage, 9 = Etalon Reflector, 10 = Oscillator Ruby, 11 = Q-Switching Cell and Prism Reflector, 12 = Schmidt Plate, 13 = Photographic Plate, 14 = Field Flattening Lens, 15 = Shutter, 16 = Hinged Cassegrain Mirror, 17 = Main Mirror, 18 = Field Stop, 19 = Interference Filter, 20 = Prism, 21 = Photomultiplier, 22 = Dichroic Mirror, 23 = Eyepiece.

3. Receiver Electronics

Since 1977 we have used a RCA C 31034 photomultiplier. The measured quantum efficiency of about 20 per cent and the dark pulse characteristics let us expect a sensitivity enhancement of about 20 times compared to the former used C 31000. This was confirmed by calibration target measurements and by successful LAGEOS tracking.

Unfortunately the C 31034 has to be operated at anode currents below 10^{-7} A for a 30 s averaging time according to the manufacturer. To guarantee this the PMT supply voltage is held at 800 V dc and switched to operating voltage of 1600 to 1800 V for some milliseconds during possible echo return. In addition a safety circuit switches off the PMT voltage if the anode dc current exeeds 10^{-7} A.

The constant fraction discriminator is of the short circuited cable reflection, zero crossing type. The superposition of the signal pulse with reflected delayed pulse of opposite polarity has a zero crossing point which is almost independent of signal amplitude /2/. A tunnel diode trigger is used as zero crossing detector.

OPERATIONAL RESULTS

Laser tracking results obtained using visual guiding are quite satisfactory. For GEOS-satellites a data rate up to the maximum, determined by laser repetition frequency has been obtained. The possibility of alternating laser and photographic observations during one passage has been verified many times. In this case the time lost for laser tracking is about 20 sec for each plate depending on satellite height. A good test of sensitivity to date is the possibility to get echoes from the newer satellites STARLET and LAGEOS. Using visual tracking we got echoes from both satellites, but LAGEOS has been found to be very close to the sensitivity limit. Table 2 shows the printout of LAGEOS measurements of September 26th, 1977. The laser energy was 0.8 J and the divergence angle 1 min of arc. The receiver trigger level was set to 2 to 3 photoelectrons leading to an overall return rate of about 20 per cent.

Tab. 2.: Printout of LAGEOS-Measurement

STATION NO.: 1181   SATELLITE NO.: 7603901
DATE.: 1977 9 26

NO	EPOCH H	M	S	DISTANCE MEGAM.	DEV.FROM PRED. KM
1	3	32	49.8073	6.2739135	-4.10
2	3	34	54.2709	6.1509417	-4.37
3	3	35	27.1611	6.1261924	-4.42
4	3	37	7.8637	6.0713424	-4.54
5	3	37	21.3421	6.0664348	-4.54
6	3	37	42.7388	6.0598334	-4.56
7	3	37	54.9485	6.0567290	-4.57
8	3	40	40.2293	6.0619274	-4.55
9	3	41	4.2506	6.0700023	-4.52
10	3	41	40.3580	6.0856035	-4.48
11	3	42	35.3354	6.1172631	-4.40
12	3	44	44.6120	6.2283076	-4.14

References

/1/ FISCHER, H.; NEUBERT, R.: In: "Arbeiten zur Satellitengeodäsie". Veröffentlichung d. Zentralinstituts f. Physik der Erde, Nr. 40, Potsdam 1976, S. 77-95

/2/ MEILING, W.; STARY, F.: Nanosecond Pulse Techniques. Berlin: Akademie-Verlag 1969

THE DIONYSOS SATELLITE RANGING LASER, 1978

W.C.Johnson and G.Veis
Dionysos Satellite Tracking Center

The Dionysos satellite laser ranging system has been improved since previously reported, (1), to increase it's rate range and accuracy. Work is in progress to further increase it's ranging rate, it's measuring accuracy and to automate the system with computer control.

A new laser has been installed to replace the previous 1 joule, rotating prism Q-switched ruby laser. The new laser was manufactured by Holobeam Laser presently of Orlando, Florida, U.S.A. This laser is water-cooled and has a single ruby rod, 6"x1/2"dia. with a hellical flash lamp. The rod output is Q-switched by a Pockels cell producing an output energy of 4.5 joules with a half energy divergence of less than 7 milliradians and a half amplitude pulse width of 25 nanoseconds. Included with the laser is a Pockels cell pulse slicer. The output energy after slicing is approximately 0.75 j. with a half amplitude pulse width of 7 nsec. This slicer will be used routinely in the near future.

The laser is installed on an optical bench in the control room and the output is directed by prisms into the altitude-azimuth (fig.1) mount above this room. In the transmitting telescope, the divergence can be adjusted to less than 1 mrad. The laser is capable of a firing rate of 60 pulses per minute at it's maximum energy, however in 1977, the laser was routinely used at 8 ppm.

The Coude' alignment of the laser ranging mount output was first used in 1977. The previous laser was mounted directly in the transmitting telescope. The mount is driven by stepping motors in altitude and azimuth in steps of 0.001 degree. The pointing accuracy of the mount and attached receiving telescope is ±0.003 degree of ±10 arcsec. However the overall pointing accuracy of the transmitted beam after passing through the mount and transmitting optics is presently only ±1 arcmin. Routine ranging with returns from all parts of the sky has been done with a laser beam diverence of 1 mrad. Work is in progress to improve output pointing to allow reduced output divergence.

To accommodate the increased ranging rate of 8 ppm, several changes were made to the control electronics (fig.2). Previously, the difference in altitude and azimuth to the next position for the mount and the predicted range delay were entered manually for the 2 ppm ranging rate. Presently, a paper tape, generated by the prediction program, provides the necessary input to track and range for each satellite pass at the 8 ppm rate.

Current work is aimed at entry of the prediction parameters through a 9825A Hewlett-Packard computing calculator (fig.3). This calculator will control the system during operation and handle the input and output of data. Connection will be made by telephone data link to the maine computer in Athens. This connection will transfer orbital elements as received at Dionysos from the Smithsonian Astrophysical Observatory and the satellite pass predictions as generated by the computer in Athens. The predictions will be recorded on magnetic cassettes and the calculator will drive the system through each pass with various adjustments possible by the observer. Returns data will be recorded together and other auxiliary information on cassette and summaries prepared by the calculator.

The ranging rate will be increased to 20 ppm in the planned system. The rate will not be fixed, but will vary within each pass. This will allow maximum pass coverage within the limits of the mount drives speeds. The calculator will record also the local temperature, pressure and relative humidity from sensors at the time of each observation.

The addition of the pulse slicer in the laser output will require improvement of the pulse detection instrumentation. Presently, the range counter uses fixed thresholds for starting and stopping. The stop pulse is derived from the received pulse after operator controlled attenuation. It is planned to use an analog system of pulse discriminators for pulse detection similar to that presently used in the SAO tanging systems,(2).

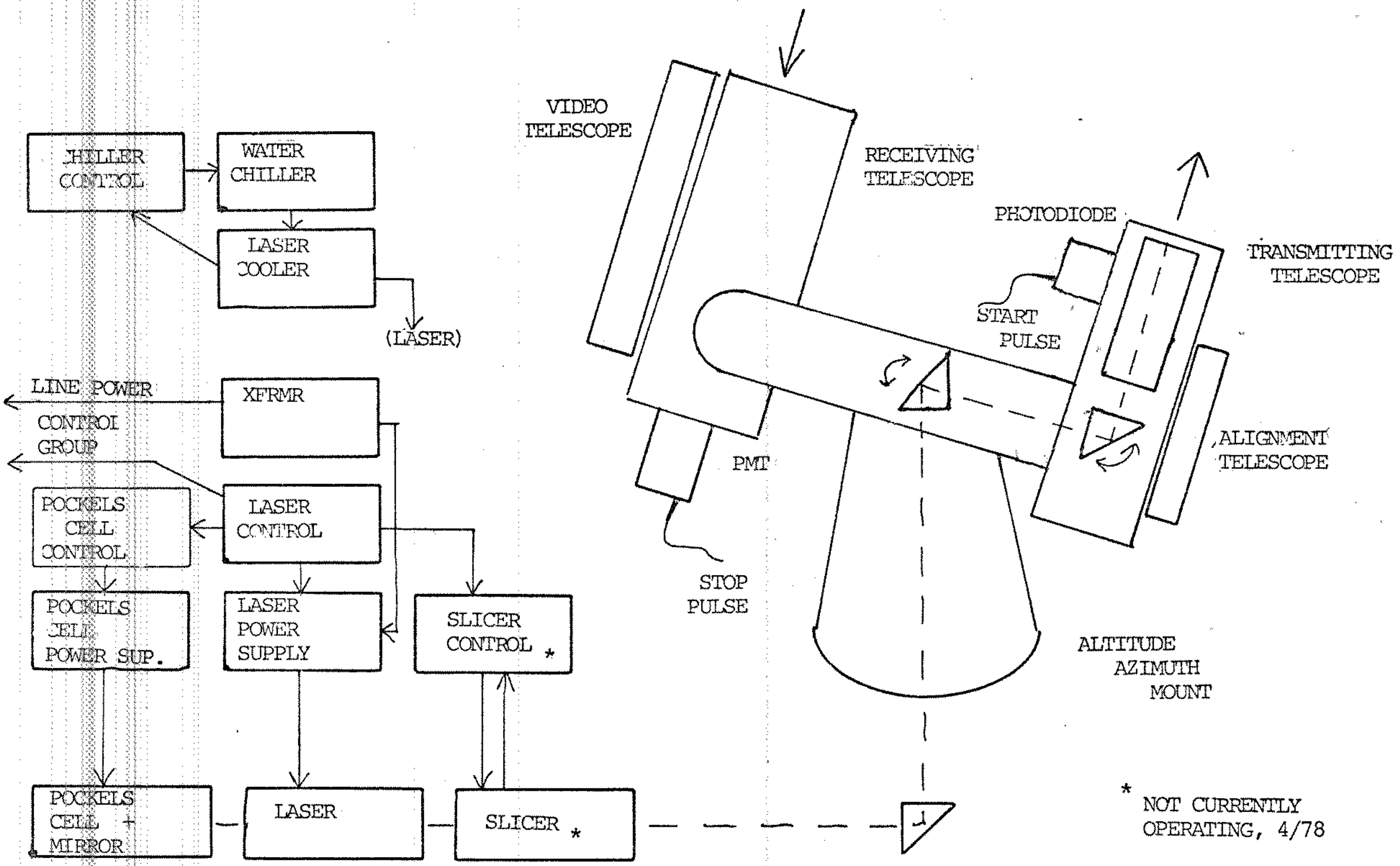
Successful measurements during 1977 using the system shown in figures 1 and 2 are totaled in the next table. The measurements had approximately an accuracy, of better than a meter.

DIONYSOS LASER

SUCCESSFUL MEASUREMENTS* (1977)

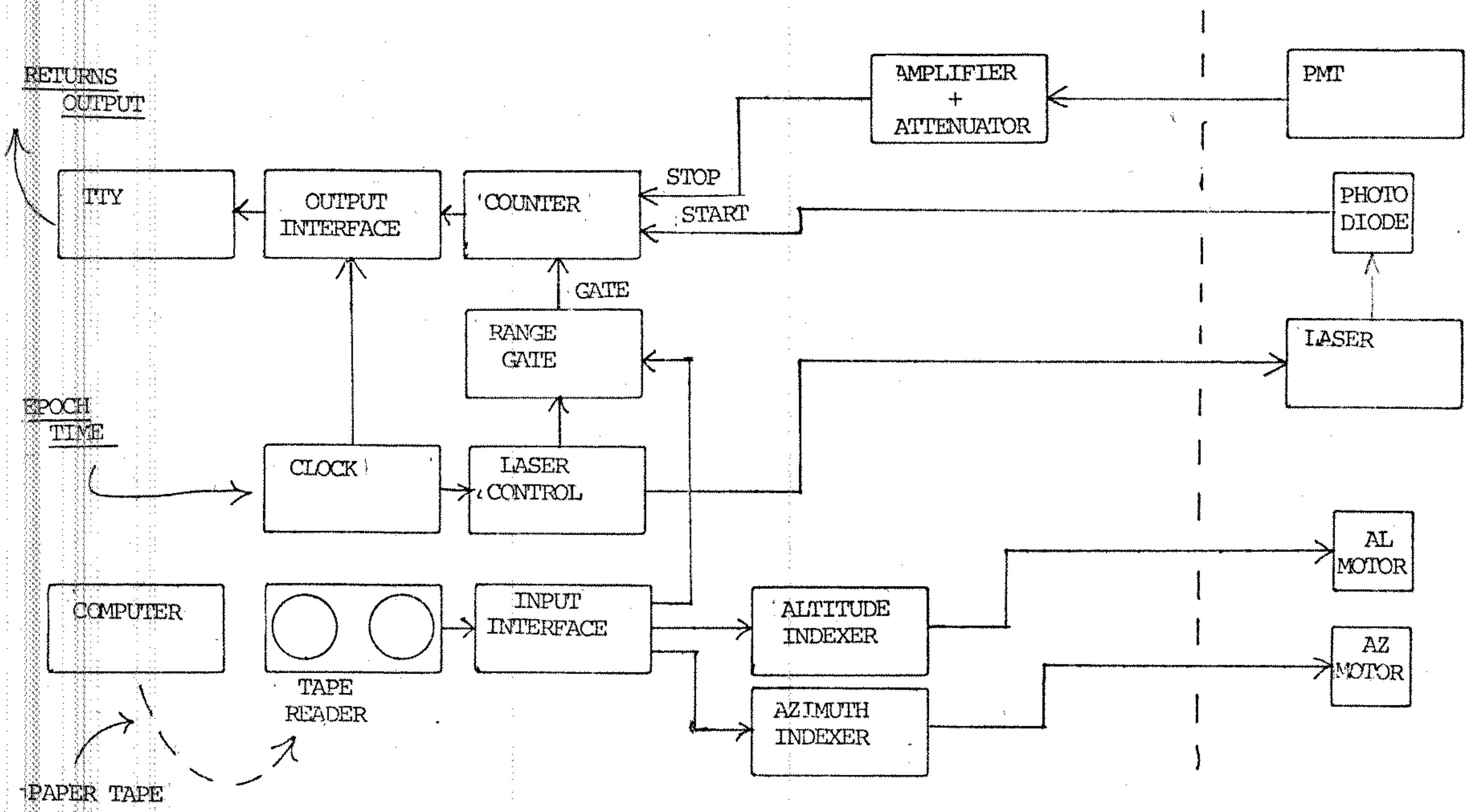
	BE-3	GEOS I	STARETTE	GEOS III	TOTALS
June	-	3(1)	-	-	3(1)
July	-	45(9)	-	85(14)	130(23)
August	555(22)	310(15)	439(31)	284(15)	1588(83)
Sept.	12(1)	36(1)	138(12)	151(7)	337(21)
Oct.	336(12)	74(4)	-	191(8)	601(24)
Nov.	-	4(1)	-	4(1)	8(2)
					2667(154)

* Numbers refer to successful return.
Number in parenthesis successful passes.

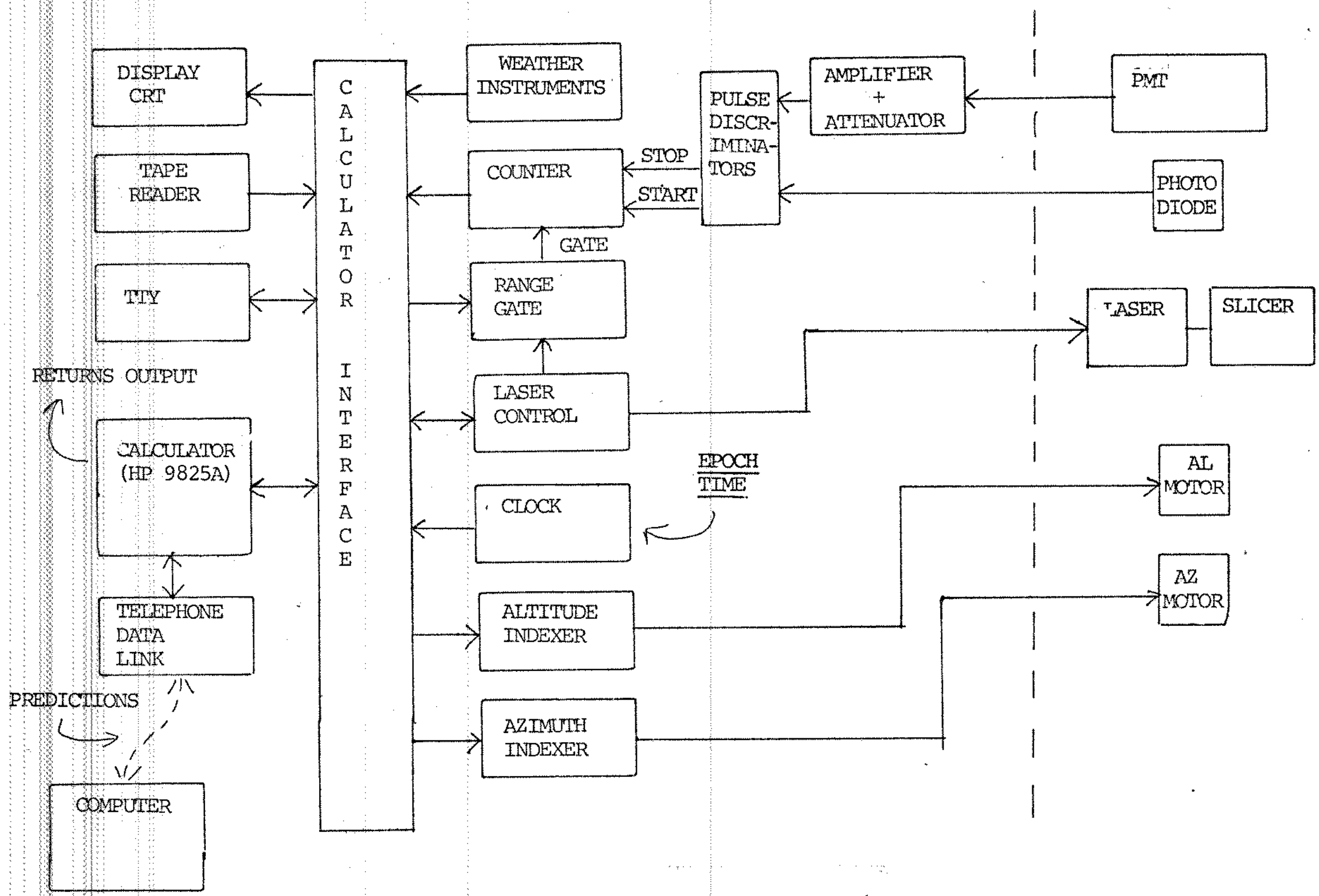


DIONYSOS LASER - LASER GROUP AND MOUNT GROUP

(FIG.1)



DIONYSOS LASER - CONTROL GROUP (CURRENT, 4/78) (FIG.2)



DIONYSOS LASER - CONTROL GROUP (WORK IN PROGRESS)

(FIG. 3)

References

(1) G.A.C.Assimakis, D.D.Balodimos, G.Veis : "THE LASER SATELLITE RANGING SYSTEM AT THE DIONYSOS STATION" Proceedings of the International Symposium on the Use of Artificial Satellites for Geodesy and Geodynamics, Athens, (1973).

(2) M.R.Pearlman, C.G.Lehr, N.W.Lanham and J.Wohn : "THE SMITHSONIAN SATELLITE RANGING LASER SYSTEM" Proceedings of the Second Workshop on Laser Tracking Instrumentation, Prague (1975).

THE SATELLITE LASER RANGING SYSTEM
AT CAGLIARI OBSERVATORY

L. Cugusi
Istituto di Astronomia
Università di Cagliari - Italy

INTRODUCTION

The laser ranging station of Cagliari Observatory was originally conceived in 1975 as an improved first generation system. Its ranging capabilities are estimated to allow to easily track the recently launched geodynamic satellites as Starlette and Geos 3.

The main scientific aim is to study polar motion and Earth's rotation by means of the satellite observational data collected. Indeed laser range observations will join at Cagliari Observatory more conventional observational techniques for geodynamic studies: VZT (operating at Carloforte since 1889), PZT (now undergoing the final testing), Doppler receiver (operating from last year) and Danjon Astrolabe (operating by the end of this year).

STATION DESCRIPTION

1. LASER TRANSMITTER SYSTEM

The optical rail assembly (Apollo Lasers) consists of a 3"x3/8" (7.5 x 1 cm) ruby oscillator, which is operated in the Q-switched mode, giving about 1 J in 20-25 ns pulse width at 30 pulses per minute.

The output of the oscillator is fed into a KD*P Pockels cell and polarizer combination, which forms an electro-optic shutter (with laser-triggered spark gap) to chop the Q-switched pulse. The output of the shutter drives a 6"x1/2" (15x1.3 cm) ruby amplifier: typical final output is 1 J in 5 ns pulse width at 30 ppm, or 200 MW peak power. The beam divergence reaches the relatively high value of 3 mrad, typical of the multimode resonant cavities.

A power supply provides pulsed energy to the flashlamps and Pockels cells. A control console includes electronics for controlling bank voltage, lamp triggering, Q-switch triggering and timing.

Both the laser heads are cooled by means of a refrigerated water-to-air system, which provides temperature controlled coolant water.

A laser energy meter and a vacuum photodiode together with a 500 MHz real-time-bandwidth oscilloscope permit to monitor the laser output.

The optical rail is supported by a granite slab, resting on a concrete foundation. The laser beam reaches the collimating telescope through a coudé optical path of five multidielectric layer coated flat mirrors.

The collimating telescope is a 6x Cassegrain quasi-afocal optical system; so the beam divergence should be at least 0.5 mrad.

2. TRACKING SYSTEM

The turret is an EOTS-B Cinetheodolite with a rebuilded optical section. Blind tracking is not jet possible (future tracking improvements are described in the last section): after sunset and before sunrise observing satellites is possible through a TV system, by controlling both azimuth and elevation motors of the mounting by means of a joy-stick.

The TV system consists of a camera tube (RCA 4804) for very low light level, controlled by a custom-built camera control unit, installed at the first focus of a 25 cm diameter Maksutov type telescope: the focal lenght of the telescope was chosen to give a 2° field of view on the TV monitor. Objects as faint as 12th magnitude fall within the capabilities of this TV system.

3. ECHO RECEIVER AND DATA RECORDING SYSTEM

A telescope of 50 cm diameter collects and focalizes the weak echoes, through a suitable filtering optical system, on the photo cathode of a Quantacon type (RCA C31034) photomultiplier. This photomultiplier is estimated to be very suitable only for night-time ranging.

Both the laser output pulse and the satellite echo reach the photomultiplier: indeed a fiber optic shunts a small fraction of the output pulse to the photomultiplier; so that only one discrimination circuit is necessary.

The anode pulses are amplified externally before discrimination is feasible in practice: a low noise, fast amplifier (ORTEC 454 TFA) has been chosen.

The discrimination is carried out by means of a constant fraction timing operation (ORTEC 473 CFD), intended to avoid that timing depend on pulse height.

The output of the discrimination circuit is a shaped pulse which trigger (start pulse) both the time interval counter (Eldorado 796, 1 ns resolution) and the preset counter (see block diagram) and allow the printing of the content of the clock register. Any pulse discriminated before preset time has elapsed is considered to be the expected satellite echo (stop pulse): it stops the time interval counter and allow the printer to record the time-of-flight. On the contrary any signal crossing the discriminator threshold after the preset time will not generate an output.

4. TIMING AND TIME SYNCHRONIZATION

A cesium master clock (Oscilloquartz B 3200) provides 1 MHz external frequency to the time interval counter; it controls also the clock register, giving 1 μs resolution.

Time synchronization is carried out by means of both Loran-C and TV techniques. In the former case, time signals of the Simeri Crichi station are usually received; in the latter, a mutual data exchange takes place with the Institute "Galileo Ferraris" of Turin.

In the best conditions, it seems possible to obtain time synchronization within less than 1 μs.

5. EXPECTED SYSTEM RANGING ACCURACY

A theoretical evaluation (L.Cugusi et al., 1975) of the final accuracy of the range data collected by means of a laser ranging station like that described, shows that a value close to 20 cm should be obtained. Nevertheless it is only a rough estimate, this value depending strongly on the height of the return signals, calibration techniques and system internal stability.

6. FUTURE IMPROVEMENTS

In the near future, priority will be given to blind tracking: real time tracking will be obtained by interfacing the Cinetheodolite electronics with our minicomputer (Honeywell Series 60, Mod. 6/43, 64 KB Memory). Another interface will allow to record on the magnetic tape unit of the minicomputer the observational data.

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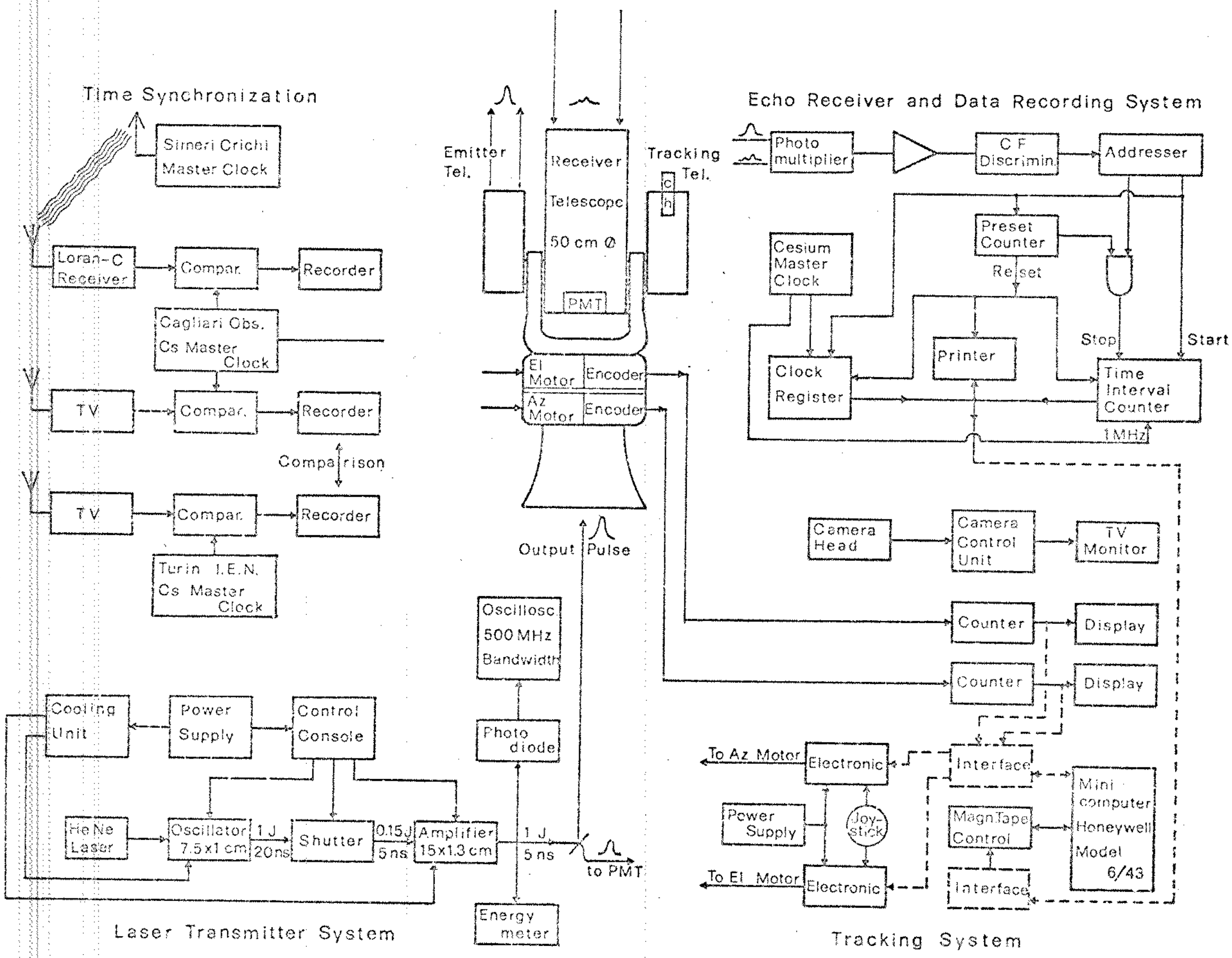
L.Cugusi, F. Messina, E. Proverbio, A Laser Range Tracking Station for Geodynamis Satellites, Publ. Staz. Astron. Intern. Latit. Carloforte-Cagliari, N°51, 1975.



Time Synchronization
Simeri Crichi Master Clock
Loran-C Receiver
Compar.
Recorder
Cagliari Obs. Cs Master Clock
TV
Compar.
Recorder
Compa rison
TV
Compar.
Recorder
Turin I.E.N. Cs Master Clock
Emitter Tel.
Receiver Telescope 50 cm Ø
PMT
Tracking Tel.
El Motor
Encoder
Az Motor
Encoder
Output Pulse
Oscillosc 500 MHz Bandwidth
Photo diode
Energy meter
to PMT
1 J
5 ns
Cooling Unit
Power Supply
Control Console
HeNe Laser
Oscillator 7.5x1 cm
1 J
20ns
Shutter
0.15J
5ns
Amplifier 15x1.3 cm
Laser Transmitter System
Echo Receiver and Data Recording System
Photo multiplier
C F Discrimin.
Addresser
Preset Counter
Reset
Cesium Master Clock
Clock Register
Printer
Stop
Start
Time Interval Counter
1MHz
Camera Head
Camera Control Unit
TV Monitor
Counter
Display
Counter
Display
To Az Motor
Electronic
Interface
Power Supply
Joy-stick
Mini computer Honeywell Model 6/43
MagnTape Control
To El Motor
Electronic
Interface
Tracking System

THE ZIMMERWALD SATELLITE RANGING STATION
TECHNICAL DESCRIPTION

I. Bauersima, G. Beutler, W. Gurtner, P. Klöckler, M. Schürer
Astronomisches Institut der Universität Bern
Bern, Switzerland

This report contains a technical description of the Zimmerwald Laser Observatory, as it has been constructed from 1975 to 1978. In the second section we state the evolution taking place during 1978. In the final section the planned completion works for the years 1979 - 1981 are listed.

TECHNICAL DESCRIPTION OF "STATUS QUO"

(see diagram)

Ruby Laser System

Energy	3 - 5 joules
Halfenergy pulse width	15 - 20 nsec
Natural beam divergence *)	3.5 mrad
Beam divergence, when leaving the telescope	0.7 mrad

Dye Laser System

Energy	12 Joules
Natural beam divergence	10 mrad
Beam divergence, when leaving the telescope	2 mrad
Halfenergy pulse width	some μsec

The Telescope

Biaxial horizontal mounting
Both axes are driven by stepping motors with a resolution of
2.7 arcsec in elevation
5.4 arcsec in azimuth
Maximum velocities: 2,5°/sec in elevation
5,0°/sec in azimuth

*) Beam divergence: Angle between axis and the outermost beam

Transmitting telescope (TT)

Three prisms to conduct the beam into the transmitting telescope. The lowest prism may be switched from the ruby to the dye system and vice versa.
The transmitting telescope is a Galilei-telescope opening the beam 5:1.

Tracking and receiving telescope (RT)

Main mirror (spherical), diameter: 52,5 cm. Triple lense system in front of the TV-Camera to correct for the sphericity of the mirror. The surface of the first lense reflects the ruby light via Barlow and Fabry lenses into the echo photomultiplier.
TV-Camera (Grundig FA 42 S): Allows the observation of objects up to the magnitude of 9.5.

Tracking

The picture of the TV-Camera is displayed on the TV-Monitor (diameter 55 minutes of arc). Direction and velocity of the telescope may be preselected and started automatically by the station clock. The image of the satellite can now be centered manually. The pointing accuracy in this mode of operation is limited by the resolution of the TV-System, which is 15 arcseconds.

Epoch Timing

A HBG-receiver ensures determination the epoch within ∿ 20 μsec.

Echo-detection

Is established by a photomultiplier RCA 7265 with S-20 cathode. In front of the photomultiplier there is a 10 Å interference filter. An electromechanical shutter and a digitally presettable range gate reduce the probability of error counts.
Light travelling time is measured by an "Eldorado 796" counter (Resolution 1 nsec).

Waveform analysis

The shapes of the outgoing and incoming pulses are photographically registered from a TEXTRONIX 556 oscilloscope. The measured flight time is then corrected to the respective centers of the pulses.

Data registration

Epoch time, light travelling time, approximate position of the telescope (azimuth, elevation) are printed on a HP 5055 A printer.

WORKS IN PROGRESS (1978)

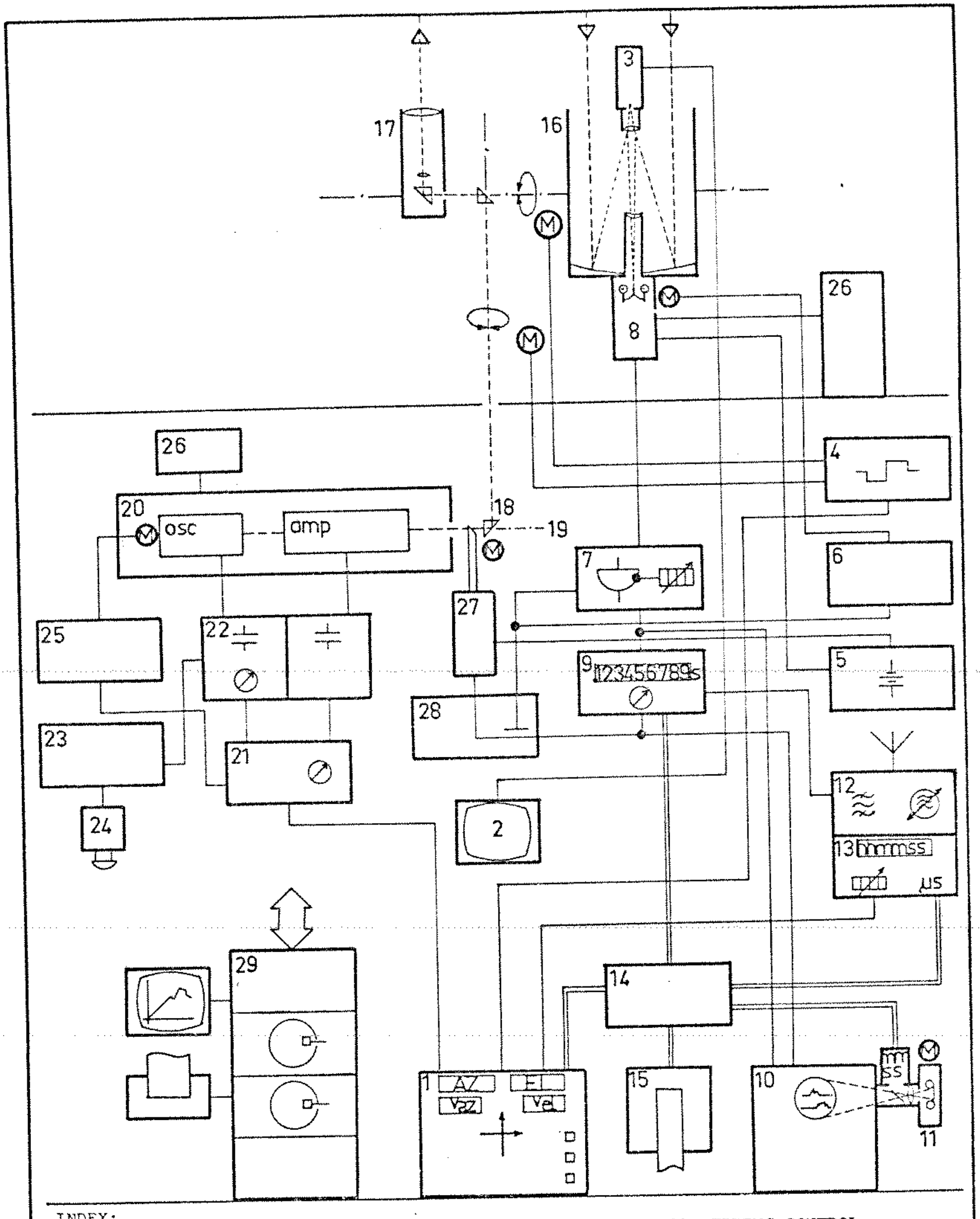
Installation of a better TV-Camera (JAI 740 ISIT) permitting the observation of objects up to the magnitude of 15.

Installation of a PDP 11/40 Computer system with two disks and 32 k words of memory.
The system will take over the following tasks:

- data registration (replacing h), Section 1)
- Satellite predictions adapted to TV-tracking.

FUTURE PLANS (1979-1981)

- Computer tracking
- new epoch timing (accuracy ± 1 µs)
- reconstruction of transmitting telescope to allow for a variable beam divergence.



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ZIMMERWALD SATELLITE RANGING STN.

THE METSÄHOVI LASER RANGING SYSTEM

S.J. Halme, M.V. Paunonen, A.B.R. Sharma
Helsinki University of Technology, Espoo, Finland
J. Kakkuri and K. Kalliomäki
Finnish Geodetic Institute, Helsinki, Finland

1. INTRODUCTION

The Finnish-Swedish Satellite Laser range finder is located at the Metsähovi Space Geodetic Station (Lat. = 60°13!2, Long. = 24°23!9) approximately 40 km from Helsinki. System planning was initiated in 1972 with financial support from the Academy of Finland, and in 1974 a cooperation agreement was made with the Geographical Survey Office of Sweden, which has provided further funding. The ranging system is now fully operational and the first range determination to the Geos-3 satellite has been done. The detailed description of the existing apparatus is reported elsewhere /1/.

2. THE LASER RANGE FINDER

2.1. Laser transmitter

The electro-optically Q-switched ruby laser oscillator consists a water cooled diffusely reflecting head (Korad K1), a helical flashlamp, a 100 mm long x 9.5 mm dia. ruby rod, a KD*P Pockels cell (Lasermetrics, Inc. Model 813), a Brewster stack polarizer (Interactive Radiation Inc.), a dielectric rear mirror and a 26 % sapphire etalon as the front mirror. The optical length of the resonator is 500 mm. The charge storage capacitor, 400 μF/5kV, is charged to 0...5kV using a conventional inductively current limited step-up transformer-rectifier system. The repetition rate is limited to 1/6 Hz by the laser head, cooling system and the charging system. The output pulse length, Fig. 1., depends on the pumping level. The length normally used is 20 ns and the pulse energy 1J. The beam divergence is about 3 mrad. The output beam is collimated using a x7 inverted aspherical Galilean telescope. The divergence can be adjusted from 0.4 to 3 mrad by defocusing. The start pulse for the time interval counter is generated by using a light guide to sample the transmitted pulse via the rear mirror, followed by opto-electronic conversion using a fast silicon photodiode and an amplifier-filter combination. The temperature-controlled laser housing is situated on top of the telescope mount.

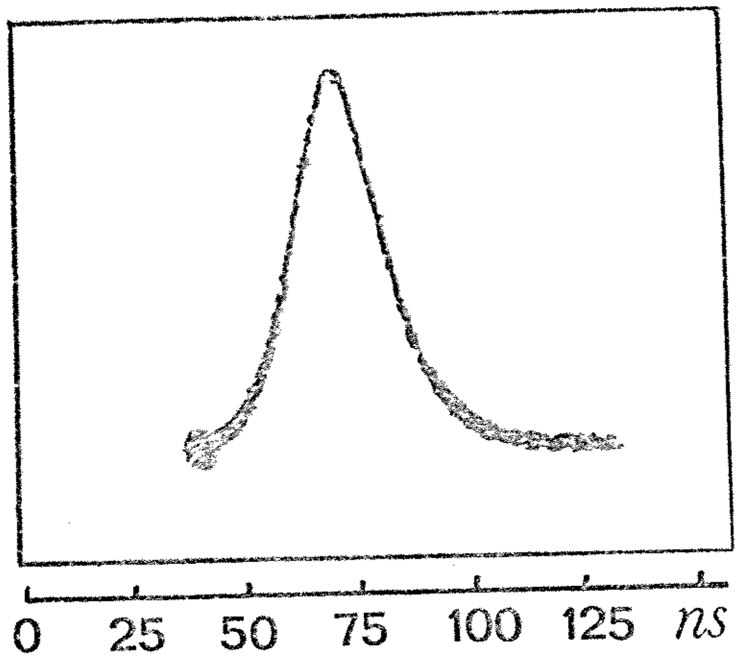


Fig. 1. Typical shape of the 25 ns long Q-switched ruby laser pulse.

2.2. Laser receiver

The return energy is collected using a 630 mm parabolic mirror with a focal length of 1730 mm. The 6 mm aperture of the electro-mechanical shutter, used for eliminating the near backscatter to the photomultiplier, defines a 3.5 mrad field of view. The background radiation is limited by a 3 nm interference filter with a transmission of 70 %. The light is collimated by a lens before it enters the filter. The photomultiplier used is an RCA C31034 which has a GaAs cathode with a quantum efficiency of 10 %, and a multiplier gain of $6 \cdot 10^5$ at 1680V. This photomultiplier is protected against excessive anode current and cathode voltage. Also an RCA 8852 with a multialkali cathode(quantum efficiency about 4 %) can be used, especially under twilight conditions or if a higher amplification (up to 10^8) is needed. The anode pulse is fed through a 12 m long coaxial cable to the electronic amplifier. To allow the use of the whole pulse for determining the range, the incoming pulse is integrated at the collector of a transistor amplifier with a long time constant.

The travel time of the light pulse is measured with a high resolution time interval counter (Nanofast 536B, modified), which has a nominal resolution of 25ps. Median detection, which uses an adaptive threshold and thus also eliminates amplitude dependent time walk, is realized using the half-max plug-in of the counter (Nanofast M/2-unit). The random error of the counter system is about 0.15 ns(r.m.s.), while the systematic error is about 2 ns within the dynamic range of 0.3 V to 12 V.

Range calibration is performed using a 332 m calibration line. A typical set of 24 pulses is shown in Fig. 2.

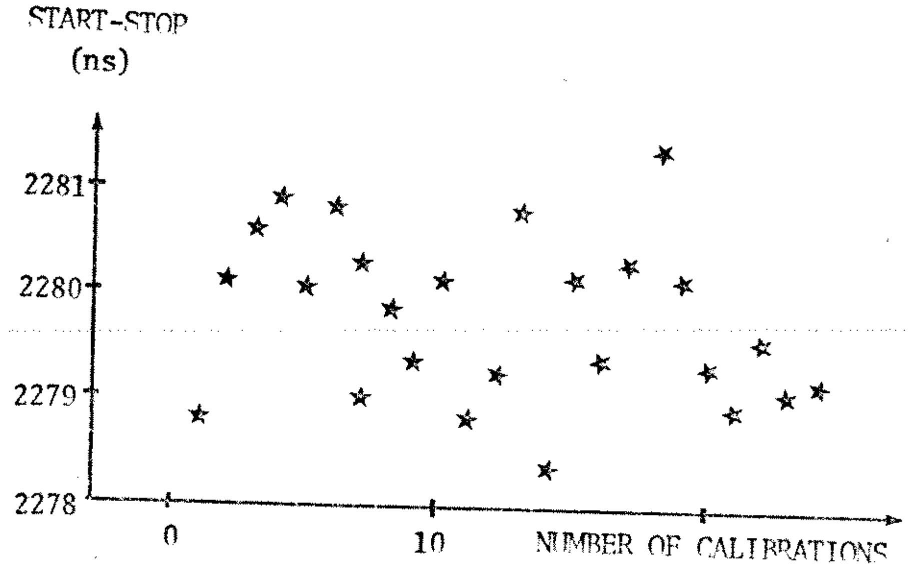


Fig.2. A calibration measurement. The average content of the return pulse was about 600 photoelectrons. The time interval between shots was 30 s. The standard deviation is 0.77 ns.

A transient digitizer (Tektronix R7912) is connected in parallel to the PMT anode cable, via a sampling resistor and an amplifier, to monitor the photomultiplier pulses.

2.3. Telescope mount and electronics

The telescope mount is equatorial and is sidereally driven, thus allowing easy calibration against known star positions. The mount, which is driven by stepping motors, is controlled by a minicomputer (D-116, Digital Computer Controls, Inc.).Position control is achieved using the open loop principle.

The pointing accuracy is better than ±0.6 mrad or ±2 min of arc. The satellite positions are calculated in advance on the basis of predictions, which are in the format of the AIMLASER programme. This programme has been received from Kootwijk /2/ and modified for the PDP 11/10 minicomputer at the Finnish Geodetic Institute.

The D-116 minicomputer gives the commands to the drive system to move the telescope to the correct position in advance of the expected arrival time of the satellite. The computer also fires the laser at the predicted time corresponding to the predicted direction. The firing times can be corrected during the satellite pass if needed e.g. after visual acquisition. Also manual speed and position control is possible using a joystick or thumbwheels. The resulting data are logged by the computer and include epoch of pulsing, nanosecond counter reading, right ascension, declination, air temperature, atmospheric pressure and relative humidity.

Station time keeping is achieved using a crystal clock which is phase locked to the LORAN-C transmission. In this way short term stability is provided by the crystal, while long term stability is assured by the atomic clocks used for controlling the LORAN-C. The accuracy obtained is between 1-5 μs.

The weather station is automatically operated using capacitive type transducers. The measurement accuracy has been found to be ±0.5°C for temperature, ±0.7 mb for air pressure, and ±3.9 % for relative humidity.

Two guiding telescopes are used for pointing purposes: a 30 mm auxiliary finder telescope with x 6 magnification, and a 203 mm Cassegrain telescope with a Schmidt plate (Celestron 8, f/10). The guiding telescope and the main parabolic mirror are aligned using a fixed star by detecting the increased anode current of the PMT. The laser transmitter is aligned towards the calibration target against marked positions corresponding to the relative positions of the guiding receiver and the transmitter telescopes. The laser beam spot at the target is well defined, and therefore its size and position can be adjusted against crossed marks.

3. CONCLUDING REMARKS

The accuracy of the present ranging system is estimated to be 1 m, as is common with other stations which are using Q-switched pulses. The instrumental resolution is about 0.5 ns which corresponds to 7.5 cm in range.

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.

4. REFERENCES

/1/ HALME, S.J., KAKKURI,J., Description and Operation of a Satellite Laser System. Rep.Finn. Geod. Inst. 77:4, Helsinki 1977.

/2/ B.A.C. AMBROSIUS, H.J.D. PIERSMA, K.F. WAKKER: Description of the AIMLASER satellite orbit prediction program and its implementation on the Delft University IBM computer. Report LR-218. Delft University of Technology. Delft - The Netherlands, 1976.

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

S. Yumi and C. Kakuta

International Latitude Observatory of Mizusawa
Mizusawa-shi, Iwate-ken, 023 Japan

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 : ϕ 250^{mm}
- Receiver : ϕ 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

L.Aardoom
Delft University of Technology,Delft (The Netherlands)

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 ± 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 μs 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

I. Bauersima, G. Beutler, W. Gurtner, P. Klöckler, M. Schürer
Astronomisches Institut der Universität Bern
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

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

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

τ_c is the calibration correction factor, p is the athmospheric pressure in mb, T is the temperature in Kelvins, and τ_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 μs.

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

Yu.L.Kokurin, V.V.Kurbasov, V.F.Lobanov,
A.N.Sukhanovsky
Academy of Sciences of the USSR
P.N.Lebedev Physical Institute

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 σ_e, is the mean square value of the error due to laser pulse duration $\simeq$ 0.8 ns; σ_{ey}, is the error in electronical and geometrical delays $\simeq$ 1 ns; σ_c, is the error due to the discreteness of the counters $\simeq$ 0.3 ns; σ_p, is the error of the photomultiplier $\simeq$ 0.5 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 ~ 5 μs.

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 $\pm$ 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

Eric C. Silverberg
McDonald Observatory
The University of Texas at Austin
Austin, Texas 78712

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

O. Calame
J. Gaignebet
Centre d'Etudes et de Recherches Géodynamiques
et Astronomiques
8 bd. Emile Zola
Grasse, France

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

Yu. L. Kokurin, V. V. Kurbasov,
V. F. Lobanov and A. N. Sukhanovsky
Academy of Sciences of the USSR
P. N. Lebedev Physical Institute

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/.

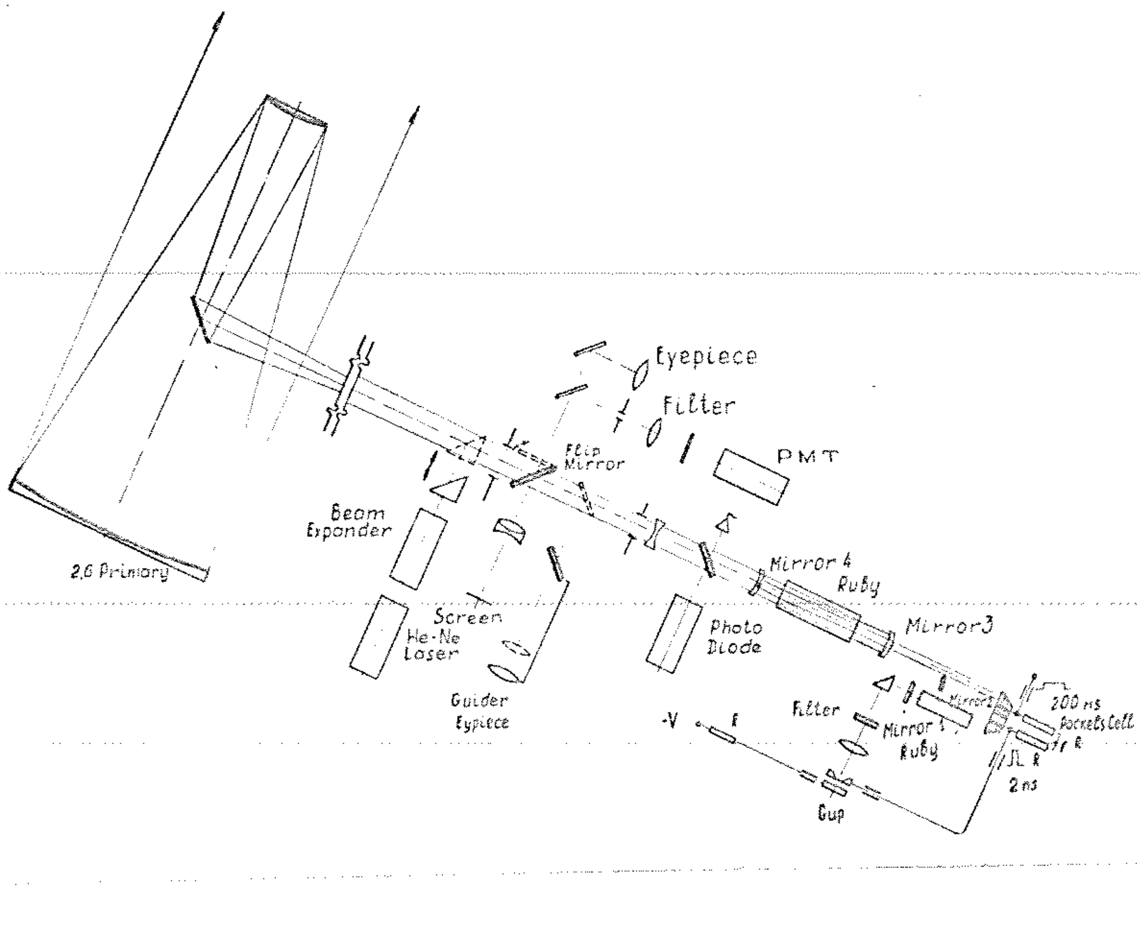
A schematic diagram of the system is shown in Figure 1. A driving oscillator, developed on the basis of /3/, consists of two cavity mirrors, 1 and 2, with reflection factors 100% and 80%, a ruby crystal 7 mm in diameter and 120 mm long, and Q-switch cell with two triggering channels. One of the control 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 λ = 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 ± 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 ± 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 σ_e is the mean square value of the error due to laser pulse duration ≈ 0.8 ns; σ_{eg} is the error in electronical and geometrical delays ≈ 1 ns; σ_c is the error due to the discreteness of the counters ≈ 0.3 ns; and, σ_p is the error of the photomultiplier ≈ 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

S. F. Cushman
The Institute for Astronomy
University of Hawaii
P.O. Box 157
Kula Maui, Hawaii

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

Eric C. Silverberg
McDonald Observatory
The University of Texas at Austin
Austin, Texas 78712

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 ± 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 ± 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.

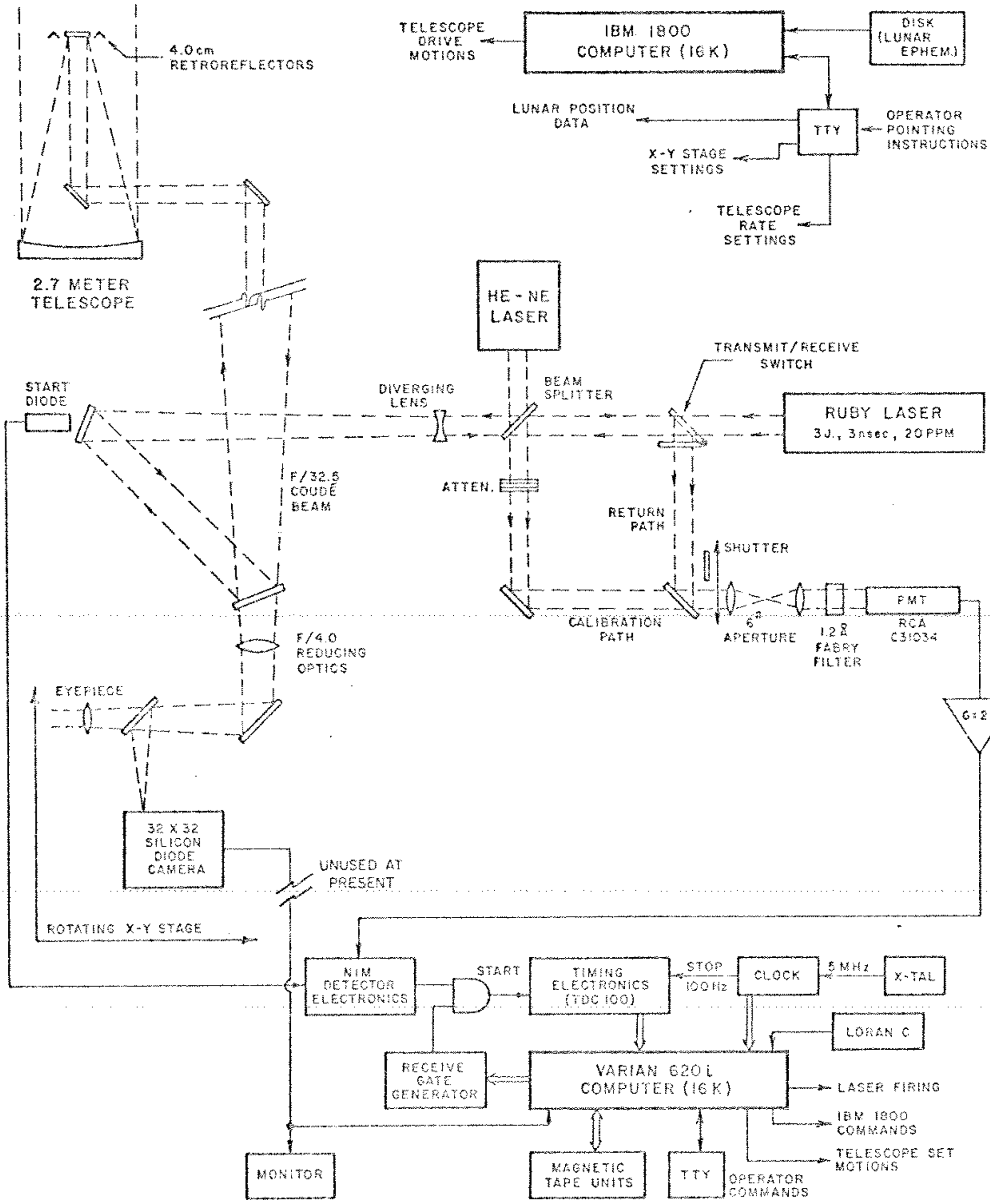


FIGURE 1 : THE MAJOR COMPONENTS IN THE CURRENT McDONALD OBSERVATORY LUNAR LASER STATION AT FORT DAVIS, TEXAS

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

Yoshihide Kozai and Atsushi Tsuchiya
Tokyo Astronomical Observatory
University of Tokyo
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

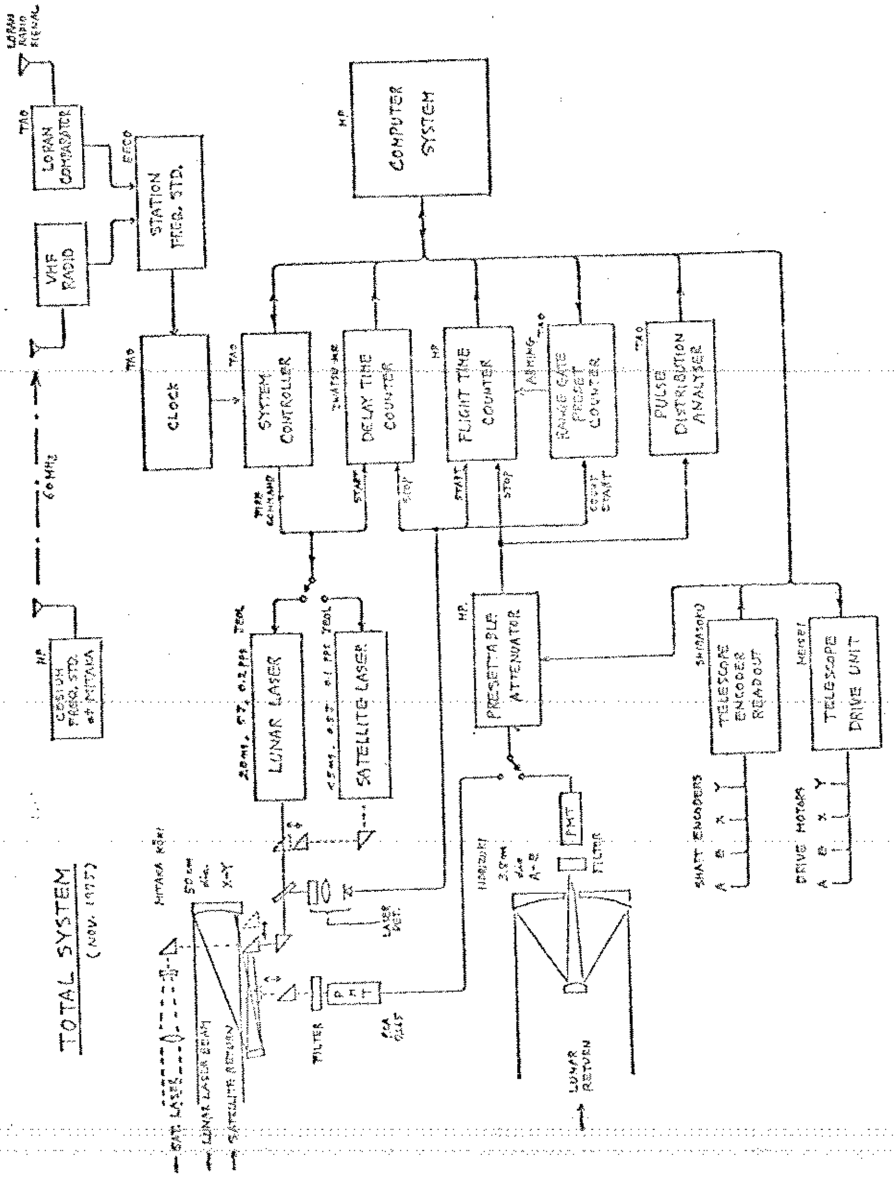
The lunar laser is a three-stage amplified ruby system. The pulse width is about 20 ns, and the maximum output power is about 8 J. With a mode-locked oscillator, the beam divergence is less than 1 m-rad.

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.

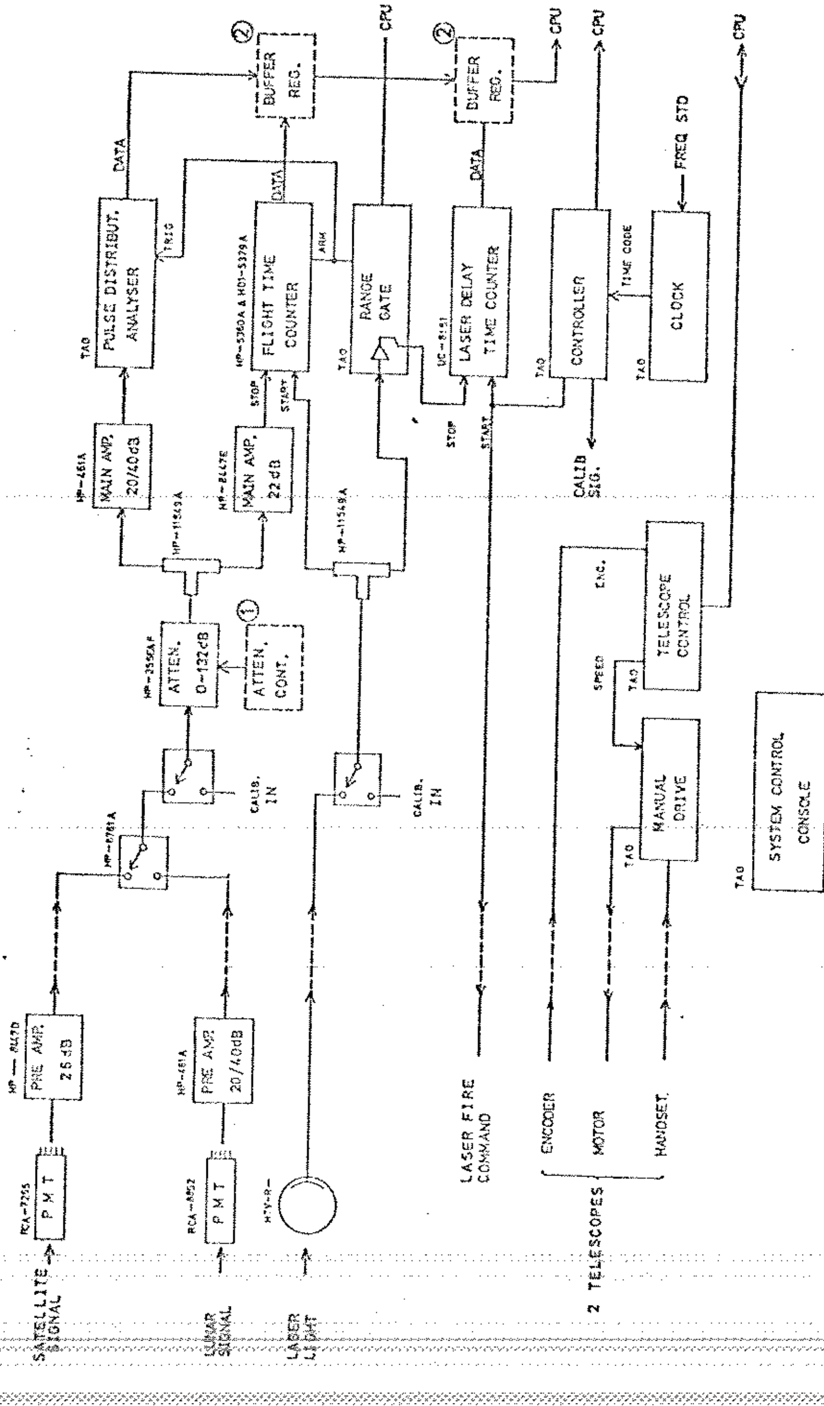
ELECTRONICS SYSTEM

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

Peter Wilson
Institut für Angewandte Geodäsie (Abtlg.II, DGFI)
Frankfurt and Sonderforschungsbereich 78,
Satellitengeodäsie, der TU München
Fed. Rep. of Germany

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

B. A. Greene*
Division of National Mapping
P.O. Box 548
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.

<u>The Laser Subsystem</u>

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

JF. Mangin and J. Gaignebet
GRGS/CERGA - Obs. Du Calern
06460 St Vallier de Thiey (France)

INTRODUCTION

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

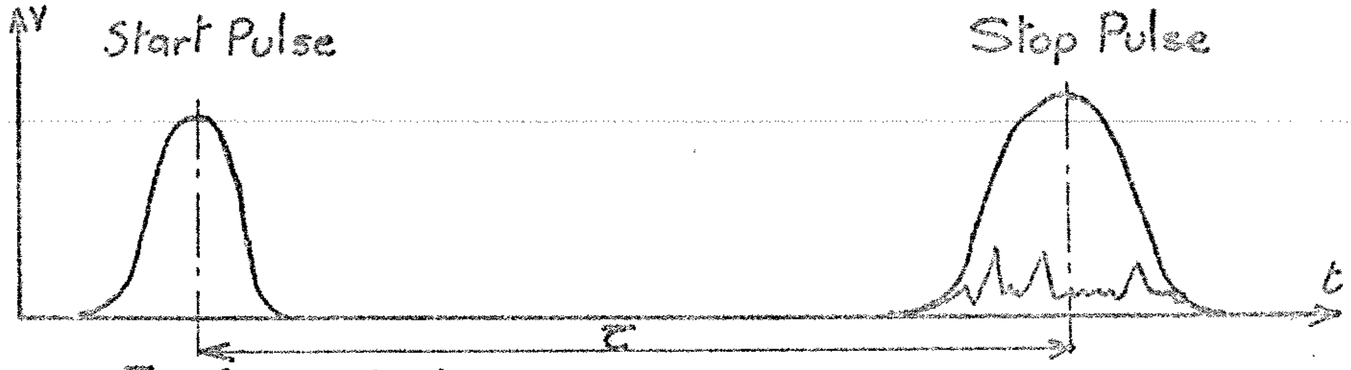


Fig 1 Definition of τ

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 ≈ 6,on a second one by N ≈ 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.

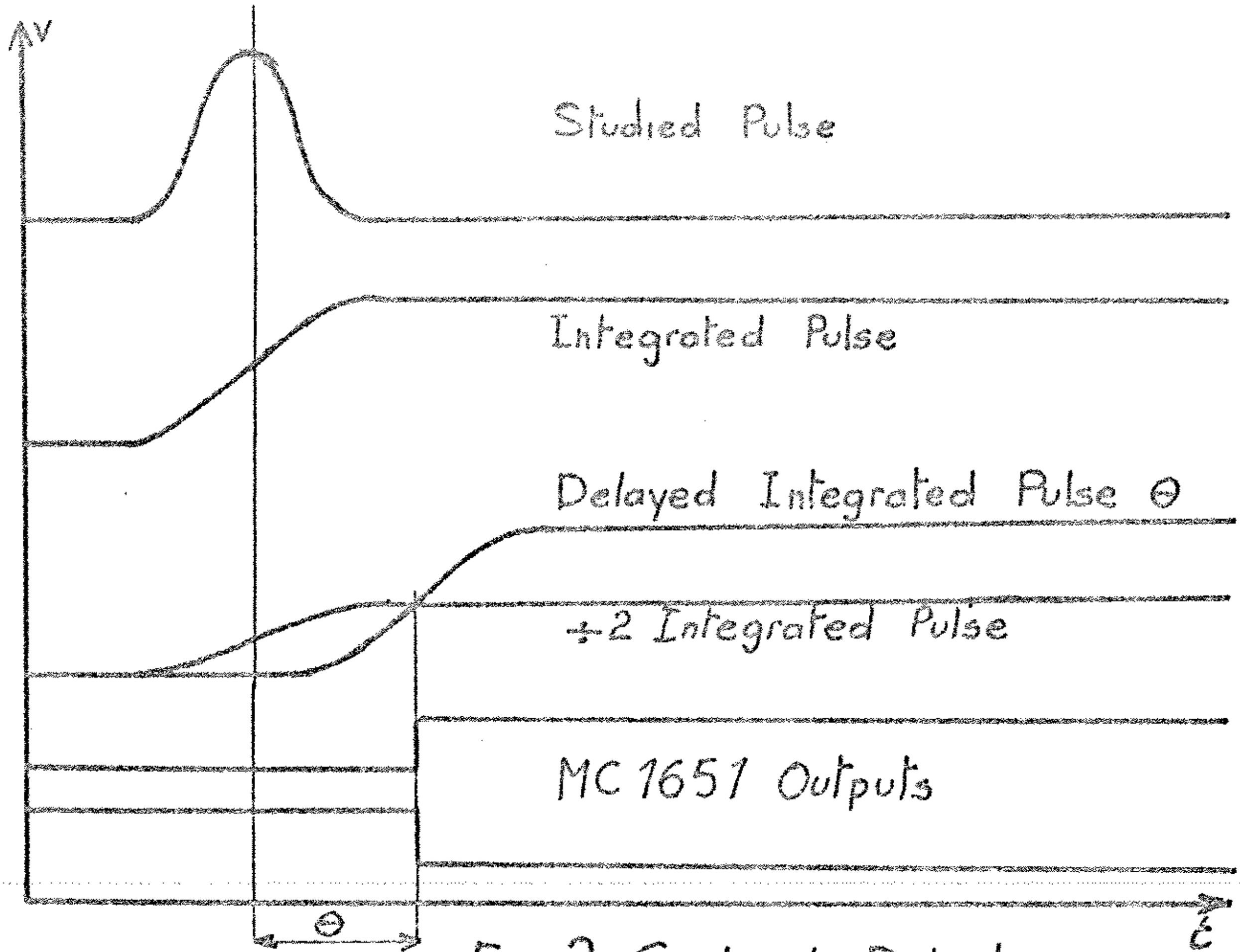


Fig 2 Centroïd Detection

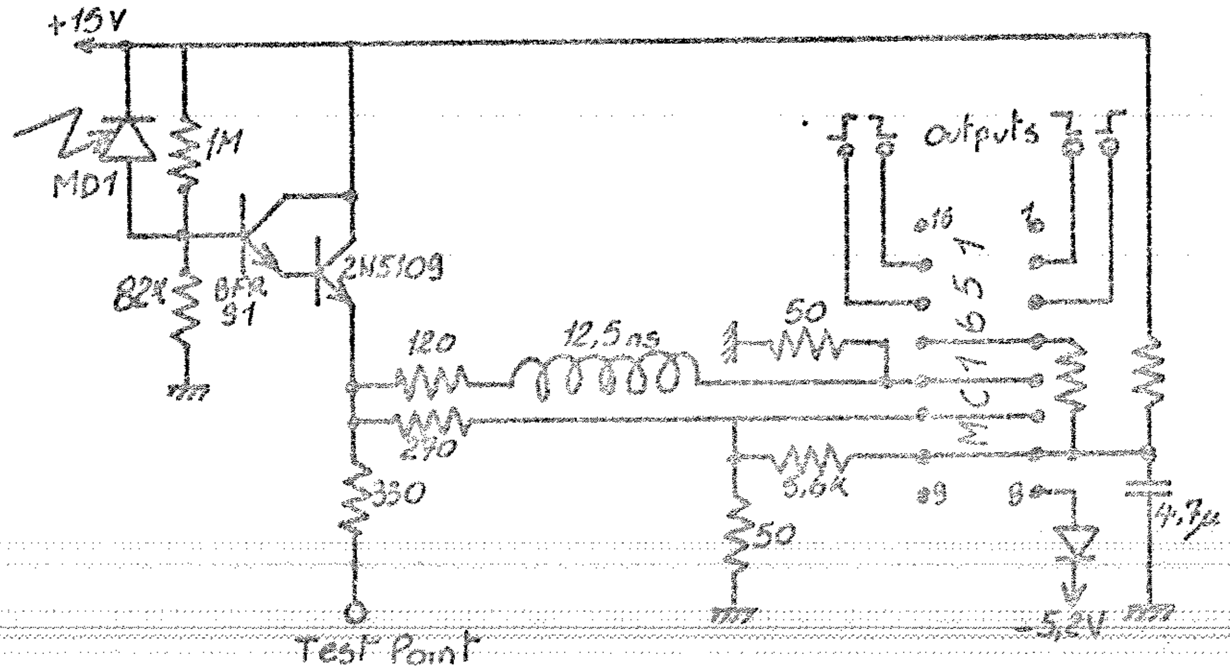
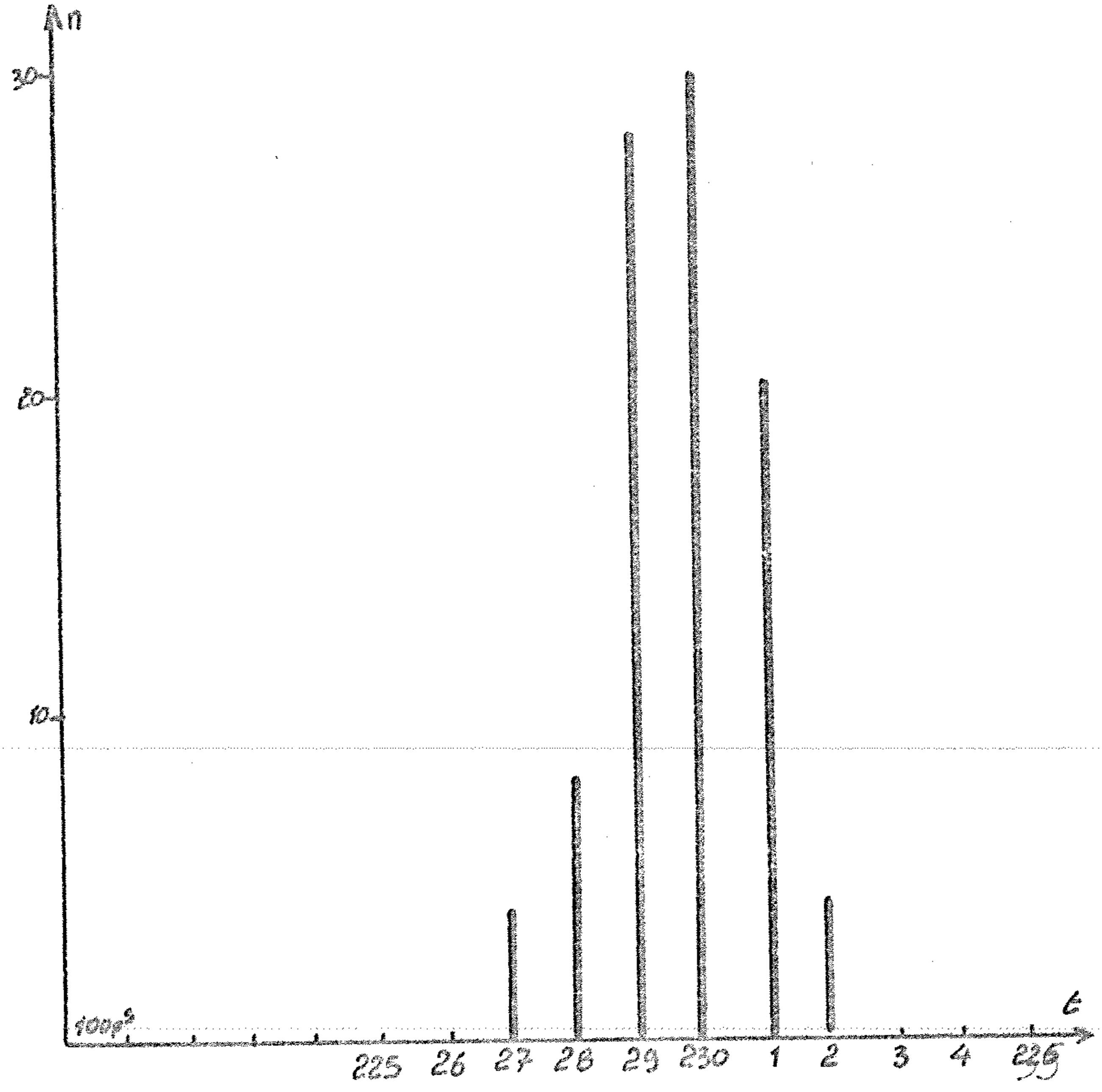


Fig 3 Schematic



Histogram of the first test

LASER WAVEFRONT DISTORTION MEASUREMENTS

Bizé D. and Duchêne B.
CERT / DERO
2 av. E Belin - 31055 Toulouse

Gaignebet J.
GRGS/CERGA
Obs. du Calern - 06460 St Vallier de Thiey

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 (θ 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.

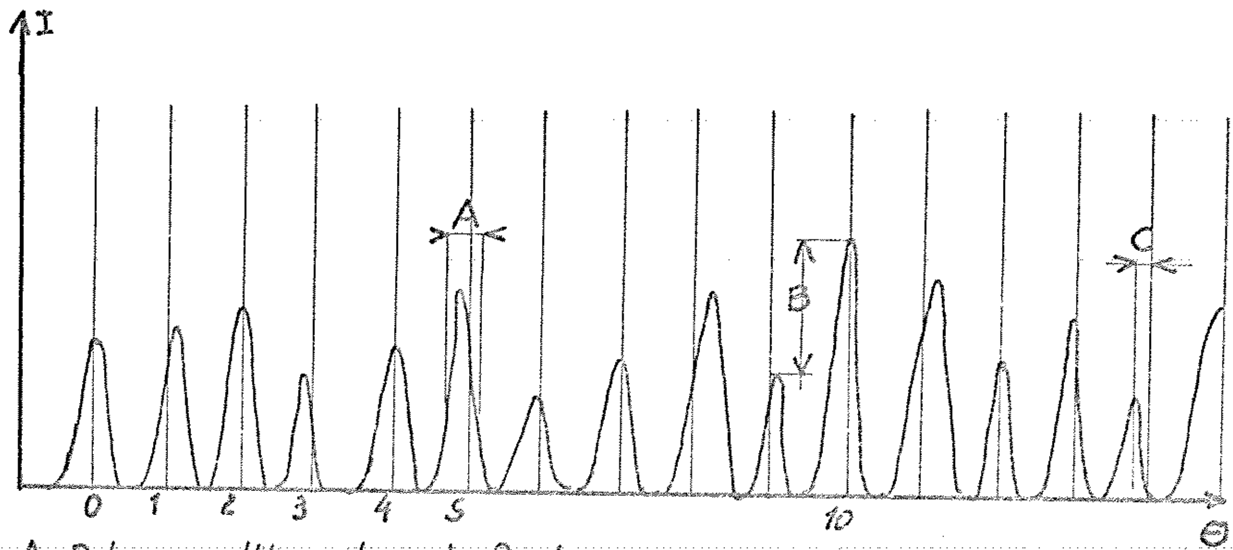
After a series of shots at various energies (2-10j, 10ns) no damage of the fiber ends and holders was found.

The signal at the output is large enough that with sensitive amplifiers ($V \leqslant 5V$) 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

P. Wilson, K. Nottarp
Institut für Angewandte Geodäsie (Abtlg.II DGFI), Frankfurt and
Sonderforschungsbereich 78, Satellitengeodäsie, der TU München
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.

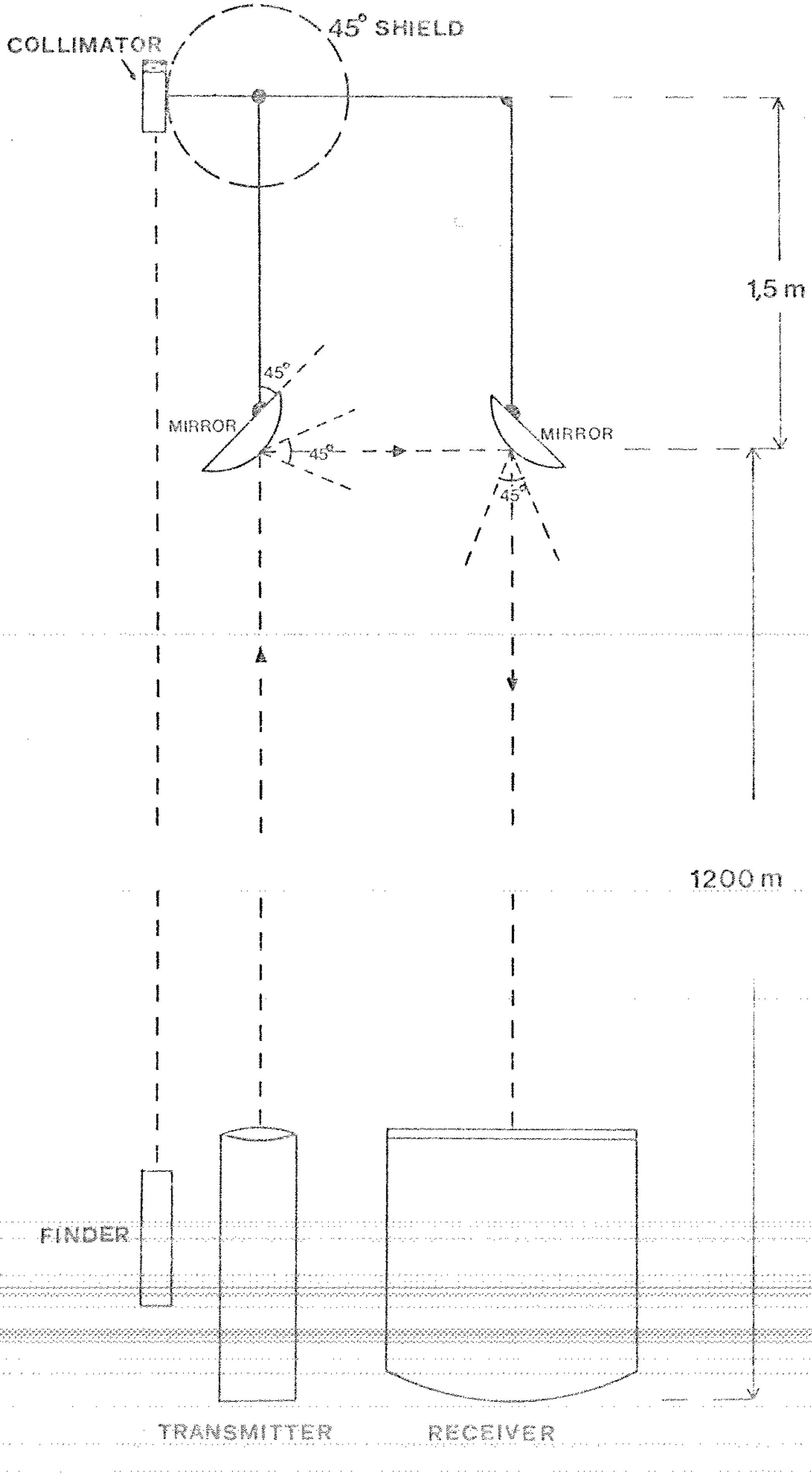
2.3 SOME PROBLEMS WITH CURRENT REFLECTOR HARDWARE

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


45° SHIELD
COLLIMATOR
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 predetermined 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

Jack L. Bufton
Goddard Space Flight Center
Code 723
Greenbelt, MD 20771

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^{o} 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^{o} elevation angle. Further data analysis showed that expected errors in the raw meteorological data (± 1 mb, ± 1 ^{o}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 ± 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° 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.

RRL Rep. No. 471 - Zanter, D.L., C.S. Gardner and N.N. Rao (January 1976), The Effects of Atmospheric Refraction on the Accuracy of Laser Ranging Systems.

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.

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

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C.S. Gardner, "Effects of Random Path Fluctuations on the Accuracy of Laser Ranging Data," Applied Optics, 15, 2539-2545, October 1976.

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SAO CALIBRATION AND SYSTEM ACCURACY

M. R. Pearlman and N. W. Lanham
Smithsonian Astrophysical Observatory
Cambridge, MA

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

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

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

Billiris, H. G., Papagiannis, M. D., Lehr, C. G., and Pearlman, M. R., 1975. Beam wavefront distortions in a laser ranging system. Smithsonian Astrophys. Obs. Laser Rep. No. 7, 19 pp.

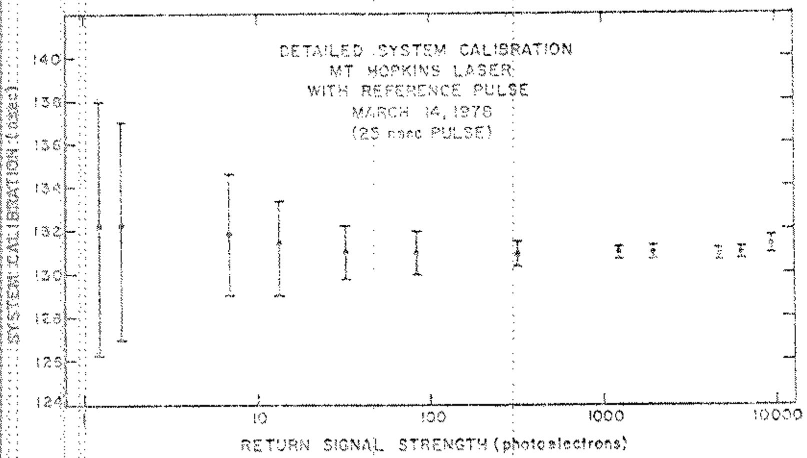

Figure 1.

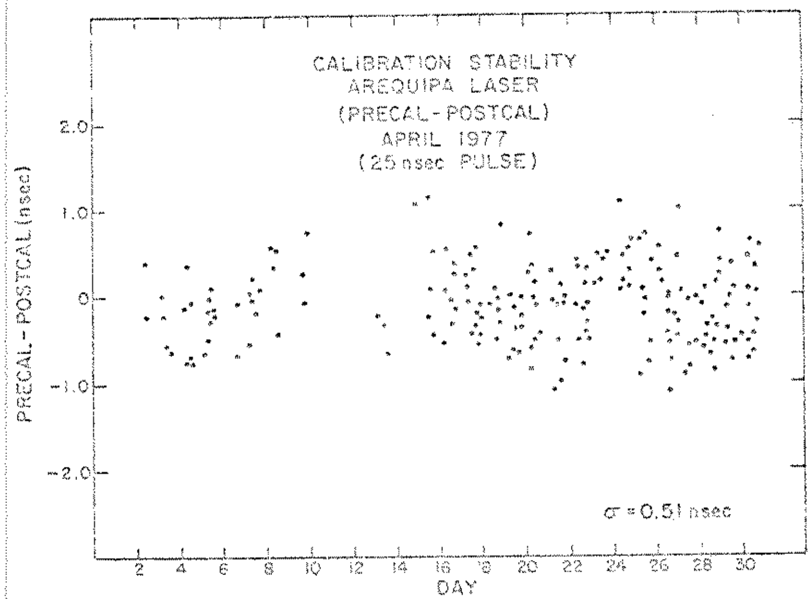

Figure 2.

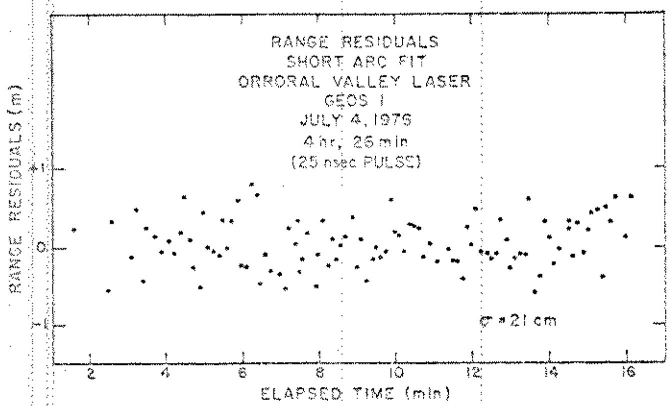

Figure 3.

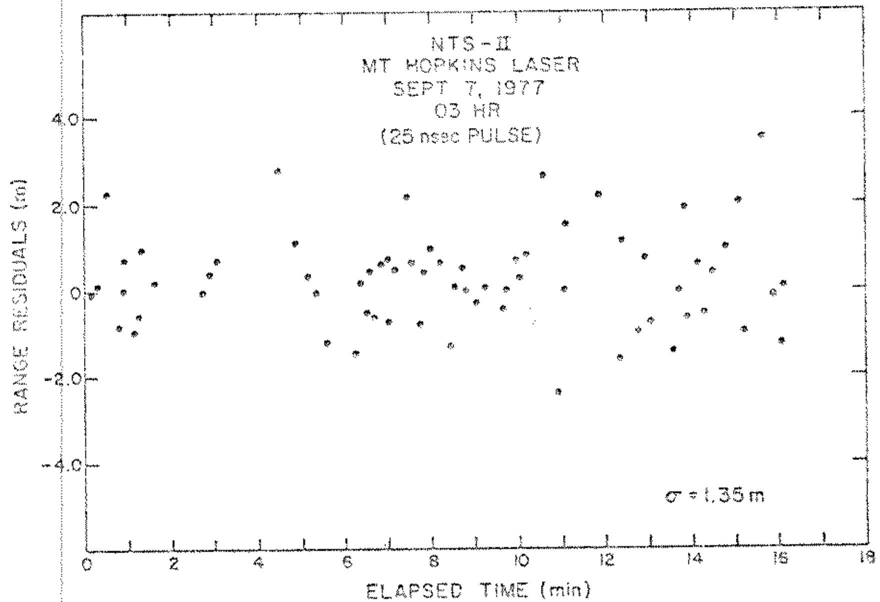

Figure 4.

CALIBRATION AND ERRORS

Yu.L.Kokurin, V.V.Kurbasov, V.F.Lobanov,
A.N.Sukhanovsky
Academy of Sciences of the USSR
P.N.Lebedev Physical Institute

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 ±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 ± 3 cm or ± 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° 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 ± 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 µsec by means of transportable clock. The correction for the delay in receiving system is also estimated with an accuracy 0.2 µsec. The summary error of the moment of the laser pulse in UTC (SU) scale is not higher than 5-6 µsec.

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 σ_1 = 0.8 ns; b) an error in electronical and geometrical delays σ_{eg} =1nsec: c) an error due to the time resolution of the counters σ_c=0.3 ε=0.3 ns, where ε=1.0ns, this error arises twice, that is, at the beginning and at the end of measured time interval: d) an error of photomultiplier σ_p = 0.5 ns: e) an error in the atmospheric correction, which may be σ_c = 0.3 ns: Thus, the summary error of the system may be σ= 1.5 ns or = 25 cm.

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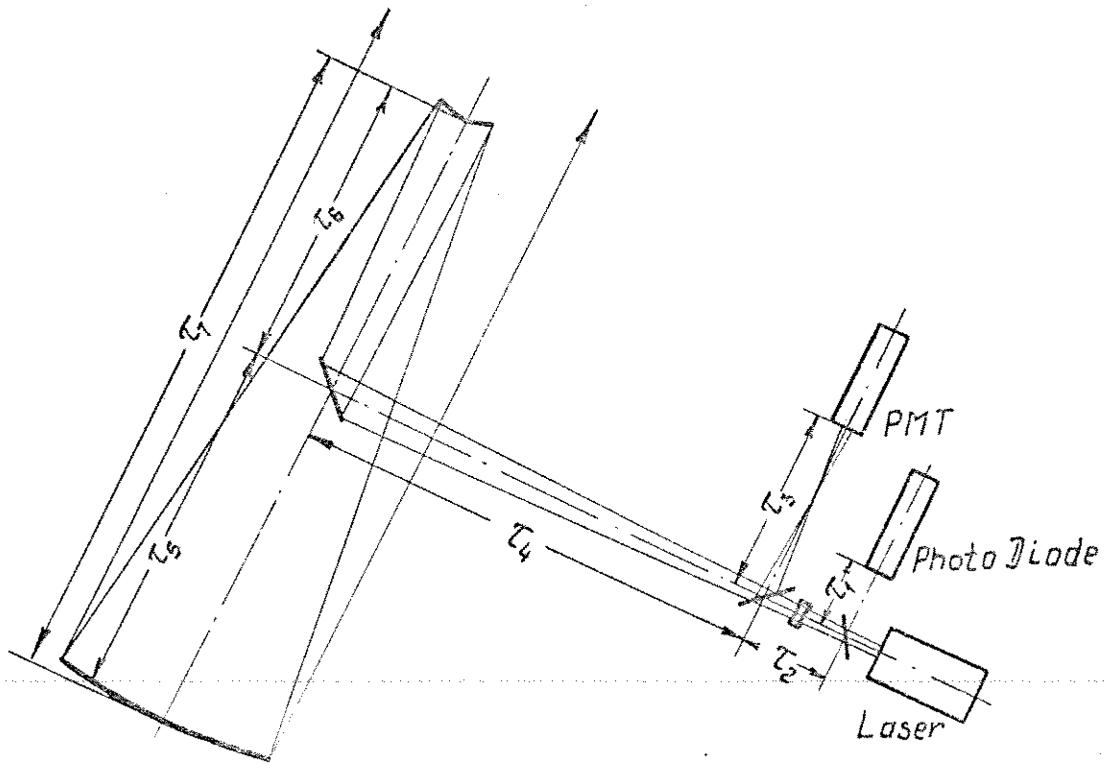

Figure 1. The optical paths in the telescope

CALIBRATION PROCEDURE AT KOOTWIJK

F.W.Zeeman

Delft University of Technology, Delft (The Netherlands)

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.

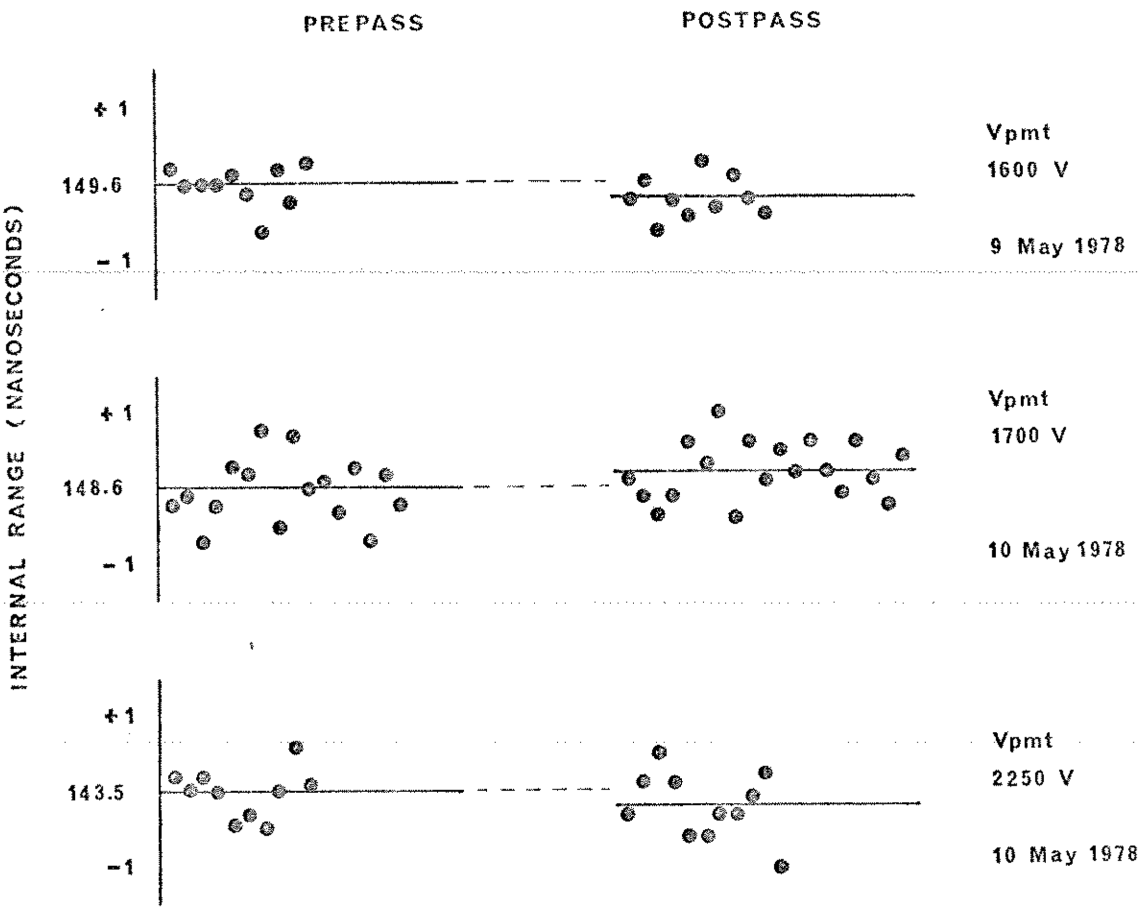

fig. 1 CALIBRATION MEASUREMENTS

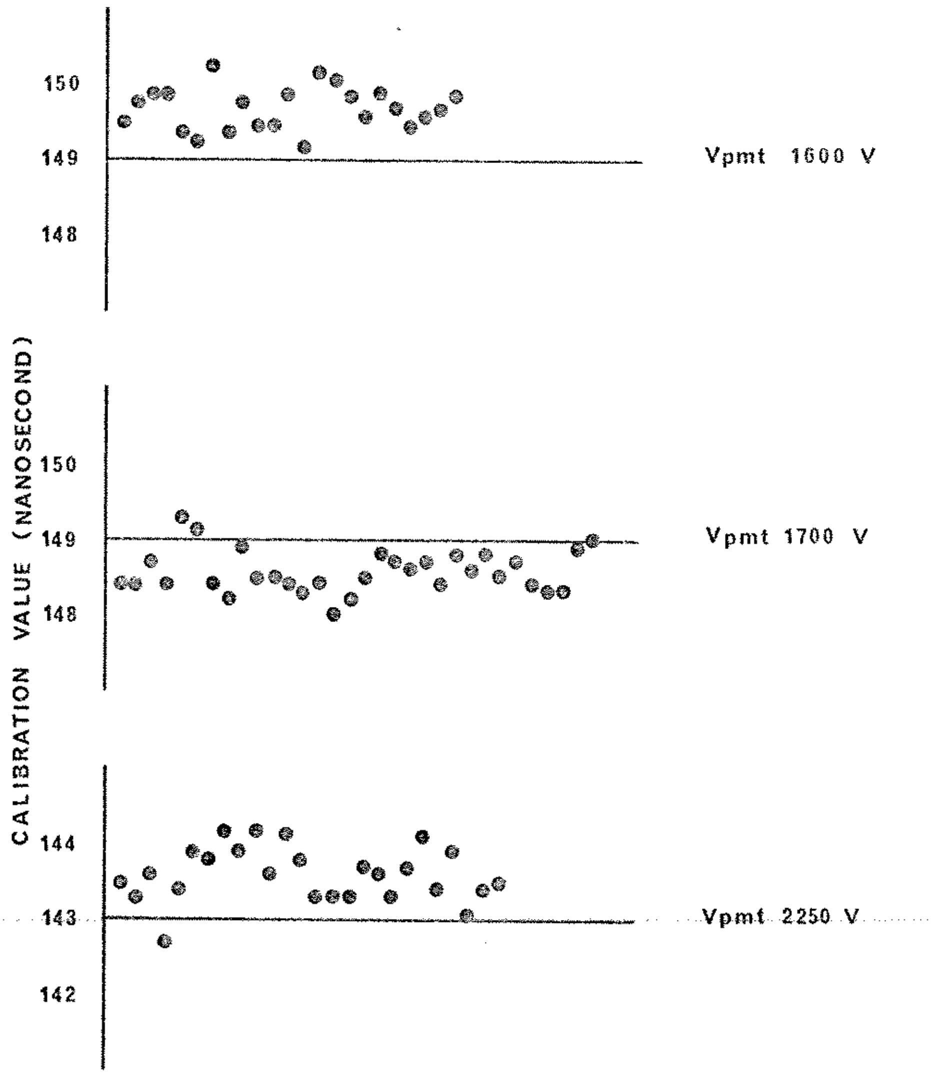

Fig 2 CALIBRATION VALUES 1. March – 11. May 1978

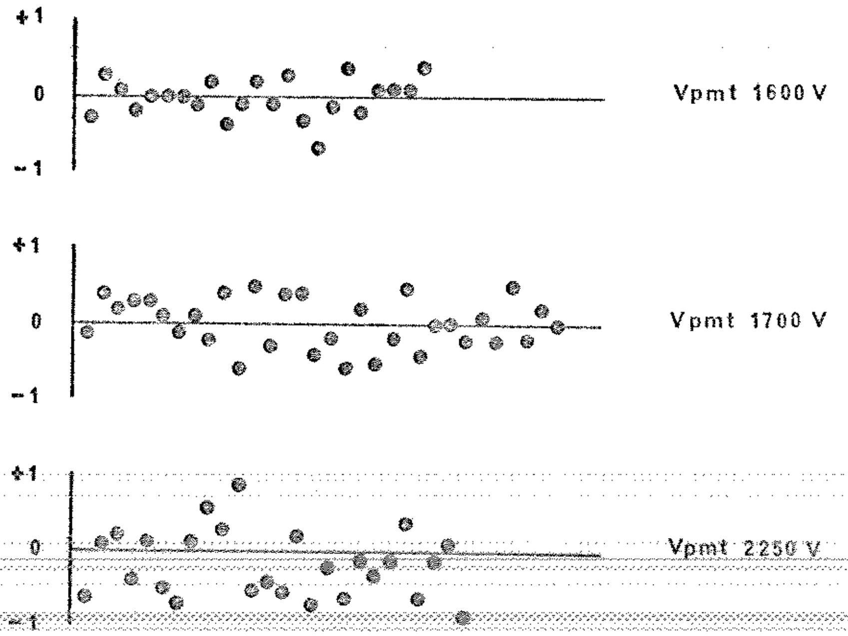

Fig 3 PREPASS minus POSTPASS CALIBRATION VALUES 1. March – 11. May 1978

CALIBRATION OF A PULSE LASER RANGING SYSTEM

H. Billiris and N. Tsolakis
National Technical University of Athens, Greece

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.

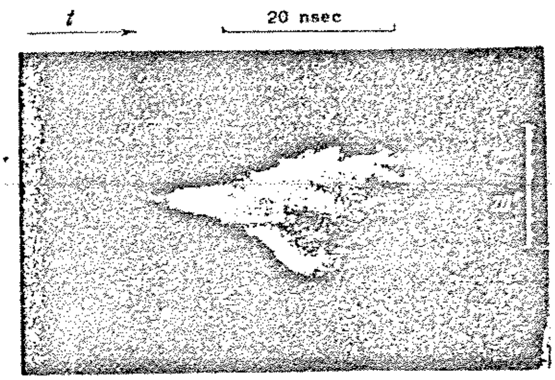

Fig. 1. Laser beam waverfront as was photografed by a streak camera (Korobkin and all, 1966).

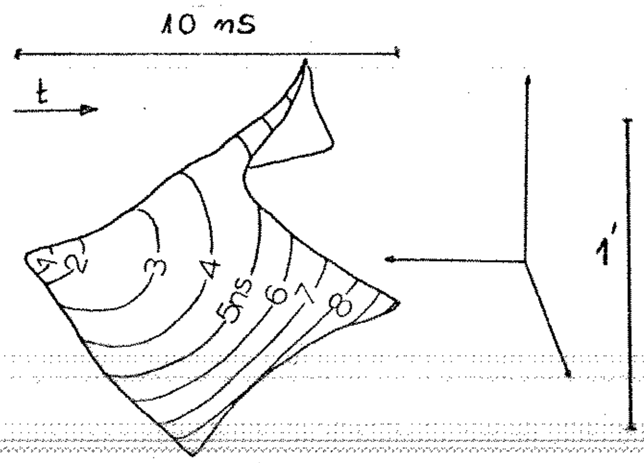

Fig. 2. Laser beam waverfront as was measured by using a matrix on a target (Billiris, 1977).

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

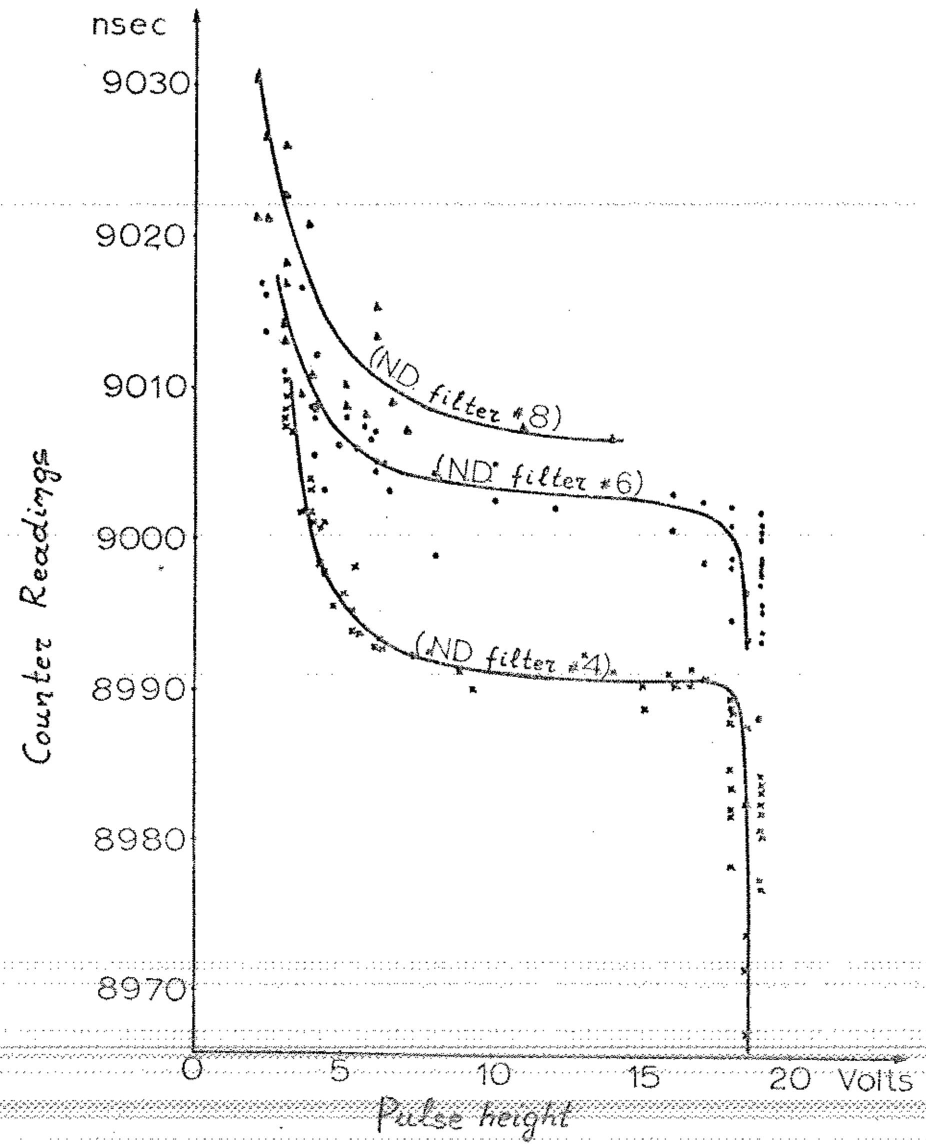

Fig. 3. Counter readings (from the close target) vs Pulse height for various ND filters.

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.

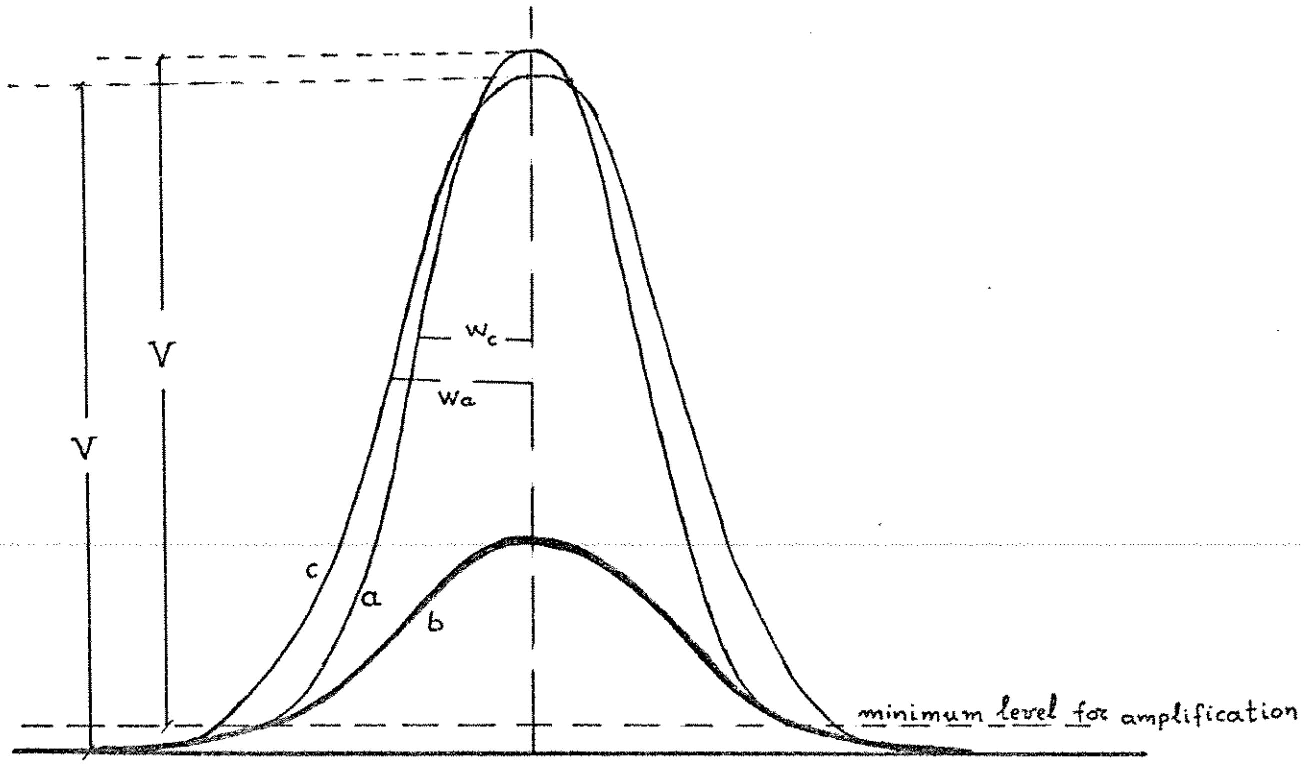

Fig. 4. An ND filter "absorbes" a given laser pulse, some parts of which remain with very low energy which is below the threshold of been amplified. In this way the pulse (a) coming out of a ND filter (b), behaves as having less width "bigger" after the amplification (c) (but with the same final pulse 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 consisted of one cube corner at a distance of about 1.3 km., and the distant targets 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.

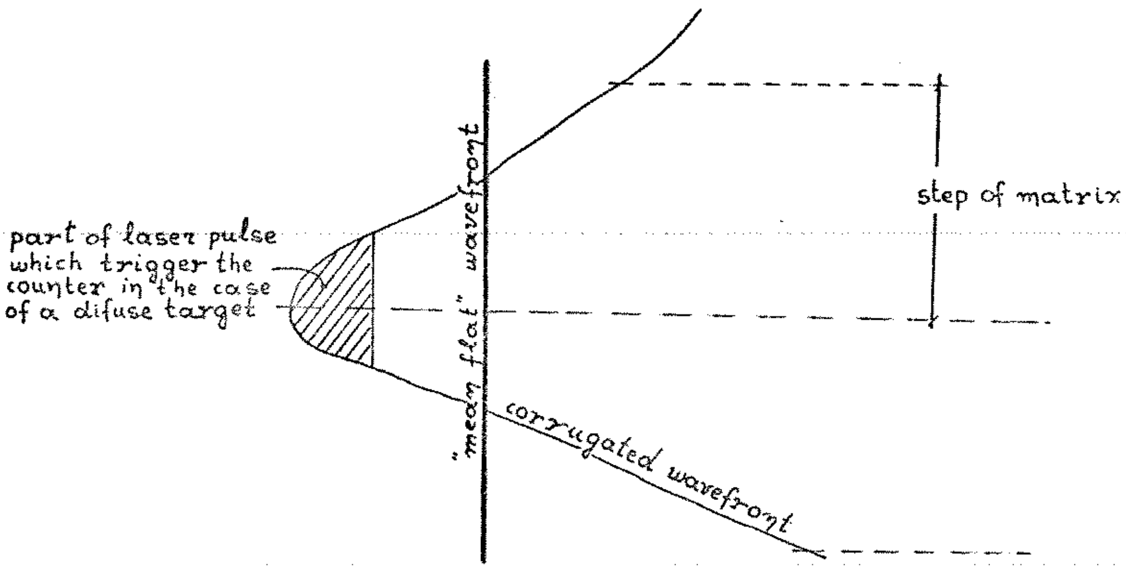

Fig. 5. The mean flat wavefront.

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 $\frac{[PT]}{[P]}$ (ns)	$\pm\sigma$ (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

K.Hamal

Faculty of Nuclear Science and Physical Engineering
Brehova 7,Prague 1,Czechoslovakia

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

E. C. Silverberg
McDonald Observatory
University of Texas at Austin
Austin, Texas

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

E. Imbier, N. W. Lanham, and M. R. Pearlman
Smithsonian Astrophysical Observatory
Cambridge, MA

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

Klemens Nottarp, Peter Wilson
Institut für Angewandte Geodäsie (Abtlg. II, DGFI), Frankfurt and
Sonderforschungsbereich 78, Satellitengeodäsie, der TU München

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

Klemens Nottarp, Peter Wilson
Institut für Angewandte Geodäsie (Abtlg.II, DGFI), Frankfurt and
Sonderforschungsbereich 78, Satellitengeodäsie, der TU München
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

Ramsden
Dewhurst /Jacoby /Ramsden
Gaignebet
Hamal /Jelinkova
Kokurin /Kurbasov /Lobanov /Sukhanovsky
Hamal /Vrbova
Paunonen
Bret
Johnson /Degnan /McGunigal
Hamal
Gaignebet

TV GUIDING FOR SATELLITE
AND LUNAR RANGING

J.Gaignebet and C. Sinet
GRGS/CERGA Observatoire du Calern
06460 Saint Vallier de Thiey FRANCE

I. INTRODUCTION

Since the first station set up in France (1966), with which only visual tracking was achievable, we felt that we must maintain that possibility.

The main reasons were :

a) To decrease the need of accurate ephemerides when satellites are visible.

b) To make visual checking and eventually to correct the ephemeridis (ΔM or ΔT)

c) To set up the overall optical system

d) To adjust the zeros of the Azimuth-Altitude encoders.

e) To ensure the safety around the laser beam path

As the developments of the stations do not allow direct visual tracking, a guiding telescope coupled with a sensitive TV camera and a remote monitor was chosen.

In addition to the preceding reasons, it was found that the sensitivity was increased, and also the tracking comfort.

II. GUIDING TELESCOPES

II.1. First generation

A . 20m diameter refractor, 1m focal length is coupled with a NOCTICON tube TV camera. The distance between the optical axes of the guiding telescope and the receiver is .60m. The reticle is etched directly on the monitor screen.

II.2. Second generation

The guiding telescope is also a 20cm aperture objective.

An optical relay gives focal lengths of 2m and 5m. The distance between the optical axes of the guiding telescope and the receiver is 85cm.
Five remote controls are located beneath the monitor screen. They are :

a) A luminous projected reticle in which the intensity may be increased from dim during night operation to bright on day time.

b) Variable optical attenuators with a zero attenuation mark (hole in the attenuator disks). They are used for day time operation or for target calibration test and they protect the photocathode.

c) Variable sensitivity of the TV tube.

d) Focusing of the telescope

e) Choice of the focal lenght (2m or 5m)

II.3. Lunar system.

The incoming light in the 1.5m telescope is picked up through a dichroïc splitting mirror. The receiving camera is mounted on a computer-driven setting device which allows the camera to follow a lunar crater while the telescope tracks the retroreflector. Three cameras will be tried : NOCTICON, ISOCON, VIDICON.

III. SPECIFICATIONS

III.1. Satellites stations.

Generations	1rst	2nd
Objective diameter	.20m	.20m
Focal length	1m	2m- 5m
viewing angle	1°	30'
sensitivity(magnitude stars)	12/13	11/12

With these specifications, STARLETT (10/12) Magnitude could be tracked. Due to the blooming effect of the Nocticon cameras, a bright satellite such as GEOS B is seen as a very white spot of 3 to 10mm diameter. The image of the satellite crosses the monitor screen (2nd generation) in approximatively 1s for STARLETT and 30 for GEOS 3 averages times.

In the second generation, two other cameras will be displayed on the same monitor.

a) a wide angle camera viewing the entire mount and telescope system, mainly for safety reasons.

b) a NOCTICON sensitive camera to display dim oscillograms of return or laser pulses. By this means, we will be able, through a digitizer, to check the quality of the laser and study the pulse processing apparatus.

To improve the manual tracking, we plan to introduce added datas on the monitor screen such as, mount position, clock time, range, error messages...

III.2. Lunar ranging system

For satellite tracking the blooming effect of the Nocticon camera is not very important. Men's eyes and brain are able to detect, with a great accuracy, the center of a nearly circular spot.

In the case of lunar tracking there are additional problems.

- On the illuminated moon the light flux is enough to track with a vidicon. The blooming must be eliminated as it masks the details.

- near of the terminator, the effect is even more critical.

- On the earth shine, the contrast is very weak and a sensitive camera is necessary. It has to be improved by contrast-processing of the video signal.

It seems that an ISOCON camera, which is blooming-resistant, could be a good choice.

SESSION 6A - SPECIAL TOPICS IN HARDWARE (MAINLY LASERS)

INTRODUCTORY REMARKS

S.A. Ramsden
Department of Applied Physics, University of Hull,
Hull, HU6 7RX U.K.

THE LASER TRANSMITTER

The first satellite laser ranging systems used Q-switched ruby lasers giving ∿ 1J in a 20-30 nsec pulse with the aim of obtaining a recognisable return pulse which was then analysed to obtain a precision better than that of the pulse width itself. Early lunar laser ranging systems were similar except that they used larger telescopes and operated with single photo-electron (or less) detection.

Many of these systems were later modified to give shorter 2-5nsec pulses, by cavity dumping or pulse-chopping techniques, and hence higher precision, and the majority of systems in use at the moment are of this type producing much valuable information.

It has long been recognised that even better accuracy is possible with mode-locked lasers giving sub-nanosecond pulses, used in conjunction with single photo-electron counting techniques, but technical difficulties have delayed their general acceptance.

Ruby lasers can be mode-locked, albeit with some difficulty, but they have low efficiency, need large power supplies and cannot be used at a high repetition rate because of cooling problems. For mode-locking Nd:YAG is the preferred material, having none of these problems but, because it emits at 1·06μ, the output needs to be converted to the second harmonic for detection purposes.

Nd:YAG lasers can be mode-locked passively, using a bleachable dye, or using an active element such as an acousto-optic modulator. In each case the output consists of a train of pulses, separated by the cavity round trip transit time, one of which can be switched out by an electro-optic (e.g. Pockels cell) switch.

The passively mode-locked oscillator gives a train of about 10-20 pulses each of about 20-30 psec duration, which can be increased up to ∿ 1nsec by choice of dye or by restricting the number of oscillating axial modes with an etalon. The energy in a single pulse is of the order of 1mj and can vary by at least ±10%. About 90% of the trains are well mode-locked but the system needs a skilled operator to keep it working satisfactorily.

Until recently active mode-locking was used only with c.w. systems, producing a continuous train of highly reproducible pulses. The energy in each pulse was very low (of the order of ∿ 1nJ) and a somewhat complex regenerative amplifier system had to be used to bring this up to a usable level, leading to reliability problems.

Now, however, an actively mode-locked pulsed system has been developed, for use in large laser fusion systems, which is very reproducible and yet contains sufficient energy in each pulse. This uses both an acousto-optic modulator and an acousto-optic Q-switch. The laser is pulsed in a quasi-c.w. way for several milliseconds during which the loss in the Q-switch is adjusted so that the laser just exceeds threshold. The modulator is on during this pre-lase period allowing the mode-locking process to reach a steady state so that when the laser is Q-switched at the end of the quasi-c.w. period a transform limited, stable, short pulse exists in the cavity leading to a reproducible Q-switched train of short pulses. The pulse duration depends on the modulation frequency and hence on the cavity length and varies from 50-100psec. The energy in a single pulse is ∿ 0.5mj and the repetition rate 20p.p.s. The reproducibility is ±2% but because such a good value is not required in a laser ranging system some simplification may be possible. The average power is about an order of magnitude lower than the 0.1 - 1.0W required, in the green, for satellites such as Starlette and Lageos and thus amplification will be necessary. It is preferable to increase the energy rather than the repetition rate to avoid problems of stress birefringence and lensing which occur at high thermal loadings.

An alternative, which may be attractive for mobile systems where size, complexity and cost are all important factors, may be to transmit the whole mode-locked burst instead. This creates additional detection and timing problems but these are perhaps acceptable in view of the better reliability of such systems. Further simplification might be possible by the use of new photocathodes which have greatly increased quantum efficiency at 1.06μ which, together with the greater atmospheric transmission at this wavelength, may make second harmonic conversion unnecessary.

Another way of obtaining higher energy might be to use a mode-locked unstable resonator configuration for the oscillator. This uses a larger volume of material and can give up to an order of magnitude increase (up to 10mj) in the energy in a single mode-locked pulse.

Some of these matters, and others, are discussed further in this session.

HIGH ENERGY PICOSECOND PULSES FROM A TWO-MIRROR UNSTABLE Nd:YAG LASER

R.J. Dewhurst, D. Jacoby and S.A. Ramsden
Department of Applied Physics Hull University,
Hull, HU6 7RX U.K.

1. Introduction

In the operation of conventional mode-locked oscillators, laser beam diameters are of the order of a few millimetres at most in order to achieve diffraction-limited outputs. At the same time, in high gain systems, there is a maximum power density which can be generated before the onset of self-focusing and subsequent damage. These two limits lead to a restriction in the useful energy developed within such resonators. The use of an unstable resonator offers the advantage of obtaining diffraction-limited output from active volumes having larger diameters[1,12]. Increased power and smaller beam divergences can then be obtained.

There are a number of unstable configurations which may be considered (Fig. 1) being classified into n- or p- branch categories. In both cases the active volume of the laser is fully exploited. However, in n-branch resonators the laser cavity is characterised by a focusing point within it and at the high peak powers developed in mode-locked oscillators, gas breakdown or bulk damage in components can then occur and thus p-branch unstable resonators are more suitable for mode-locked unstable laser oscillators.

It is worth noting the unusual characteristics of travelling wave ring resonators when used in unstable configurations; the high magnitude of the losses leads to irreversibility of the path of the light rays and to the possibility of constructing unidirectional ring generators. Fig. 1 shows two types of system of this kind. The first of these, Fig. 1d, utilises a ring resonator with a mirror configuration equivalent to that of Fig. 1b; placing a small aperture in the plane of the real centre of the wave propagating in one of the directions eliminates the appearance of waves travelling in the opposite direction. In the second type, Fig. 1e, the resonator is similar to that shown in Fig. 1c; the unidirectional property is achieved by appropriate positioning of an angular radiation selector. In both cases, introduction of one additional element (aperture or selector) provides simultaneously the unidirectional property and angular selection of radiation.

We have used mode-locked ring resonators in stable configurations[3] in the past but have experienced difficulty in maintaining alignment for more than a few hours. With a ruby rod, Pozzo et al[4] constructed a mode-locked unstable ring laser using prisms. As expected, large intensity discrimination between the two opposite propagating waves was obtained, the intensity ratio being 400:1. The resonator could therefore be said to be operating unidirectionally, giving pulse durations of $\sim$ 100ps. However, since the resonator configuration was n-branch, with the beam focusing in the resonator, such a laser is unlikely to be useful in the generation of very high powers. Experimental work on two-mirror unstable systems has been carried out using CO_2 lasers[5,6][15,16], Nd:glass lasers[2,8], HF/DF lasers[13,14] and Nd:YAG lasers[9,10,11]. However, in all cases the pulsewidths have been of nanosecond duration or longer. We have now examined mode-locking in such a system, generating pulses on picosecond timescales from a p-branch resonator.

2. Experimental Work

Our experimental configuration is shown in Fig. 2. The cavity was designed using the formulations given by Siegman[1,12]. Mirror radii of curvature for the positive confocal cavity are given by

$$R_1 = -\frac{2L}{(M-1)} \quad \text{and} \quad R_2 = \frac{2ML}{(M-1)}$$ where L is the empty cavity length, and M is the magnification, equivalent to the ratio of the rod diameter to the output mirror diameter. The geometrical output coupling is $\delta = 1 - \frac{1}{M^2}$, though in practice diffraction effects reduce this coupling to values slightly less than δ. For approximate correspondence with conventional cavities, the equivalent Fresnel number is

$$N_{eq} = \frac{(M-1)}{2M^2} \frac{D^2}{4L\lambda} ,$$

representing the number of half-periods in the phase change along the mirror for a spherical wave in the geometrical approximation[2]. Transverse modes with least loss have values of N_{eq} = 1·5, 2·5, 3·5 .... $(n + \frac{1}{2})$ .... where n is integer.

As a general rule, the unstable resonator should have the largest possible magnification compatible with output coupling requirements. One of these demands sufficient feedback for stimulated laser action to develop. Since the saturable absorber used for mode-locking, in our case Kodak 9860, is a lossy element, preliminary experiments used a modest magnification of two.

In the final stage of the design it would be necessary to include the effect of thermal lensing in the rod which becomes important for Nd:YAG lasers operating at repetition rates in excess of 1pps but to maintain simplicity and study only the mode-locking capabilities of the laser, we operated at 0·1pps. Our initial design parameters were:

$M = 2, \quad R_1 = -2m, \quad R_2 = +4m, \quad \delta = 0{\cdot}75,$

$L = 1m, \quad N_{eq} = 1{\cdot}2$

Satisfactory mode-locked trains were obtained, Fig. 3, using a pumping energy of 51J. Peak output energies of ∿ 2mJ in single pulses were recorded, with good shot-to-shot reproducibility.

Since it was possible to increase the pump energy to ∿ 150J, resulting in higher gains within the Nd:YAG rod, the magnification was then increased to M = 3·0 with R_1 = -1·3m, resulting in mode-locked pulses with peak energies of ∿ 11mJ.

Further work is required to improve the spatial structure of the pulse, which can be dependent on the pumping geometry of the laser rod; we used a one flashlamp elliptical system for these preliminary results, but for homogeneous pumping it may be necessary to construct a four flashlamp system. For the same input energy, flashlamp lifetimes would then be greatly lengthened - an important consideration in high-repetition-rate laser ranging systems.

3. Conclusions

We have shown that it is possible to extract 11mj pulses from a mode-locked two mirror unstable resonator, which is considerably in excess of that obtained with a conventional TEM_{00} resonator.

With similar magnifications others have shown that unstable resonator Nd:YAG lasers can be operated with diffraction limited beam outputs of approximately 0.25mrad[9], at repetition rates of 20pps[11]. Combining these characteristics would make the unstable Nd:YAG laser an extremely attractive device for lunar/satellite ranging.

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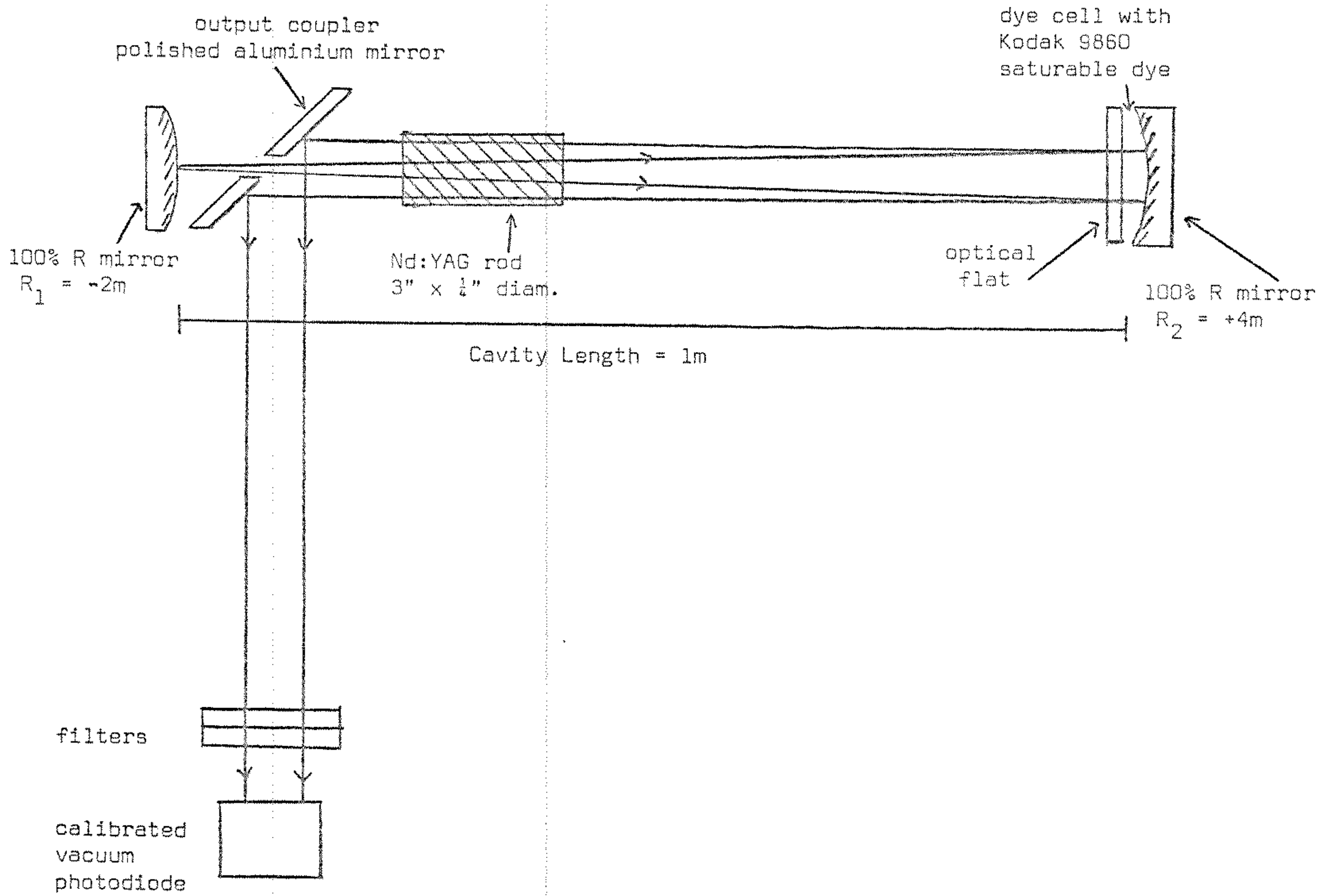

Figure 2 Nd:YAG mode-locked unstable laser

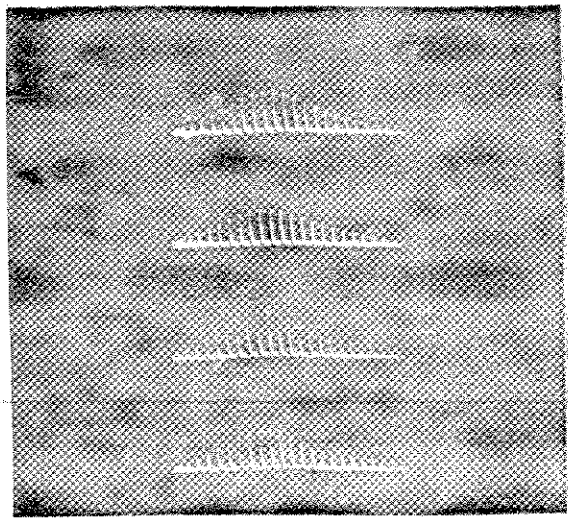

Fig 3   Mode-locked trains from an unstable resonator

Timescale 20ns/div

NEW DEVELOPMENTS ON LASER TRANSMITTERS FOR THE GRGS/CERGA SATELLITE AND LUNAR RANGING SYSTEMS

J. Gaignebet
GRGS/CERGA Obs. du Calern
06460 St Vallier de Thiey -France

Here after is a brief description of the last two laser transmitters used for the GRGS/CERGA ranging systems.

The satellite laser has now been operating since 1976 and we have gained some training through unexpected troubles.

The Lunar laser has been delivered in March 1978 and its simplicity of design and use seems to be good both from the viewpoint of operations and reliability.

I - SATELLITE SYSTEM

I.1. Introduction

When designed in 1974 only a ruby system was able to have the following advantages :

- wavelength 6943 A° where PMT cathodes have an acceptable efficiency
- Good space and time coherence
- Narrow bandwidth
- Short adjustable pulsewidths and mode-locked possibilities
- Mean power important for a Q-Switched laser
- High peak power to allow pulse shape processing
- High degree of reliability

Hoped to be transportable and versatile, the system is rather heavy and complex and needs trained operators.

I.2. Hardware

The ruby laser system shown in fig.1 is built in an oscillator - preamplifier-double pass amplifier - power amplifier configuration.

The oscillator cavity consists of a concave mirror MS immerged in a dye cell (Dicarbocyanine*)and two Fabry-Perrot etalons FP_1 FP_2. The overall assembly is a 1.5m long cavity designed for 23ns pulse width. A pin hole, placed between the output end of the 6.35 diameter 122mm long oscillator rod and the first FP, acts as a selector for a TME_{00} mono-longitudinal mode operation.

By switching the FP etalons it is possible to mode-lock the oscillator.

Through a pulse slicer P,PG the width is reduced to 2ns, 6ns, 10ns. The outgoing beam goes through a divergent lens L_1 to cover the following rods and is amplified by a preamplifier (6,35x122mm), a double pass amplifier (12,7x203mm) and, after a collimating lens, a power amplifier (19,05x197mm).

I.3. Specification

0.2 Hz repetition rate

Energy output	Pulsewidth FWHA
12j	10ns
8j	6ns
3j	2ns

0.5 Hz repetition rate

2j	10ns
12j	6ns
4j	2ns

- 70% of the energy within.25x10^{-3}rad.beam divergence
- 80% of the pulses within ±10% energy stability
- 100,000 shots flash tubes lifetime

In the mode-locked operation the oscillator delivers seven 200ps pulses in 10ns the energy has not yet been tested.

II. LUNAR SYSTEM

II.1. Introduction

In order to ut down the expenses for a completely new system, a rebuilding of the old 6ns / 6j multimode las r was achieved. The compoments are now installed on a new granite bench. The higher stability thus achieved, as well the larger dimensions giving better access to the compoments, assures that the settings are less critical than before.

In addition a new arrangements of the ascillator generates 3ns pulses in a TEM_{00} mono-longitudinal mode.

II.2. Hardware

The ruby laser system shown in fig.2 is built in an oscillator-double preamplifier- amplifier configuration.

The oscillator cavity consists of a concave mirror M_1 immersed in a dye cell (Dicarbocyanine*Jelikova, Hamal) and the combination of the output face of the rod with a 1cm Fabry-Perrot etalon.

The overall assembly is close coupled on each side of the 6,35mm diameter 132mm long ruby rod to shorten the cavity as much as possible. The mode selection is a pinhole between the mirror M_1 and the frontface of the ruby.

The outgoing pulse is collimated by two concave mirrors M_3M_4 and travels twice through the preamplifier head H_2(9,52x152mm). A telescope L_1L_2 expands the beam to cover the 14,3mm-diameter,204m-long power amplifier rod.

II.3. Specifications

The tested and guaranteed specifications are :

4j 3ns pulses

0,3 Hz repetition rate

70% of the energy within 10^{-3}rad beam divergence

80% of the pulses within $\pm$5% energy stability

100,000 shots flash tubes lifetime

II.4 Conclusion

It seems possible to enhance the energy output,as some shots delivered 6j without damage.

The development of the Dicarbocyanine-Methanol dye(Jelikova Hamal) opens the possibility of passive Q-switching with a very high degree of reliability a it seems almost unaffected by temperature (20 °C $\pm$ 10 °C) and time (3 months tests).

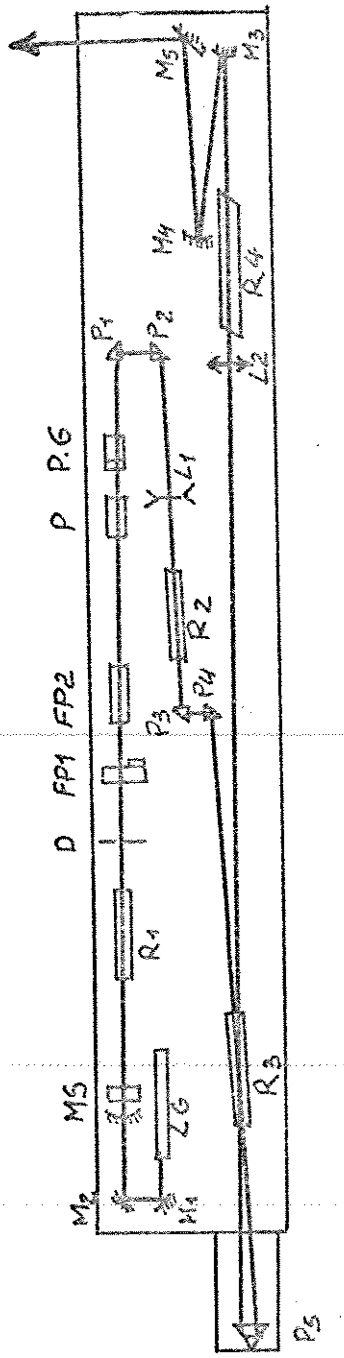

Fig. 1

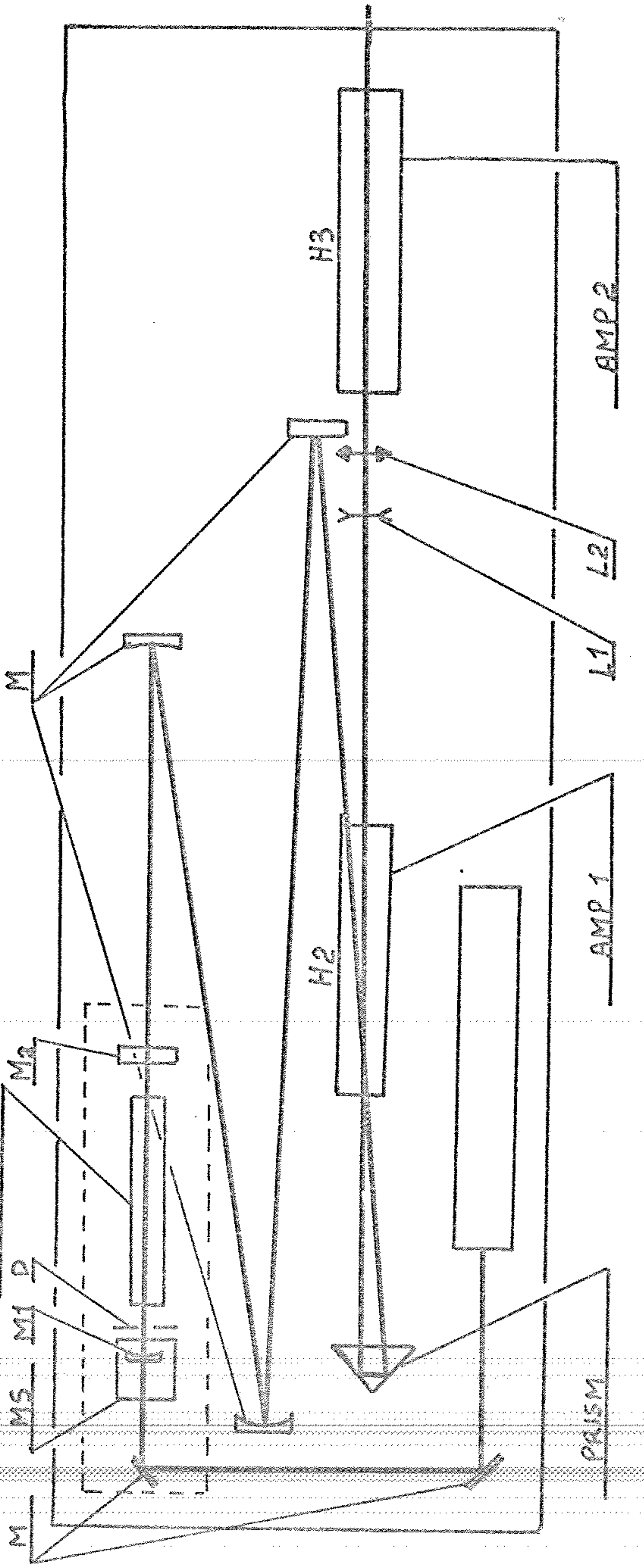

Fig 2

COMPACT SATELLITE RANGING LASER SUBSYSTEM

K.Hamal,H.Jelínková
Faculty of Nuclear Science and Physical Engineering
Brehova 7,Prague 1,Czechoslovakia

The accuracy of 10 cm is expected from the second generation of the satellite laser radar |1|.Except the satellite retroarray and atmospheric transmission there exist also error sources in the laser radar itself,mainly due to finite length of the laser pulse and the jitter of the electronics including the time base.From the point of view of the pulse length,to obtain the required 10 cm noise level, there are in principle two solutions,either using a nanosecond pulse laser together with a centroid detection technique or using a subnanosecond laser.Subnanosecond pulses of the required peak and average power were obtained from the sophisticated YAG oscillator-amplifier system |2| installed at the Coudé focus.However,there are still certain advantages of the simple altitude-azimuth mount with movable laser transmitter.The altitude-azimuth mount gives strong limitations on the size of the laser subsystem.To obtain satisfactory retrosignal from Lageos,the laser transmitter should deliver about one Joule in 5 nsec in multimode regime.The requirements can be fulfilled with the oscillator-amplifier system.The cylindrical arrangement pumping cavity creates inhomogenities which can lead to laser rod distortion.The rotational ellipsoid gives a better inversion distribution |3|,|4|;on the other hand,it requires more space.

We would like to report on the arrangement,where two rubies and two flashlamps are placed symmetrically inside one rotational ellipsoid according to its axis (Fig.1).This arrangement exploits the advantages of the rotational pumping symmetry and saves the space.We were using ruby rods 15 cm long and 10 mm in diameter,and two flashlamps with the inner diameter of 12 mm.Having one ruby and one flashlamp in this pumping cavity,the threshold pumping energy was 1600 Joules.Having two rubies and two flashlamps,the pumping energy decreased by 20% for each flashlamp.

To obtain 4 nsec pulses,we were using PTM technique with $\lambda/4$

voltage.The Pockels cell is driven by two air spark gaps;the first is electrically triggered,the second coaxial optically triggered |5|,both of them at atmospheric pressure.To obtain a short risetime,a new technique was applied |6|.The risetime is less than 0.8 nsec.To obtain a short fall time,the Pockels cell was carefully terminated.It was found that even a little mismatch causes remarcable fall time lengthening and distortions.To avoid postlasing resulting from piezoelectric retardation,two different voltages are applied on Pockels cell.The polarizer P2 in Fig.1 is used to reflect the pulse to the amplifier and to decrease the background as well.To obtain acceptable reliability usually required for ranging at remote observatories,the oscillator is kept at medium values.The output of the oscillator is between 0.2-0.3 Joule.The amplifier gain is about three.Both flashlamps are kept at the same pumping voltage to simplify the power supply.

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Figure Capture

Fig.1. Two rubies pumping cavity

Fig.2. The output pulse.The multiple exposure shows the reproducibility.The time scale is 2 nsec/div.

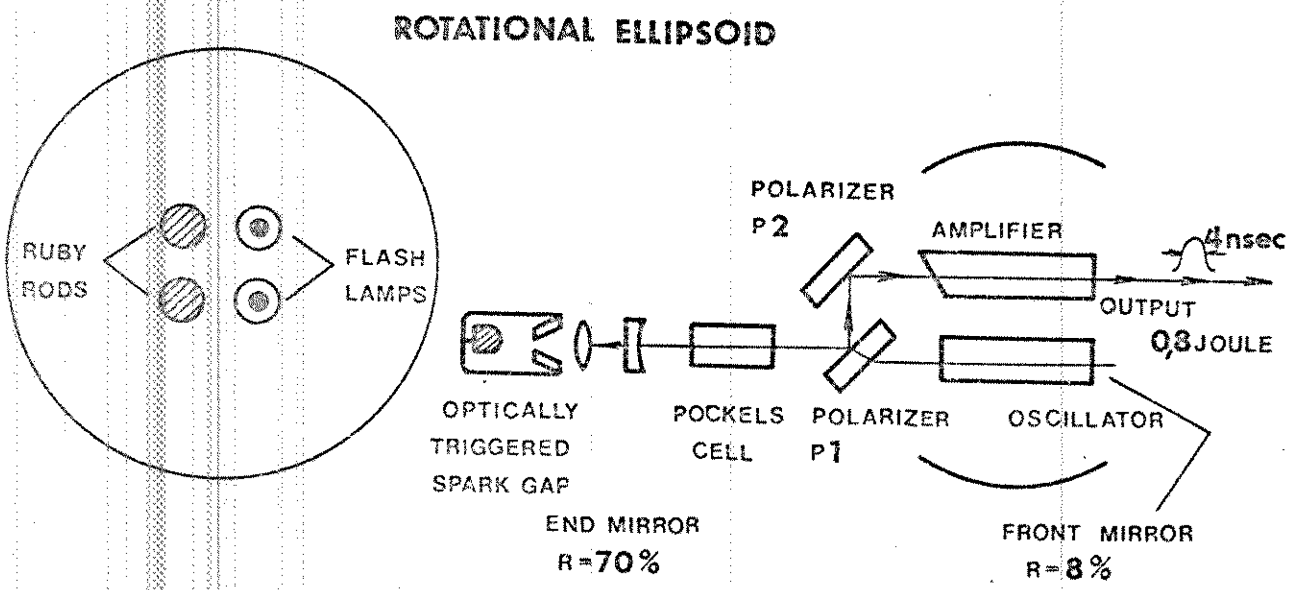
ROTATIONAL ELLIPSOID
RUBY RODS
FLASH LAMPS
OPTICALLY TRIGGERED SPARK GAP
END MIRROR R=70%
POCKELS CELL
POLARIZER P2
POLARIZER P1
AMPLIFIER
OSCILLATOR
4nsec
OUTPUT 0,8JOULE
FRONT MIRROR R=8%

Fig.1.

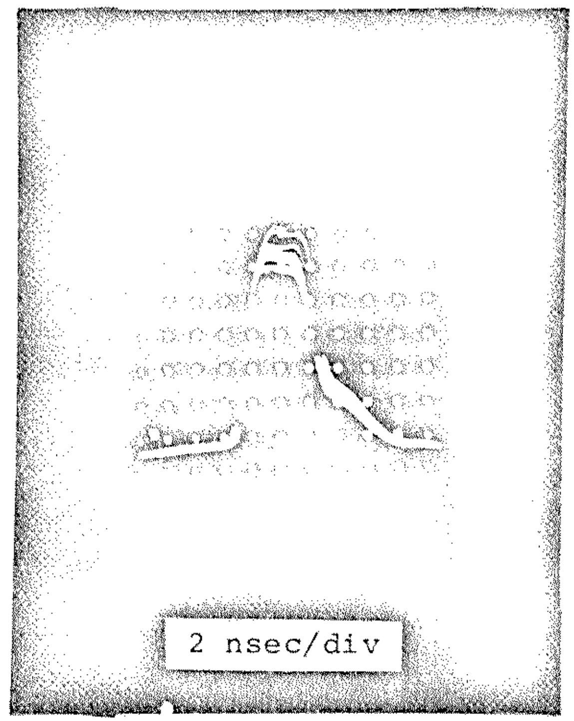
2 nsec/div

Fig.2

EFFICIENCY OF THE RUBY TELESCOPIC AMPLIFIER

Yu.L.Kokurin, V.V.Kurbasov, V.F.Lobanov,
A.N.Sukhanovsky
Academy of Sciences of the USSR,
P.N.Lebedev Physical Institute

INTRODUCTION

Obtaining laser pulses with duration < 10ns is inevitably connected with the loss in the driving oscillator pulse energy, therefore, ruby laser transmitters of the second generation become significantly complicated by application of the multistage amplifiers /1,2/.

There exist more efficient types of amplifiers, based on multi-pass amplification in a single stage. In /3/ the description of the neodymium multi-pass resonant laser amplifier, which was modified in /4/ for Nd-YAG laser for intermediate amplification of weak light pulses with duration $\sim 10^{-10}$s, is given. We shall turn down to the discussion of the telescopic amplifier, that has been studied in /5/ for glass laser for the first time. Telescopic amplifier has such important advantages, as: 1) high amplification factor; 2) small size; 3) relative simplicity of the optical alingment and maintenance. Moreover, the amplifier can be used not only for intermediate amplification, but as the last amplifying stage.

Schematic Diagram of a Three-Pass Telescopic Amplifier

Schematic diagram of the amplifier (Fig.1a) looks like inverted Mersenne afocal telescopic system /6/, where the space between the mirrors is filled with laser medium. Depending on the parameter of the mirrors, three, five and more passes may be carried out in an amplifying medium. In one of recent papers /7/ a three-pass telescopic amplifier for CO_2-laser system with amplification factor $\simeq 10^3$ was described. The ruby telescopic amplifier has some characteristic features due to filling of the space between the mirrors by the optically heterogeneous medium, which has a refraction factor > 1.

Sufficiently complete consideration of the main characteristics of the telescopic amplifier is based on an unstable cavity theory /8/. In view of a relatively low ruby amplification factor one can confine himself to a geometrical approach, neglecting the problems of stability of the amplifier. A simple calculation for two-mirror telescopic system /6/, that has ruby length 240 mm, gives $R_1 \simeq 800$ mm, $R_2 \simeq 250$mm, where R_1, is a curvature radius of a big mirror, and R_2, is a curvature radius of a small mirror. Diameters of a small mirror and the hole in a big mirror for three-pass amplifier are $\simeq 0.3D$, /6/, where D, is the diameter of the big mirror.

Experimental Results

The telescopic amplifier has been investigated for schematic diagram presented in Fig. 1b. Reflecting prisms were used as mirrors, and a telescopic configuration of beam path was provided by lens with a focal length $\simeq$ 1m.

An entry prism was prepared as a double roof-prism. The top of the prism was cut off to ensure optical coupling of the amplifier with the oscillator. The ruby crystal 16mm in diameter and 240 mm long had tapered edges inclined at 2° angle to the geometrical axis of the rod.

At energy density on the output ruby edge $\simeq 1.3$ J/cm^2 the amplification factor for one pass was $\simeq 5$. Telescopic amplifier for the same conditions had the factor $\simeq 60$.

Divergence of the input beam was 5', and the output divergence was practically the same.

The output mirror of the telescopic amplifier is in the powerful light field, therefore, it is necessary to take measures to avoid optical surface contamination by the vapour of the holder material. One can use Maksutov-Mersenne telescopic system /6/ for the amplifier (Fig. 1c), in this case there are no elements of the mirror holder in the light beam.

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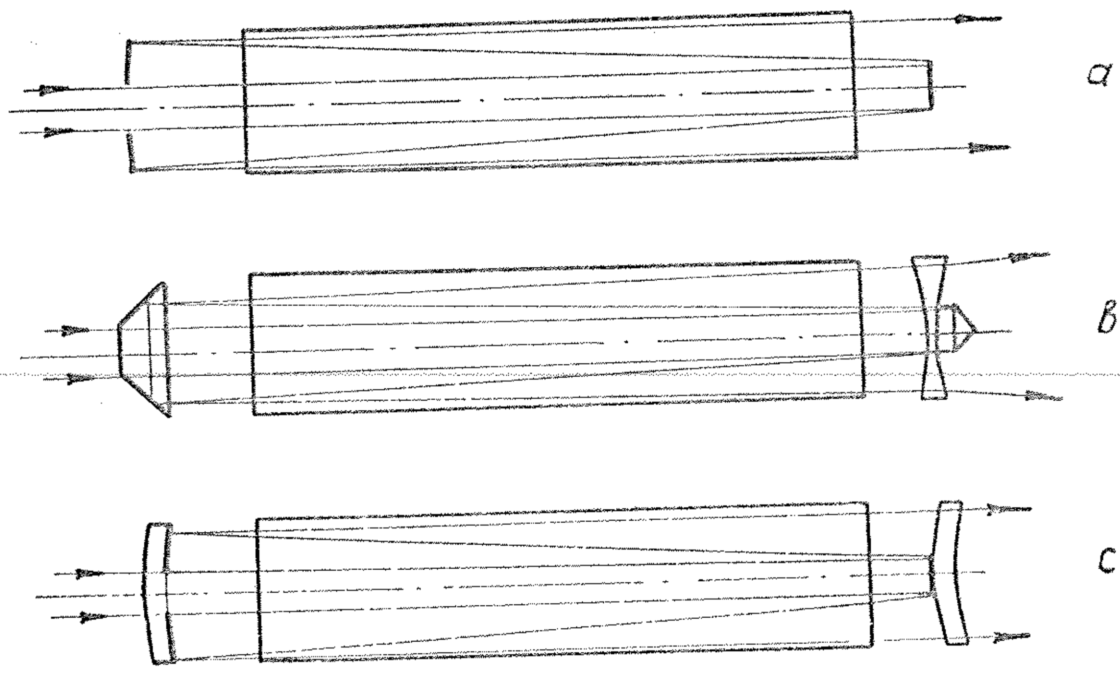
Figure Captions

Fig. 1. Schematic diagrams of the telescopic amplifiers.



QUANTUM LIMITED 4 NSEC LASER RANGING ACCURACY

K.Hamal, M.Vrbova

Faculty of Nuclear Science and Physical Engineering
Brehova 7, Prague 1, Czechoslovakia

The 4 nsec trapezoidal and gaussian laser pulses of different power level were compared from the point of view of laser radar measurement accuracies. Pulse centroid correction procedure was taken into account. The computer simulation of the detection procedure was done using HP 9830 as reported in [1]. The statistical ensembles of at least 50 stochastic photomultiplier current realizations were compared. Representative results are summarized on Figs.1,2,3.The photomultiplier response time equals 1 nsec. Fig. 1 shows the spreads of ranges in the case when laser pulse shape is gaussian of 4nsec FWHM and the signal level equals 100 photoelectron. The same pulse duration but lower signal level (20 photoel.) leads to the histogram shown as Fig.2. Fig.3 summarizes the simulation results for 20 photoel. trapezoidal pulses of 4 nsec FWHM and 0.5 nsec rise time.

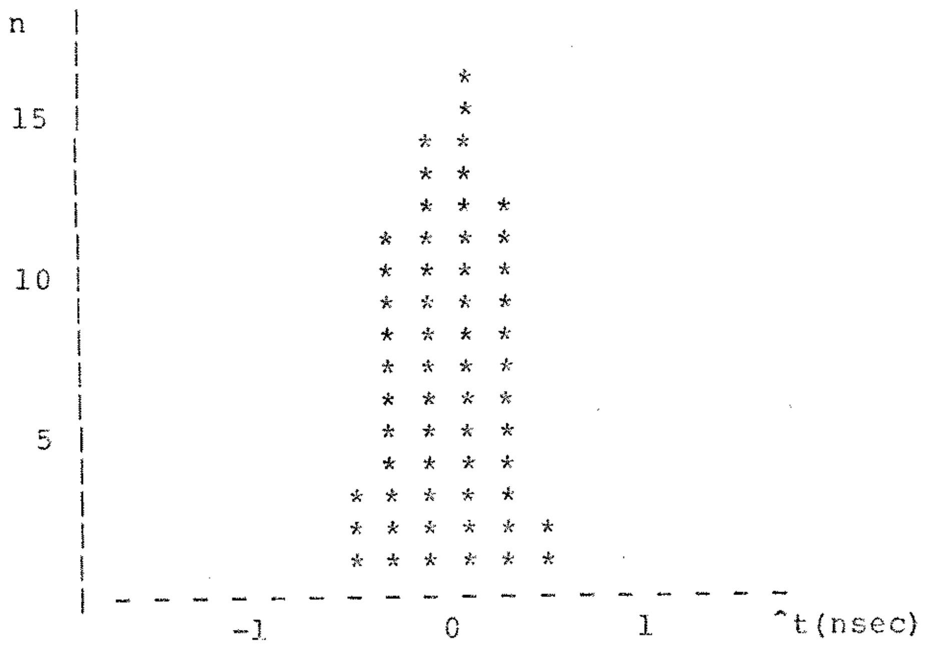


Fig.1: Histogram of the range inaccuracies (quant.limited)
horizontal scale: 0.2 nsec/div
gaussian pulse, power level: 100 photoel.,
FWHM : 4 nsec

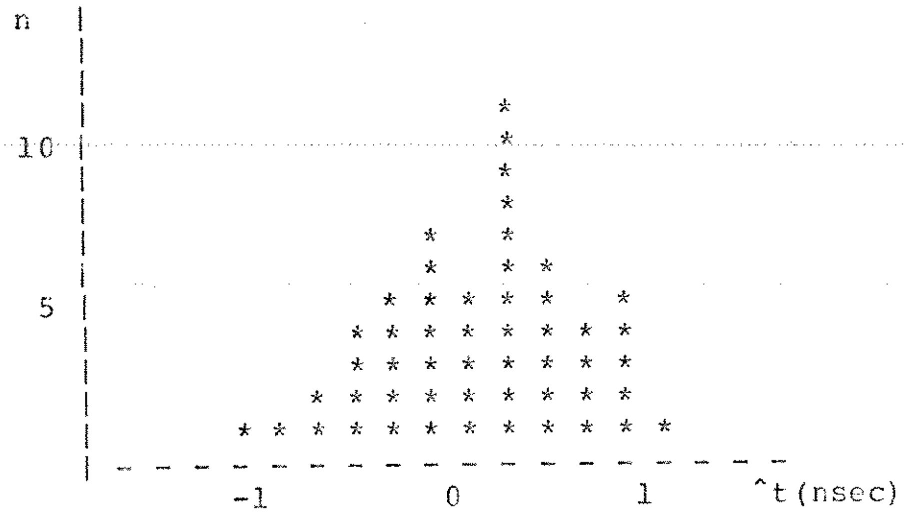


Fig.2: Histogram of the range inaccuracies (quant.limited)
horizontal scale: 0.2 nsec/div
gaussian pulse, power level : 20 photoel.
FWHM : 4 nsec

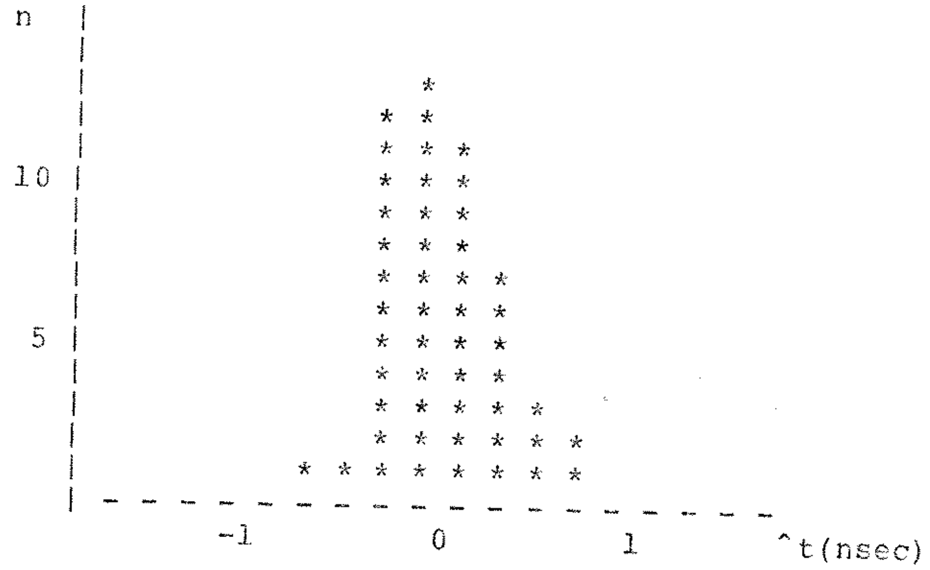


Fig.3: Histogram of the range inaccuracies (quant.limited)
horizontal scale: 0.2 nsec/div
trapezoidal pulse, power level : 20 photoel.
FWHM : 4 nsec

In accordance with these graphs we can conclude:

(1) The gaussian pulse shape,100 photoelectron signal, 4nsec and analog pulse centroid correction procedure assure that the quantum limited accuracy is higher then ±half nsec.

(2) Whenever the signal level decreases five times the quantum limited range inaccuracy increases approximately two times (compare Figs.1 and 2).

(3) The trapezoidal pulse with 0.5 nsec rise time,4 nsec FWHM has at the signal level about 20 photoelectron the quantum limited accuracy better then ±0.6 nsec. This value is almost two times higher than that for the gaussian pulse shape of the same width and the same signal level (compare Figs.2 and 3).

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A FAST LASER TRIGGERED SPARK GAP DRIVEN ELECTRO-OPTICAL SHUTTER SYSTEM

M.V. Paunonen
The Finnish Geodetic Institute, Helsinki

INTRODUCTION

Desirable features of a good laser ranging pulse are a short duration, high power and small beam divergence, i.e. high radiance. The Q-switching lacks the first prerequisite, but fortunately this drawback can be readily remedied by using an external electro-optical shutter to tailor the pulse.

The present paper describes the construction and preliminary test results of an electro-optical shutter intended for use in the Metsähovi satellite laser range finder /1/ to shorten a 20 ns Q-switched ruby laser pulse to 5 ns or less. A more detailed description can be found elsewhere /2/.

APPARATUS

An electro-optical shutter (or slicer) typically consists of a Pockels cell situated between crossed polarizers. The time dependent transmission T(t) of the shutter can be described by the equation

$$T(t) = T_{max} \cdot \sin^2\left[\frac{\pi}{2} \cdot \frac{U(t)}{V_{\lambda/2}}\right], \qquad (1)$$

where T_{max} is the maximum transmission, U(t) is the applied time dependent voltage, and $V_{\lambda/2}$ is the half wave voltage of the Pockels cell. If the cell is driven via a coaxial cable with the impedance Z_o, the voltage V(t) is ideally given by $V(t) = V_{max} \cdot \left[1 - \exp(-t/\tau)\right]$, where V_{max} is the final value of the voltage pulse and the electrical time constant, τ, is given by $\tau = Z_oC$, where C is the cell capacitance. V_{max} can be selected to be $V_{\lambda/2}$ (= half wave shuttering) or $2V_{\lambda/2}$ (= full wave shuttering). The transmitted optical pulse shapes are shown in Fig. 1.

The schematic diagram of the electro-optic shutter tested is shown in Fig. 2. A high speed, 50 Ω, KD*P Pockels cell of coaxial cylindrical ring electrode structure is used (Interactive Radiation Inc., Model 262-150). The electrical rise time is specified as 550 ps, from which a cell capacitance of 10 pF can be calculated ($T_r = 2.2\tau$, where τ is now 0.5 Z_oC). The N_2-pressurized laser-triggered spark gap (LTSG) employed is a small 50 Ω transversally triggered unit (Lasermetrics, Inc. Model SG-201). A Glan-laser polarizer was used (Lasermetrics Inc.).

The pulse shape was measured by a high speed vacuum photodiode (Instrument Technology Ltd, Model HSD-1850, S-20 photocathode, the nominal rise time 0.1 ns) and a Tektronix Transient Digitizer R 7912 (500 MHz band-width). The rise time of the detecting system was 0.7 ns.

RESULTS AND DISCUSSION

The shutter was first tested in the conventional mode, where the cable L_3 was the long terminated cable and the cable L_1 was the charge storage cable of 50 cm length (RG214/U), designed to give a 5 ns electric pulse. The measured rise and fall times of the shuttered pulses were near 1 ns.

The shutter system was also tested in a less common inverted configuration, shown in Fig. 2, where a bias voltage of 2 $V_{\lambda/2}$ was continuously applied to the Pockels cell without the external cable L_3. If the electro-optical crystal is located at the very end of the cable, the bias voltage goes smoothly from $2V_{\lambda/2}$ to zero when the LTSG is switched on and the optical transmission follows the full wave shuttering curve, Fig. 1b. However, in this case, there is a small intrinsic length of transmission line on both sides of the crystal because of continuous 50 ohm coaxial construction, and therefore the ideal pulse shape becomes modified by the voltage reflections. The theoretical transmission curve is shown in Fig. 3a. The estimated optical rise time is 500 ps and the pulse length 2 ns (FWHM). A measured optical pulse shape is shown in Fig. 3b. The front end of the pulse is integrated by the detecting system and the real amplitude is thus not known exactly.

The values measured support the conclusion that the rise time is about 500 ps and the pulse length 2 ns as calculated. This experiment also shows that the rise time of a matched LTSG can be considerably less than 500 ps.

CONCLUDING REMARKS

If the crystal is located at the end of the cable, the theoretical pulse width is 550 ps (FWHM) and the rise time 350 ps, Fig. 1b, with

$C = 10$ pF, $Z_o = 50$ ohm, $\tau = 0.5$ ns. This might be obtainable with some suitably designed capacitive Pockels cells. A faster operation could be obtained using the pulse-on method and the full wave shuttering (two transmitted optical pulses, $\tau = 0.25$ ns), but the charge voltage needed would be $4V_{\lambda/2}$. The use of a double crystal Pockels cell might be profitable in this case. A recent report on optical rise time measurements on KD^*P transmission-line Pockels cells /3/ shows that the rise time of a shuttered laser pulse would be restricted to rise times of about 300 ps when half wave shuttering and a spark gap driver is used. Faster operation, to less than 100 ps, could be obtainable with silicon photoconductive switches /4/.

If the Pockels cell is fed by a $V_{\lambda/2}$-voltage instead of the $2V_{\lambda/2}$-voltage, the whole Q-switched pulse is transmitted without shuttering action, Fig. 2. This feature might be useful in a ranging process where the satellite is first detected by a long, higher energy pulse and then the transmitter is switched to a short pulse mode for precise range measurements.

It is a great pleasure to acknowledge the financial aid of the Geographical Survey Office of Sweden, Gävle, in procuring the electro-optic shutter components used. Support from the Academy of Finland is also acknowledged

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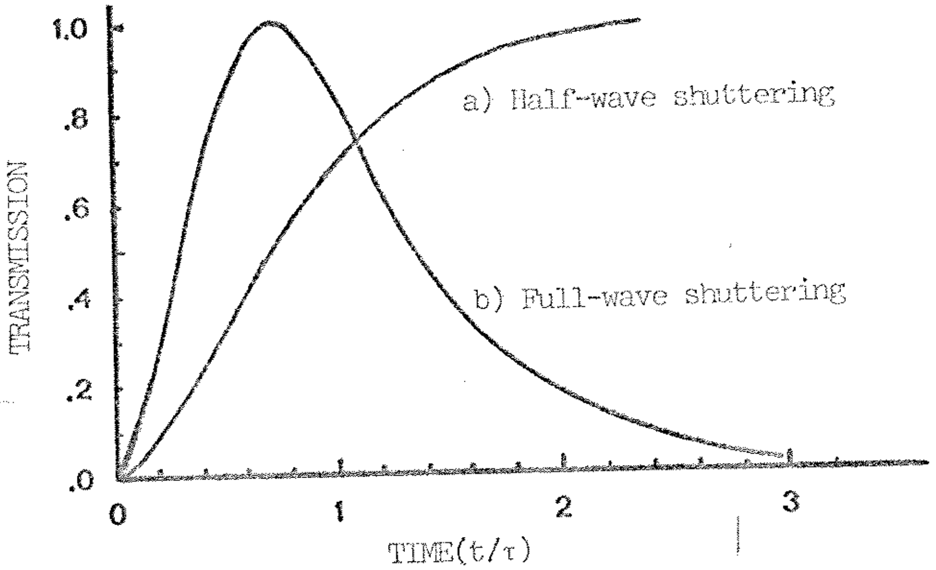

Fig.1. Transmission of the electro-optical shutter.

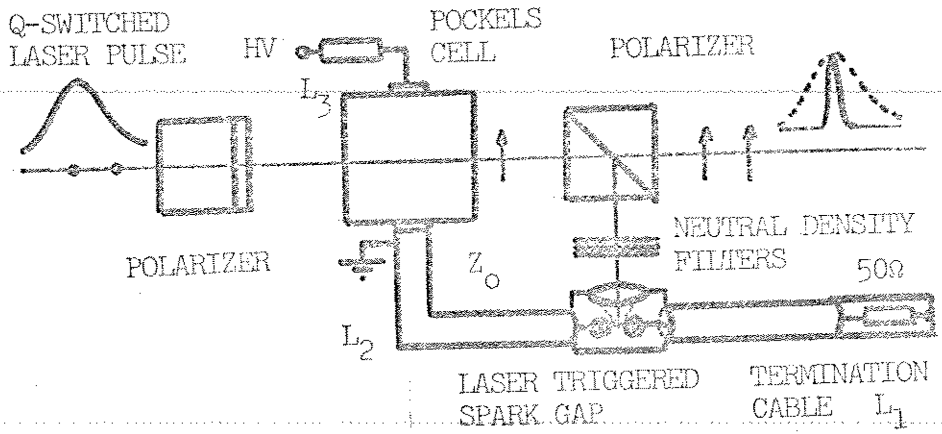

Fig.2. Schematic diagram of an electro-optical shutter.

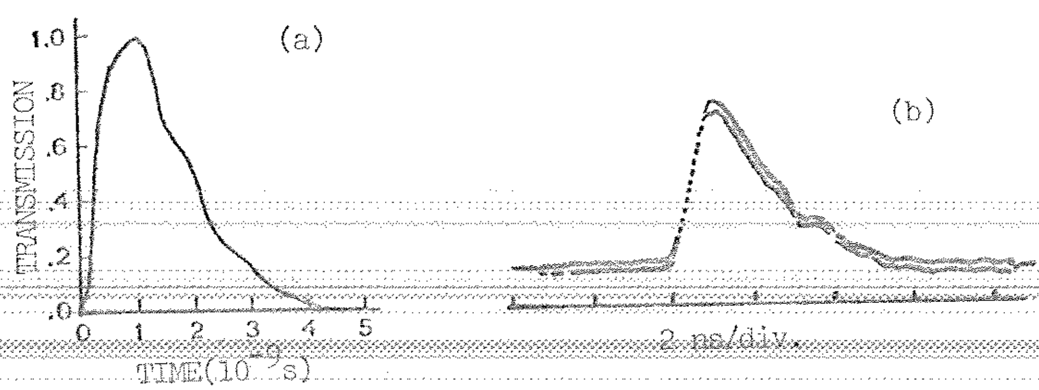

Fig.3. Calculated (a) and measured (b) transmission of the shutter shown in Fig.2.

LASER FOR SATELLITE RANGING

AT QUANTEL

Georges G. BRET

QUANTEL AVENUE DE L'ATLANTIQUE 91400 ORSAY FRANCE

Today's satellite tracking and ranging laser systems are concerned with two types of satellites :

Geodesic satellites of small size including retroreflecting mirrors that allow for high precision low loss tracking, in the ultimate precision range of 1 to 5 cm when a good atmospheric model is available.

Other satellites of larger size allowing only for high losses, low precision ranging (100 cm).

Geodesic satellites ranging systems can make full use of mode lock lasers. Such lasers tacking advantage of the prelase technic are under development at QUANTEL and are described in paragraph 2. However they are still expensive instruments devoted to very specific experiments and most measurements can be made with pulses a few nanoseconds long.

A new Q-switch system is now available from QUANTEL that can cover in a simple ruggedized unit all tracking needs for both types of satellites since it's pulse duration can be as short as 2.5 to 3 ns.

1/ A simple Q-switch laser for satellite ranging

Let's consider a laser emitting a single reproducible pulse of full width half maximum duration τ.

In the case of high loss tracking at low precision τ must allow for 1 meter ranging precision with no shape analysis (single photon return). Therefore we must have $\tau \leq$ 4 to 6 ns with an energy of the order of 100 mJ or $2.5.10^{17}$ photons.

When used on geodisic satellites the collected energy from the same pulse is around 10^4 to 10^5 photons and an increase in ranging precision on a factor 10 is possible using threshold and shape analysis methods.

If a final precision of 5 cm is needed a pulse of duration τ = 3 ns is sufficient. Our present laser emits such pulses with the following characteristics :

- FWHM pulse duration $\leq$ 3 ns
- Diffraction limited beam
- A single amplifier stage for :
- Output energy at 1,06 μ 300 mJ
- Output energy at 0.53 μ 100 mJ
- Repetition rate 1 to 10 Hz.

Higher energy can be obtained with a second amplifier.

The short pulse is produced directly by a short length laser cavity that includes a high gain short YAG rod.

In order to keep a high beam quality the laser oscillator works on a TEMoo mode and uses the Polarex(T) technic described in (1). It's general organization is given on figure 1.

Figures 2 and 3 show the laser bench with the different components in the case of one and two amplifier stages.

Pulses shapes are given on figure 4.

2/ <u>A stable mode lock laser</u>

High energy mode lock laser system are usually very expensive (regenerative amplifier systems) or rather unstable (passively mode lock lasers).

There use in laser ranging is therefore limited and cumbersome.

We have experimented at QUANTEL an actively mode lock laser (Acousto optic modulator) Q-switched by a Pockels cell driven by a D.C. power supply with controlable current.

This system gives stable reproducible pulses with a relatively unexpensive equipment.

It is possible to run this laser in a quasi continuous fashion since the current in the flash lamp is precisely controlable and to have a long period to develop a stable mode lock behaviour (2).

When the laser is then Q-switched with the Pockels cell a stable pulse arrises (Figure 5).

In an other configuration giving similar results a standard pulsed power supply was used and a controle loop was driving the DG voltage on the Pockels cell in order to keep the output power of the laser constant around 10 W.

The same prelase operation was observed with the same type of pulse stability. Figure 6 shows the output pulse of the laser when it is not Q-switched.

This laser is followed by a fast pulse selector working at high repetition rate and by two stages of amplification.

Output energy for 0.3 ns pulse can be 100 mJ at 1,06 μ and 50 mJ at 0.53 μ at a 10 Hz repetition rate.

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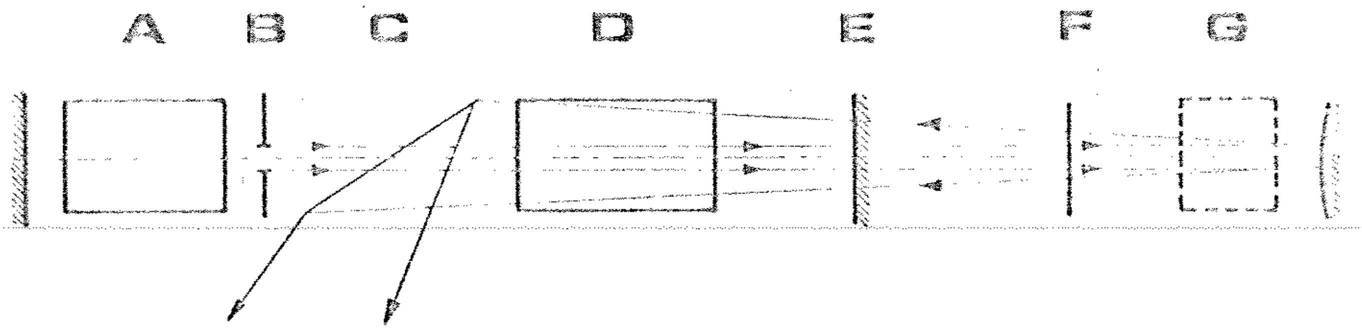


FIGURE I

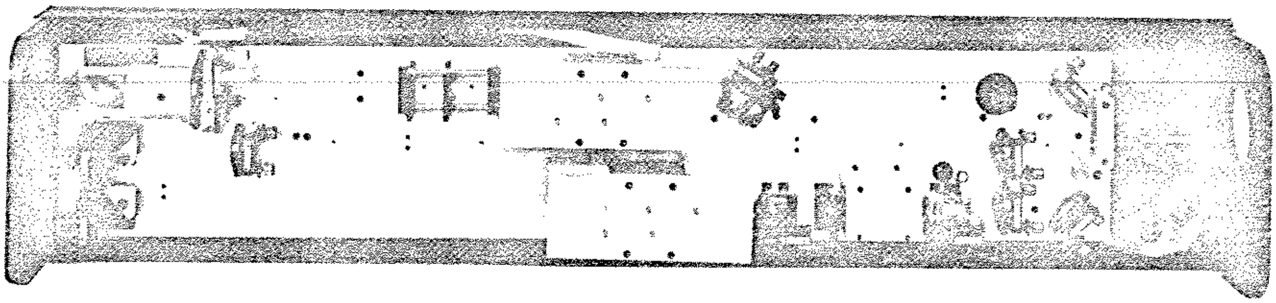


FIGURE 2

View of the short pulse Q-switch YAG laser.

The two laser heads (oscillator + amplifier) are clearly visible.

The second harmonic generation crystal is in its at the far left of the bench.

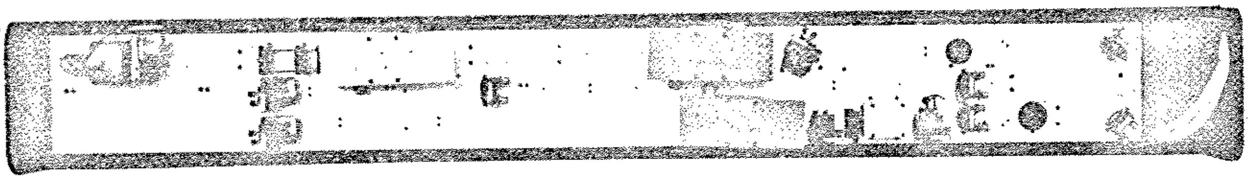
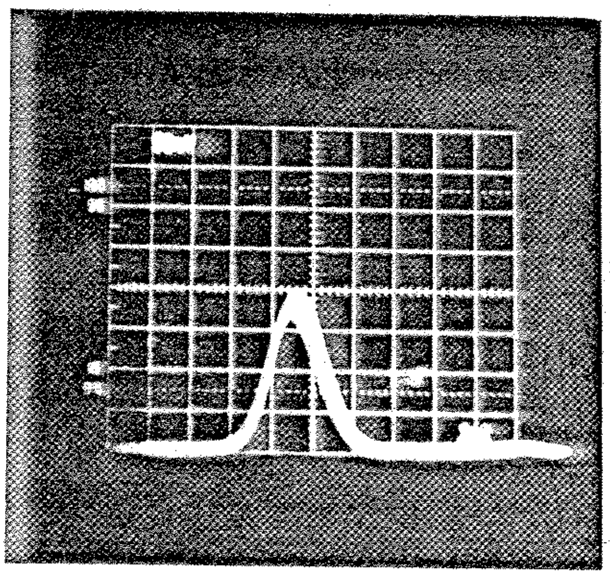


FIGURE 3

View of the short pulse Q-switch YAG laser with two amplifiers.

(A)



(B)

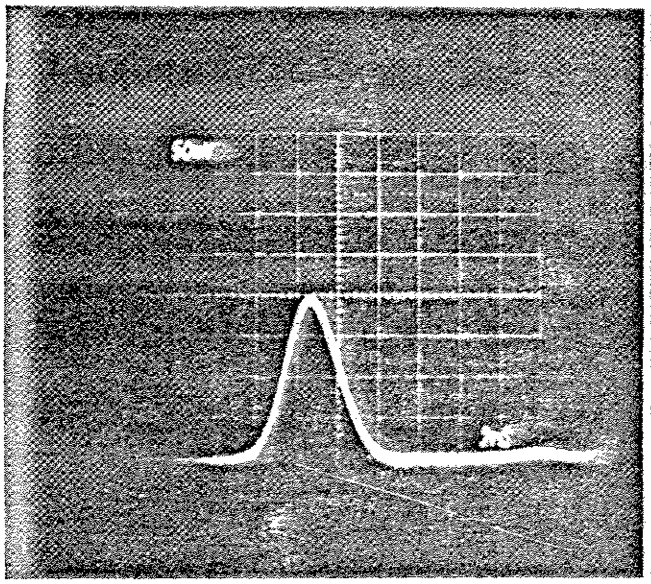


FIGURE 4

Laser pulse (A) and second harmonic pulse (B) from a short pulse Q-switch laser.

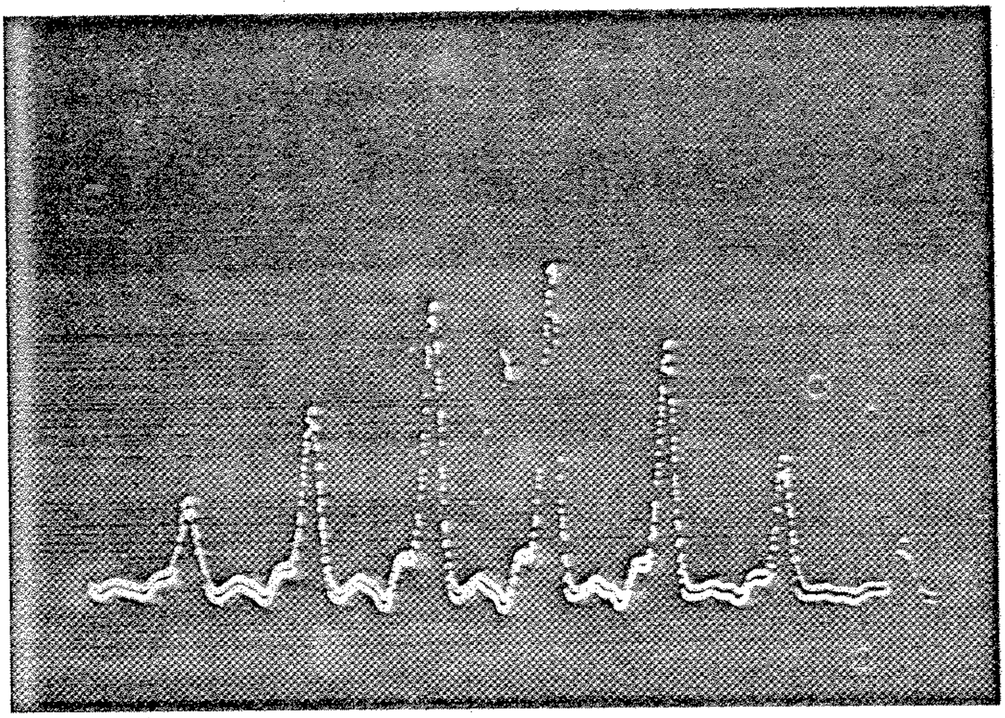


FIGURE 5

Mode lock pulses obtained with the prelase technic.

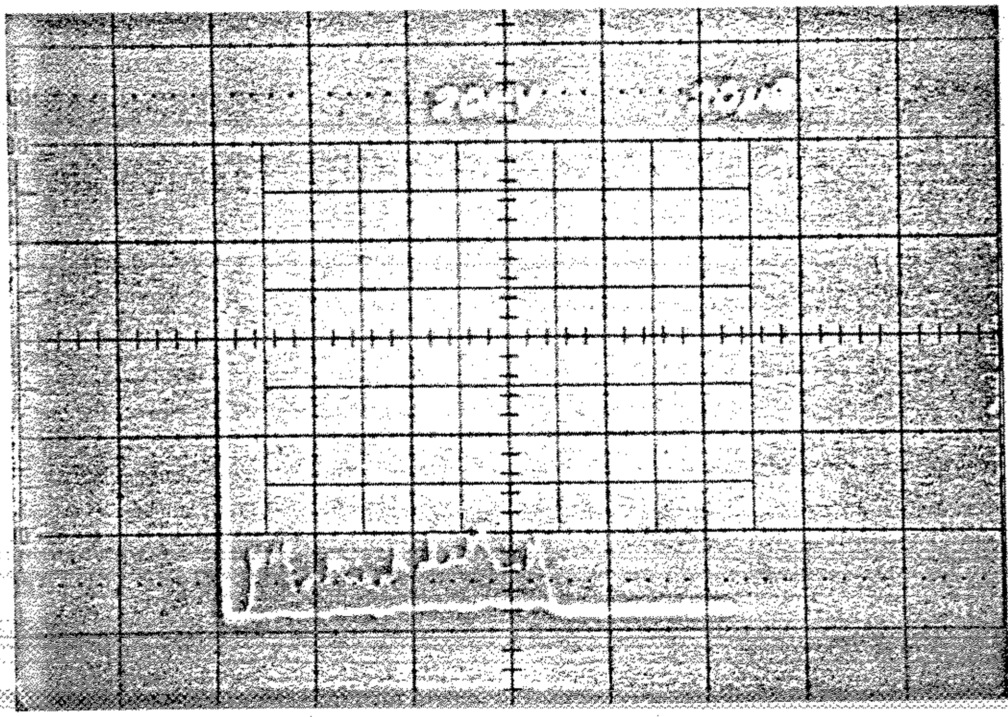


FIGURE 6

Output of a laser in the prelase mode when the Q-switch (a Pockels cell) is not opened.

200 PICOSECOND LASER DEVELOPMENT - A STATUS REPORT

T.S. Johnson, J.J. Degnan and T.E. McGunigal
Goddard Space Flight Center
Code 723
Greenbelt, MD 20771

An important long term goal of the laser ranging R&D program at Goddard has been the achievement of 2 cm overall ranging system accuracy. In order to achieve this goal it has been our consistent belief that the pulsewidth of the laser transmitter must be reduced by approximately an order of magnitude below the 3-5 nanosecond pulsewidth which can be achieved using Q-switched or cavity dump techniques. To this end, we sponsored the development beginning in the early 1970's of a high energy frequency doubled Nd:YAG laser with a cw modelocked oscillator at GTE Sylvania. This laser was intended solely for ground based applications. We have now had an opportunity to gain operational experience with this laser and to make certain improvements in its design. Beginning in 1975, we sponsored the development of a flash pumped modelocked laser transmitter at International Laser Systems. The goal of this development was to develop a laser with a configuration that would permit operation in a spacecraft environment. Obviously, if the laser can be made to operate properly it can be used in ground based systems.

The operational characteristics, performance and status of these developments is the subject of this paper.

THE CW MODELOCKED OSCILLATOR APPROACH

The high energy, short pulse, Nd:YAG laser system manufactured by GTE Sylvania, consists of a cw modelocked oscillator, a regenerative amplifier, three single pass amplifiers, and a type II KD*P second harmonic generator. The laser system is capable of operating at 5 pulses per second emitting a nominal 250 milljoules of energy at .53 micrometers with a pulse width of less than 200 picoseconds fullwidth half max. (FWHM).

In operation, the cw oscillator is modelocked by an acousto optical modulator and generates a continous train of 200 picosecond, 6 nanojoule coherent optical pulses at a 150 megapulse/sec. rate. This train of pulses passes through the selector pockels cell which rotates the polarization of a single pulse by application of a short pulse of halfwave voltage in syncronization with the modelocked output of the cw oscillator. This single seed pulse is directed into the regenerative amplifier by calcite polarizers and passes through the regenerative amplifier "Q" switch pockels cell. The "Q" switch pockels cell is biased at the quarterwave voltage and the seed pulse after reflection from the regenerative amplifier cavity end mirror passes back through the "Q" switch pockels cell. The quarterwave voltage on the "Q" switch pockels cell is then reduced to O preventing any additonal pulses from the cw oscillator from entering the regenerative amplifier and allows the regenerative amplifier circulating energy to remain in the cavity. The initial seed pulse reflects back and forth between the regenerative amplifier cavity end mirrors and is amplified each time it passes through the regenerative amplifier rod. After several round trip passes (typically 10-30) through the amplifier rod the circulating energy reaches a maximum value and the cavity dump pockels cell is operated. This rotates the polarization of the circulating energy by a halfwave and the energy is coupled out of the regenerative amplifier and through the isolator pockels cell to the three single pass amplifiers. The original seed pulse from the cw oscillator is amplified from $6x10^{-9}$Joules to about 10^{-3} Joules by the regenerative amplifier. The three single pass amplifiers amplify the one millijoule regenerative amplifier output to the 500 millijoule level. The output of the final amplifier is expanded and doubled by the type II KD*P second harmonic generator with a nominal 50% conversion efficiency.

The successful operation of this laser system depends on several factors. Principle among these factors are the maintenance of proper alignment or opto-mechanical stability, the precise and stable control of the optical radiation and switching and the maintenance of good beam homogeneity throughout the system. Except for the question of damage to the various optical components, introduced by beam inhomogeneities, optical instability, dirt or operation at unusually high power levels, the control of the optical radiation throughout the laser effects its performance for the ranging application as much as any other single factor. In fact, proper control of the radiation through stable reliable operation of the drive voltage to the electro optic switches will tend to prevent the destructive effects of changes in alignment and the beam inhomogeneities introduced by these changes. As manufactured, the 4 Kilovolt pulses for the pockels cells were generated by krytron driver boards. The voltage transitions were typically 3-5 nanoseconds in duration with a jitter of 1.5-3 nanoseconds. In addition, the transition risetime and jitter would materially change over both short and long term operation, requiring constant adjustment to maintain operation of the laser. These changes would cause the laser to operate with multiple or long pulse operation, and with a large variation in output energy. Furthermore, the timing between the "Q" switch and cavity dump transitions was fixed by an adjustable delay synchronized to the cw oscillator optical output. Any variations in the Gain of the regenerative amplifier from misalignment or pump energy fluctuations would cause the buildup of the circulating seed pulse to occur at different times with respect to the fixed cavity dump timing. In order to stabilize this buildup time, the regnerative amplifier was usually pumped at a very high level which would give an output pulse with energy close to or exceeding the damage threshold of some of the optical components.

Two modifications have been implemented in one of the laser systems to achieve stable and reliable control of the electro-optical switching. The original pockels cell driver boards were replaced with EG&G (Ortec) HV100/N high voltage pulsers. These pulsers supply the pockels cells with the correct voltages with a risetime of less than 1.5 nanoseconds and a jitter with respect to the input trigger pulse of less than 1.5 nanoseconds over long periods of time. The cavity dump driver trigger was changed from the original fixed timing synchronized to the cw mode locked output to a trigger generated by a radiation detector sensing the buildup in the regenerative amplifier itself. This radiation detector was fabricated from an avalanche mode transistor with the top of the can cut off and the junction illuminated by leakage radiation from one end of the regenerative amplifier. Control of the cavity dump pockels cell driver is better than 1 ns and cavity dumping always occurs at a given energy level within the regenerative amplifier cavity. This allows operation of the regenerative amplifier at a level low enough to preclude the development of any pulse energetic enough to damage any optical components. Furthermore, triggering on the energy buildup itself compensates for minor misalignment changes in the regenerative amplifier which normally manifests itself as a major change in buildup time rather than a large reduction in buildup energy.

Those applications requiring a high energy, short pulse laser can be satisfied under certain limitations with this laser system if the modifications as described are made. However, this laser system does require frequent alignment by highly trained personnel and the lifetime of optical components is directly related to the required output energy.

THE FLASHLAMP-PUMPED APPROACH

The goal of the ILS program is the development of a rugged, frequency doubled, subnanosecond pulse, flashlamp-pumped Nd:YAG oscillator/amplifier system capable of ranging from the Space Shuttle to ground-based retroreflectors with a single shot accuracy of two centimeters. Present ruggedized lasers are Q-switched oscillators having pulsewidths of 10 nanoseconds or more which, with realizable receivers, are not capable of such precise ranging. Flashlamp-pumping the oscillator reduces the system prime power requirements to about 200 watts compared to over 3000 watts for ground-based systems which use CW-pumped, mode-locked, oscillators to generate a subnanosecond seed pulse for the laser amplifier chain.

The ILS system uses an RF-driven, electro-optic KD*P modelocker in combination with a dielectric thin film polarizer to provide a sinusoidal modulation of the cavity loss during the pre-lase period. During this period, which lasts for several microseconds, the laser oscillates at a very low level just above threshold while the modelocker gradually reduces the temporal width of the circulating pulse to its steady state value of approximately 200 picoseconds. A voltage-programmable KD*P Q-switch and a second dielectric polarizer provides a variable loss for three separate cavity conditions: (1) the pre-lase condition (moderate voltage) during which the modelocker acts on the circulating low-level radiation to produce a subnanosecond pulsewidth; (2) the Q-switched condition (zero voltage) during which the subnanosecond pulse builds up rapidly in energy; and (3) the cavity-pump condition (quarter wave voltage) in which the circulating pulse is ejected from the cavity. The pulse is then amplified in a double-pass amplifier and frequency-doubled in a Type II KD*P crystal. The use of a double-sided convex-concave mirror and the crossed TIR prism resonator enhances the mechanical alignment stability while providing a long resonator length for the oscillator within a compact volume. The long resonator length relaxes the switching time requirements for the cavity dump operation and provides large spot sizes within the resonator which in turn improves the mode volume and energy extraction efficiency within the Nd:YAG rod and raises the energy threshold at which optical damge will occur. In addition to providing a subnanosecond pulsewidth, the prelase period also allows the TEM_{00} or gaussian spatial mode to become dominant.

The breadboard consists of four separate units: (1) the transmitter unit; (2) the modelocker driver unit; (3) the power supply unit; and (4) the cooling unit.

Experiments to date have verified the generation of a single subnanosecond pulse (less than 800 picoseconds detector limited) with an energy of 35 millijoules at the 1.06 micrometer wavelength. The output of the oscillator/amplifier exhibits virtually no prepulse although a small postpulse is observed. Efforts are being directed toward an improvement in the postpulse extinction via a reduction in the cavity-dump switching time.

FIGURE OF MERIT OF A LASER FOR RADAR APPLICATIONS

K.Hamal

Faculty of Nuclear Science and Physical Engineering
Brehova 7,Prague 1,Czechoslovakia

The applications requirements on lasers can be expressed by a figure of merit.Born and Wolf /1/ separate the brightness and a time bandwidth product of a light source.We examine /2/ some pulse laser applications and demonstrate the ratio of the brightness and the spectral width defined as *the spectral brightness* can be used as a figure of merit for a laser source in most applications including a laser radar.

The radar scheme has a transmitter,target and receiver. The received energy S is determined by the radar equation /3/. Assuming the transmitter terms only

$$S \,\alpha\, \frac{1}{R^4}\,\frac{E}{\Theta_T^2} \quad . \tag{1}$$

Here E is the transmitted energy,air is the target distance and Θ_T is the beam divergence due to the transmitter.The factor E/Θ_T^2 is controlled by the transmitter.The transmitter beam divergence Θ_T refers to a laser beam collimated by a telescope and can be expressed as

$$\Theta_T = \frac{D_L}{D_T} \,.\, \Theta_L, \tag{2}$$

where D_L is the diameter of the input laser beam,D_T is the diameter of the telescope output beam and Θ_L is the laser beam divergence.Combining (1),(2) we obtain

$$S \,\alpha\, \frac{E}{D_L^2 \,.\, \Theta_L^2} = B \,.\, \Delta\tau \,. \tag{3}$$

where B is the brightness of a laser and $\Delta\tau$ the pulse length. The thermal noise energy N of the detector with bandwidth Δf_G and time gate $\Delta\tau_G$ is proportional to

$$N \,\alpha\, \Delta f_G \,.\, \Delta\tau_G . \tag{4}$$

The figure of merit of a laser radar can be determined by a signal noise ratio SNR.The maximum SNR corresponds to the conditions $\Delta f_G = \Delta f$ and $\Delta\tau_G = \Delta\tau$.$\Delta f$ is the spactral width of a laser radiation. Then

$$\text{SNR} \propto \frac{B}{\Delta f} \quad . \tag{5}$$

Thus the spectral brightness is the figure of merit of a laser for radar applications.

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2. K.Hamal, "Figure of merit for some pulse laser applications", *IEEE J. Quantum Electron.*, vol. QE-14, June 1978.
3. L.D.Smulin and G.F.Fiocco, "Project Luna See", *Proc. IRE*, vol. 50, pp. 1703-1704, July, 1962.

session 6B laser safety

chairman F. Nouel /co-chairman F. Zeeman

Nouel
Thorp /Pearlman
Visser /Zeeman
McGunigal /Bebris
Hatat

LASER SAFETY

F. Nouel

Groupe de Recherches de Géodésie Spatiale, Toulouse, France

INTRODUCTION

During the two previous workshops, the problems of laser safety have been talked about and some major ideas or actions were developped :

- we are responsible by our vocabulary (fire the laser, shot, target) for maintaining the reactions of authorities to the laser ranging systems which are different from those for military applications.

- the standards in most of the countries are either not yet defined or under consideration.

- besides injuries that concerned people at the laser station which still keep, in most cases, the character of laboratory, aircraft safety is a problem as far as concerns us.

At the workshop hold in Prague, it was decided to make literature readily available by sending documents or biographies to Dr. M. Pearlman from SAO. He would distribute copies to requesting individuals. This action will be looked at as far as its result is concerned and further developments given if necessary or wished.

1. Evaluation and control of Laser hazards

In U.S.A., since 2 years a national standard list is used. It was defined by the Bureau of Radiations Health.

In other countries, it seems that utilisation conditions are under investigation (R.F.A., Australia) or not existing (France except for medical use of laser).

A NATO Standardisation Agreement (STANAG 3606) has been written. The issue should be finalised in the near future.

On the other hand, the International Electrotechnical Commission (CEI) has a technical Committee (N° 76) on Laser equipment that defined standards and publishes security levels for the parameters.

The Société Française de Radio Protection organized an international congress at Corbeil (near Paris) in May 1978 and where a special panel is devoted to laser.

2. Parameters in Laser hazard evaluation

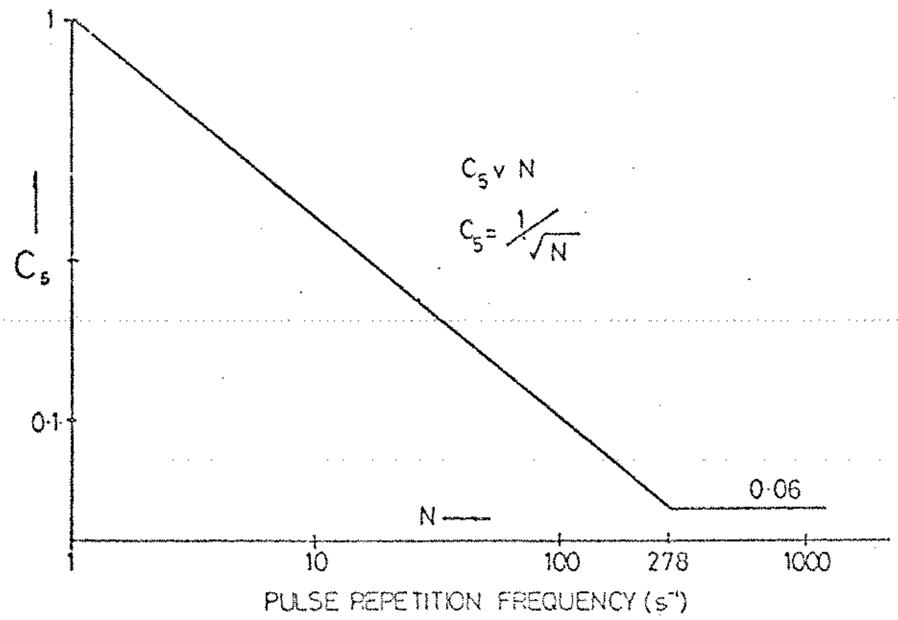
These parameters are :

- the wavelength,
- the pulse duration,
- the pulse energy,
- the natural beam divergence,
- the emergent beam diameter,
- the pulse repetition frequency.

Laser are grouped in four classes which correspond to output of these parameters. Then a Nominal Ocular Hazard Distance (N.O.H.D.) can be computed. It corresponds to the distance where safety for the eyes or skin is respected with respect to the appropriate Protection Standard.

However, factors are affecting this distance, such as atmospheric effects, magnifying optical instruments, reflection hazards, beam pointing accuracy, pulse repetition frequency.

All these parameters are important in order to choose the appropriate attenuating glasses to wear.



For example, it is specified that with repetitively pulsed lasers, it is appropriate to reduce the standard values for maximum permissible exposures of individual pulses, using the correction factor C_5 .

$$C_5 = 1/\sqrt{N} \quad \text{for} \quad 1 \leqslant N \leqslant 278\ s^{-1}$$

$$C_5 = 0.06 \quad \text{for} \quad N > 278\ s^{-1}$$

3. Aircraft safety

Several devices are used by the groups for aircraft safety. It can goes from a permanent watching by radar for example to simplier systems which operate almost automatically by stopping laser emition when a plane is coming too closely to the laser beam. Such systems should be developped because they require less personnal contribution when operating the stations.

The device used at Kootwijk station is operating since the last workshop and reliability will be examined.

The autorities might become more conservative as they already were after reading the paper on "Laser Satellite Ranging as a Hazard to Overflying Aircraft" published by G.J. Pert in Optics and Laser Technology - April 78 -. As it is often the case, the reader looks through the abstract only and he will find that "application of the formula to a typical case shows that one such incident (causing eye damage to an occupant of the aircraft) might occur every year.

CONCLUSIONS

The issue of the work initiated by Dr. M. Pearlman should be a kind of "booklet" where parameters and cautions would be summarized in table easily readable as soon as the international community will have establish their propositions which are now studied.

Moreover an easy system for detecting aircrafts should be installed in stations which are mobile or semi-mobile in order to facilitate their installation in a new site.

LASER SAFETY AT SAO STATIONS

J. M. Thorp and M. R. Pearlman
Smithsonian Astrophysical Observatory
Cambridge, MA

Several safety measures have been taken at the Smithsonian Astrophysical Observatory laser stations. Warning signs have been installed at all exposed accessible places. In addition, red area lights at exposed locations flash when the capacitors are charged and lasing is possible. All electronics for the laser transmitter and charging are enclosed and shielded; all chassis have safety interlocks. A STOP button to discharge the system is located on the laser transmitter head, with a second one near the operator. A discharge hook built into each system allows manual discharge to a ground rod in case of an emergency. Each observer has an eye examination once a year to evaluate any change in the retinal appearance. Records are kept at each site and passed on to new sites when an observer is transferred. To date, no tests have shown any eye damage.

Aircraft safety procedures vary from site to site, depending on traffic density and scheduling. Orroral Valley is near a highly traveled air corridor, but traffic is restricted to specific, predictable hours. For each operating shift, the air-traffic controllers for the region are given a laser pass schedule that includes the time of day and the sectors of the sky. Sector plot information, in eight sectors with high and low subsectors, is produced routinely by the station's prediction software. A direct telephone line between the site and the controllers is used to warn the station of airplane-sector conflicts. The sites at Mt. Hopkins, Arizona, and Arequipa, Peru, are located in mountainous areas, over which air traffic is light. Commerical flights above these sites are closely scheduled. At Mt. Hopkins, private flights are usually below the minimum elevation of the laser; in Arequipa, they are essentially nonexistent. In Natal, Brazil, air traffic is also very light and scheduled. Visual spotters are used at all three sites.

When observers are in a potentially exposed area during calibration, they are required to remain in contact with the laser operator by two-way radio. Targets are located at remote locations, which have been marked as dangerous areas. Pulsing below the horizon is prohibited except at calibration targets.

LASER SAFETY AT THE KOOTWIJK OBSERVATORY

H.Visser, Institute of Applied Physics, Delft (The Netherlands)
F.W.Zeeman, Delft University of Technology, Delft

INTRODUCTION

Apart from legally dictated safety measures (warning signs, goggles, optical and electrical shielding, etc.) there are three area´s of special importance for a laser tracking station:

a. the control system and lay-out of the installation
b. calibration measurements to ground targets
c. overflying aircraft

In this paper the solutions for problem area´s b. and c. at the Kootwijk observatory will be described.

CALIBRATION MEASUREMENTS

For this activity we have two arrangements available:

1) Ranging to a fixed target at 1 km distance.

Instead of the common practice to fire with full power to a diffuse reflective target, we attenuate the beam directly at the laser to a level in agreement with the safety standards. This implies the use of a retroreflective target in order to get returns of the desired signal level. We use 1 m^2 of plastic reflectors (as used for traffic signs). The properties of the reflected light, as seen by the receiver, are similar to diffuse reflection because of the bad quality and the amount of retroreflectors. This retroreflective target is also very useful for alignment of the transmitting optics to the receiving optics with a HeNe laser, especially at daytime.

Using this set-up there is no danger for operating personnel or people outside the station when firing in horizontal directions.

The beam attenuator used for this purpose is of a special design to avoid any chance of damaging neutral density filters with the full output power of the laser (figure 1.)

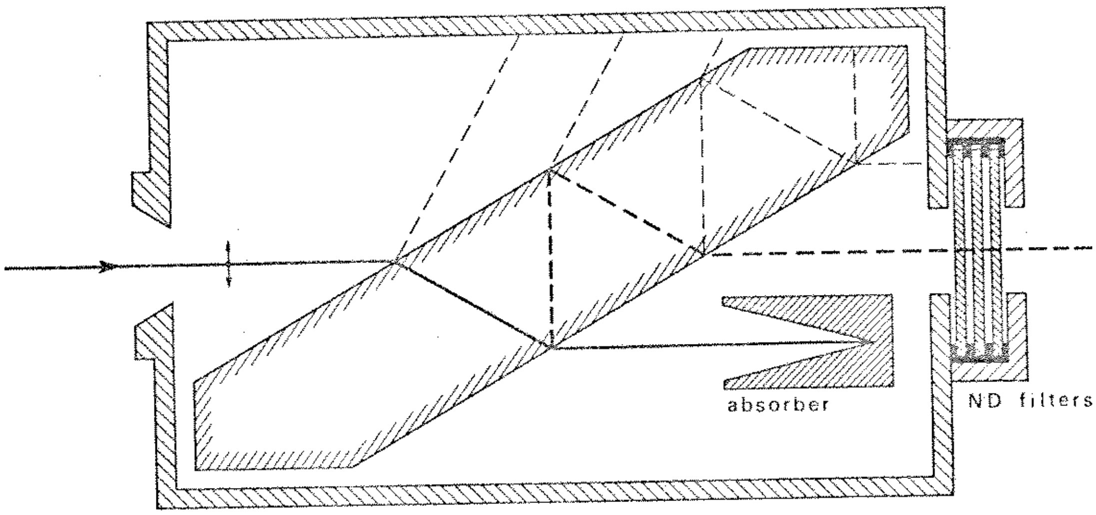


figure 1

The major part of the incident energy is dumped into the cone shaped absorber. The energy left over 2 internal reflections is used for the measurements (after extra attenuation with normal ND filters). The attenuation of this plane parallel plate of glass can be adjusted by turning it around the axis of the incident beam. If the polarization of this beam is in the plane of the drawing,as indicated,the attenuation has a maximum value. When the complete attenuator structure is turned 90° around its axis the transmittance (for vertically polarized light) increases to a maximum of a few percent.

2) Ranging via an internal light path.

For routine calibration of the ranging system the light from the total cross-section of the attenuated outgoing beam is reflected via a secondary light path and an extra optical step attenuator directly to the photomultiplier.

AIRCRAFT SAFETY

Althoughthe total risk for an airline passenger will not be significantly increased by the operation of a laser ranging system at Kootwijk (conclusion of a thorough study) we have established two independent safety measures:

- a look-out near the mount. The protective glasses in his safety goggles are made out of interference filters giving minimum attenuation in the visible part of the spectrum, especially in the red part, in order to have a maximum visibility of the red running lights and anti-collision lights.

- a passive optical airplane detector with automatic laser disabling (fig.2).

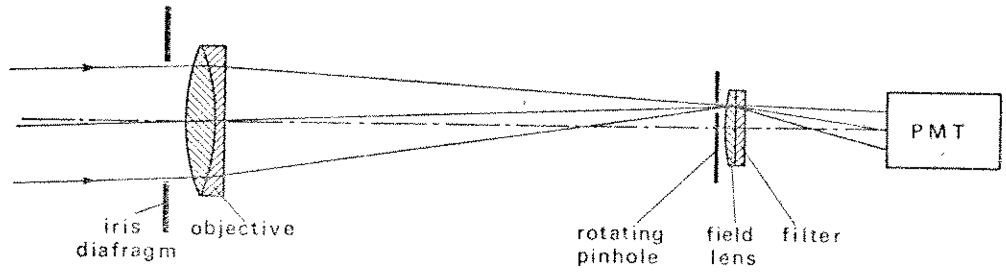


figure 2

For daytime and nighttime operation two different detection techniques are used:

Daytime Detection

The instrument measures the contrast of an airplane, or any other object) against the uniform background of the blue sky. A small off-axis field of view scans continuously around the axis of the transmitted laser beam (fig.3a). The field of view is smaller than the apparent size of an airplane, therefore a good on - off ratio is obtained.

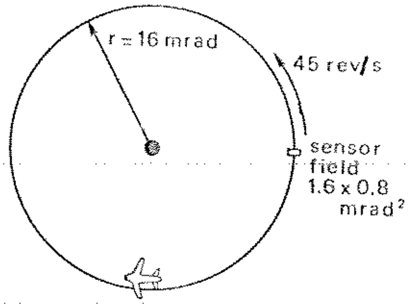


fig. 3a

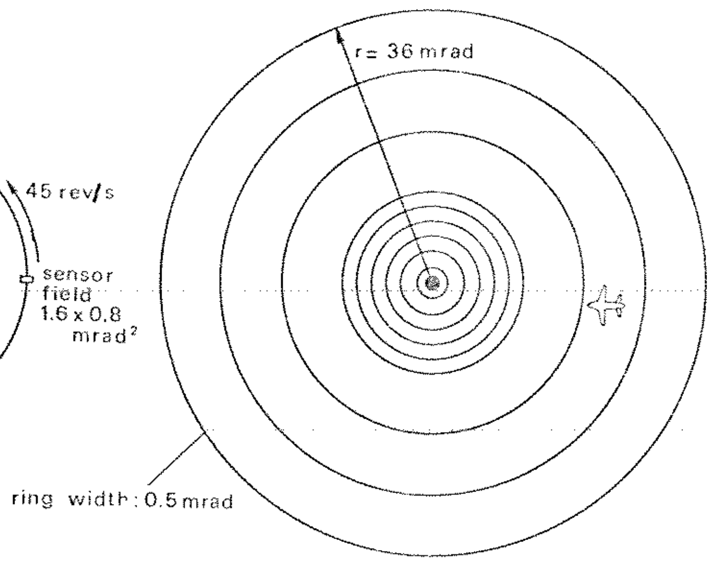


fig. 3b

When the AC signal from the photomultiplier exceeds a fixed discrimination level the firing of the laser is interrupted for 5 seconds. This gives ample time for any airplane to fly out of the danger area. The scanning rate has been adjusted in such a way that no airplane can enter the danger area undetected.

Because the contrast over great distances through the atmosphere is best in the red part of the visible spectrum, a blue absorbtion filter (Schott type GG 475) has been placed near the field lens. A RCA 8852 photomultiplier has been chosen as detector because of its good red and near-infrared sensitivity.

The average light level is reduced to an acceptable level by means of the iris diafragm in front of the objective.

Nighttime Detection

During the night when only the running lights and anti-collision lights of the airplanes are visible, the field of view of the daytime system is inadequate.

Instead a static pattern of concentric transparent rings is placed in the focal plane of the objective (fig. 3b.). When an airplane light passes a ring the AC coupled photomultiplier will produce an electrical pulse that will inhibit laser firing for 5 seconds.

Measurements of the brightness of airplane running lights on the ground and comparisons of running lights against stars have shown that the great majority of airplanes above 30° elevation can be seen with a visual magnitude between +4 and 0.

The main problem of this detection system is to avoid false triggerings from stars. To reduce the chance of false alarm to a level of about 1% the following three provisions have been made:

- the effective area of the field of view has been reduced to 1 degree square by using very narrow rings
- the photodetector is sensitive mainly in the red part of the spectrum (as for daytime detection) in order to favour the incandescent lamps of the running lights above stars
- the detector is effective only one second before firing when the mount has already been positioned.

THE USE OF THE AIR TRAFFIC CONTROL RADAR BEACON SYSTEM (ATCRBS) FOR LASER GROUND STATION RANGE SAFETY

Thomas E. McGunigal and Janis Bebris
Goddard Space Flight Center
Code 723
Greenbelt, MD 20771

INTRODUCTION

A continuing concern in the operation of high energy laser ranging systems is the avoidance of accidental illumination of overflying aircraft by the laser. The generally accepted standard for maximum permissible exposure in the visible and near visible regions of the spectrum widely used by pulsed laser ranging systems is $5X10^{-7}$ Joules/cm^2 (Ref.1). The irradiance from most laser systems currently in use exceeds this level by a substantial margin and because of the use of highly collimated beams, the danger zone may extend for many miles. The use of a safety observer is a substantial help at very close ranges but even the optically aided human eye cannot reliably spot aircraft under hazy conditions at distances corresponding to the danger zone. Radar systems can be quite useful but large and expensive systems are necessary if ranges out to 50Km are required. The system suggested here is one that takes advantage of the fact that all aircraft flying in controlled aerospace (i.e. over 3800 m in altitude or under instrument flight rules) must carry a transponder. The transponder can be interrogated with a relatively simple ground system compared to a radar. The two main elements of this ground system are a phased array antenna with eight elements and a interrogator/amplifier system. The system uses a sidelobe suppression system which produces an effective beam width of $\pm 6^{o}$ in azimuth and approximately 29^{o} (Half Power) in elevation. When it is boresighted with the laser ranging system's telescope, it can easily detect the presence of transponder equipped aircraft nearing the laser beam at ranges in excess of 100Km in sufficient time to permit stopping the laser radiation. Closein aircraft which are not transponder equipped can be detected with a relatively simple skin tracking radar.

DETAILED SYSTEM DESCRIPTION

Since the late 1950's, the ATCRBS has become the primary means of air traffic surveillance, with the radars to which it was added assuming a backup role.[2]

The ATCRBS consists of airborne transponders, a ground interrogator-receiver processing equipment, and an antenna system. The antenna may or may not be associated with, or slaved to, a primary surveillance radar. In operation, an interrogation pulse group is transmitted from the interrogator-transmitter unit via an antenna system triggers each airborne transponder located in the direction of the main beam, causing a multiple pulse reply group to be transmitted from each transponder. These replies are received by the ground receiver and, after processing are displayed to the controller.

The ATCRBS has a number of interrogation modes to accommodate its various uses. EAch interrogation consists of a pair of 0.8 s pulses (P1,P3) transmitted on 1030 MHz carrier. An additional pulse, the P2 pulse, is transmitted 2 s after the initial (P1) pulse from interrogators equipped with sidelobe suppression.

The mode is designated by the P1-P3 interpulse spacing. Modes 1 and 2 are used only by military interrogators. Mode 3/A is the basic air traffic control (ATC) identity mode, common to both civil and military systems.

The transponder reply consists of a sequence of up to 15 pulses on the 1090 MHz carrier, each of nominal duration 0.45 s and with an interpulse period a multiple of 1.45 s. Each reply includes the two bracket or framing pulses F1 and F2, spaced by 20.3 s. Thirteen uniformly spaced pulse positions are defined between the bracket pulses.

The Federal Avaiation Regulation, General Operating and Flight Rules require that after July 1, 1975, all aircraft in controlled airspace above 3810 meters must be equipped with an operable coded radar beacon transponder having a Mode3/A 4096 code capability.

1. A Simple Interrogator Ground Station:

For the purpose of laser ground station range safety we will use a narrow beam interrogator antenna boresighted with and slaved to the laser tracking telescope. An Air Force airborne AN/APX - 76A or equivalent interrogator set can serve as a convenient ground station.

If a transponder equipped aircraft, either civil or military, flew into the microwave antenna pattern, its presence would be detected and laser firing would cease until the aircraft was clear. The maximum range of interest for this application is 50 kilometers although the system is effective at ranges up to 200 kilometers.

2. Subsystem Description

The AN/APX - 76A interrogator set consists of the following subsystems:

1. Interrogator Set Control
2. Receiver - Transmitter
3. Switch - Amplifier
4. Synchronizer

A. Interrogator Set Controls. Each AN/APX - 76A interrogator set controls contains five thumbwheel switches to select the desired interrogation mode or standby and the desired code. A momentary two-position toggle switch (TEST/CHAL CC) permits loop testing the interrogator set or providing a correct code challenge.

B. Receiver - Transmitter. The assembly consists of: a receiver module, a pressurized transmitterpower supply module and four plug in printed circuit boards. The printed circuit boards mount on a "mother" board which provides the necessary board interconnections. The power supply operates from a nominal 115-volt, 400 Hz source. The transmitter module contains five coaxial tube amplifier stages and operates at a fixed frequency of 1030 MHz with three possible power outputs (high, medium, or low) selectable by a front panel switch. Cooling air must be provided to insure safe operating temperatures within the unit.

C. Switch - Amplifier. The switch - amplifier implements switching of the interrogator system R-F output from the sum antenna channel to the difference antenna channel for the duration of the interrogator side lobe suppression (P2) pulse. The assembly consists of three printed circuit board assemblies: a coaxial cavity tube amplifier; a high power, high speed solid state R-F switch; and a diplexer. The unit has a self-contained power supply which is operated from a nominal 115-volt, 400 Hz source. Performance monitoring circuitry samples all critical operating parameters and signals a failure by a front panel fault indicator.

D. Synchronizer. In itsintended application as part of an airborne interrogator system, the synchronizer uses the main surveillance radar trigger pulses to generate the various signals necessary for initiation of an interrogation cycle. In our application, appropriate external trigger pulses are provided.

E. Antenna. An effective beamwidth of about 12° is achieved with an array of eight (8) L-band dipoles mounted on 46x66 cm ground plane. By radiating the required interrogation signal and the control pulse signal on the sum and difference patterns, (see Fig.1) respectively, of a dual feed L-band antenna array, responses to sidelobe interrogation are supressed at transponders equipped with interrogation side-lobe suppression (ISLS) circuitry for all angles beyond about ± 6 degrees from the center of the antenna main beam (sum pattern).

F. Interrogator System Size, Weight and Power. The AN/APX-76A interrogator system was developed for airborne application. Its size and weight are minimized. The largest unit, the Receiver Transmitter, has the dimensions of 19.4x12.7x44.5 cm and weights 8.6 kg. The total weight of the four (4) units is 16.8 kg. Input power - 115V, 400 Hz, 230 volt - amperes; 28 Vdc, 1.3 amperes.

CLOSE-IN RANGE SAFETY

Because not all low flying (less than 3810 m) aircrafts are equipped with operable coded radar beacon transponders, we must provide close-in safety by other techniques.

The Goddard ranging stations do not operate below 20° in elevation. Therefore, the maximum distance from the station a low flying aircraft may be in the pass of a laser beam is 11Km.

Our calculations show that for 35.DB X-band antenna gain, a 10 KW LN66 Radar Set, manufactured by Canadian Marconi Company, will provide the required additional protection. This radar set has been specifically designed to serve as a shipboard navigator aid for reliable detection of surface obstacles or other vessels. The LN66 radar is being extensively used by the U.S. Navy.

In our experiment, we need employ only the LN66 transmitter - receiver, control unit and the A/C power supply with no need for the PPI display.

I. LN66 Radar System"

Description

A. Receiver - Transmitter Unit. The Receiver - Transmitter Unit contains the transmitter and the receiver circuitry, and the power supply for the

Radar Set. The transmitter circuitry generates the high power 9,375.MHz pulses which are fed to the Antenna Unit via a waveguide. The time interval between any two transmitted pulses is used by the receiver circuitry to process the signal reflected back by the targets.

B. AC Power Unit. The primary power required by the LN66 Radar Set is 26.4 Vdc. However, in situations where a 26.4 Vdc power source is not available, the Radar Set is supplied with the AC Power Unit which is a simple power supply to convert the 115. Vdc primary power into the 26.4 Vdc.

C. Antenna Unit. The Antenna Unit transmits the high power RF pulses and receives the signal reflected back by the target.

We are employing Scientific - Atlanta, Inc. Series 22 Reflector (1.22m dia.) and the Model 23 - 8.2/4 Feed. The nomial beamwidth is 2^{o} and 39.DB gain. The 4.ft reflector with the x-band feed and the L-band dipole array are mounted on an Azimuth/Elevation mount which is slaved to the laser tracking telescope.

D. Size, Weight and Power.

Unit	Dimensions (cm.)	Weights (kg.)
Receiver - Transmitter	47x31.75x21.6	20.4
AC Power Unit	21x34.8x18.9	13.6

The Receiver - Transmitter unit require 26.4 Vdc, 10. amps. The AC Power Unit converts the 115 Vdc primary power into 26.4 Vdc.

Theory of Operation

Transmission

The transmission from the Radar Set is in the form of narrow, high power RF pulses which ar radiated by the Antenna Unit. Depending upon the range selected and mode of operation (narrow or wide pulse), either 2500, 1250, or 800 pulses per second are transmitted.

Reception

Because the antenna in operation is following the tracking telescope in azimuth and elevation, and the transmitter PRF is relatively high, the LN66 Radar transmitter pulses strike all targets within the main antenna beam. Immediately after transmission of each pulse, the antenna acts as a receiving antenna and picks up the signal reflected back by the low flying aircraft target.

STATUS

The Interrogator - Transponder link has been exercised with excellent results. The observed antenna patterns were very nearly as expected. The range is more than adequate for the present and expected future laser transmitter power.

The LN66 radar subsystem is not yet completed and no experimental results are available. We expect to complete the full system evaluation by September 1978.

ACKNOWLEDGMENT

The authors wish to acknowledge the excellent technical and administrative assistance and cooperation of: Martain Natchipolsky, Donald Asker, Richard Haskin and Gerry Markey of Federal Aviation Administration; Joe E. Smith of Department of Defense; Donald Brennon of Westinghouse Corporation; Dwight Pasek of Hazeltine Corporation and Calvin Rossey and James Scott of Goddard Space Flight Center. Also, we wish to extend a special acknowledgement to David Grolemund of Bendix Corporation who performed the integration of the AN/APX-76 interrogator subsystem.

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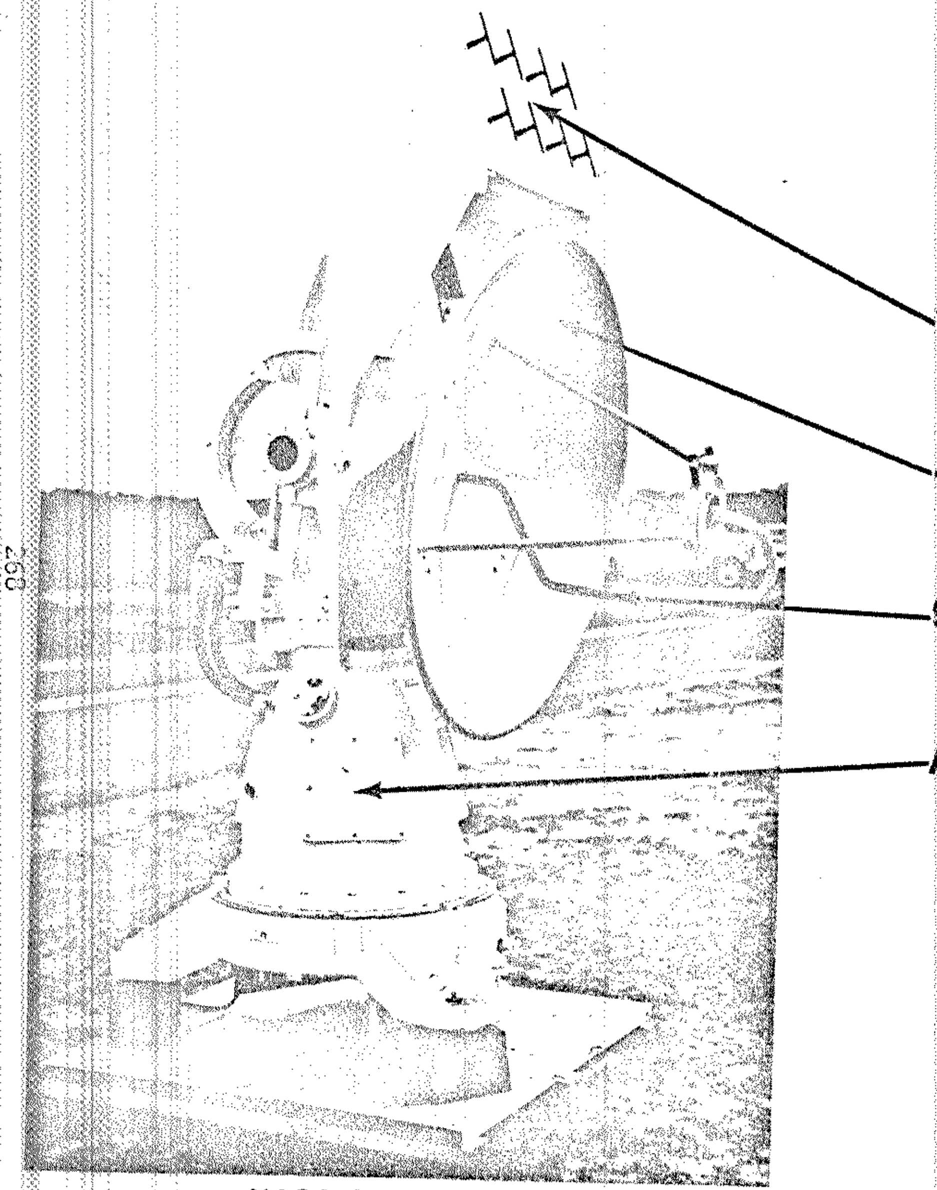
2. Drouelhet, Paul R. Jr., "The Development of the ATC Radar Beacon System: Past, Present and Future," IEEE Transactions on Communications, Vol. Com 21, No. 5, May 1973.

AIRCRAFT SURVEILLANCE SYSTEM
ANTENNA SYSTEM



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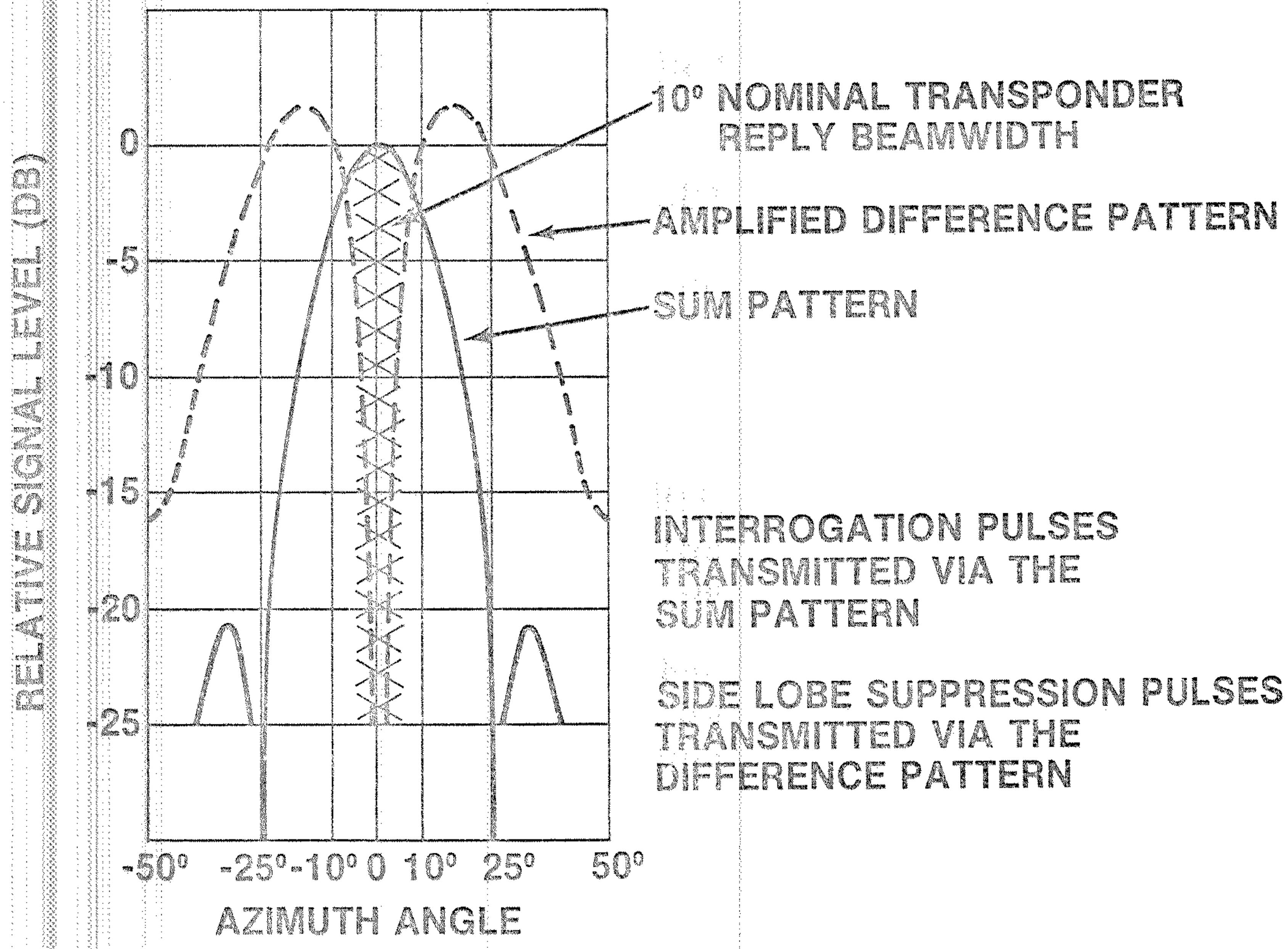
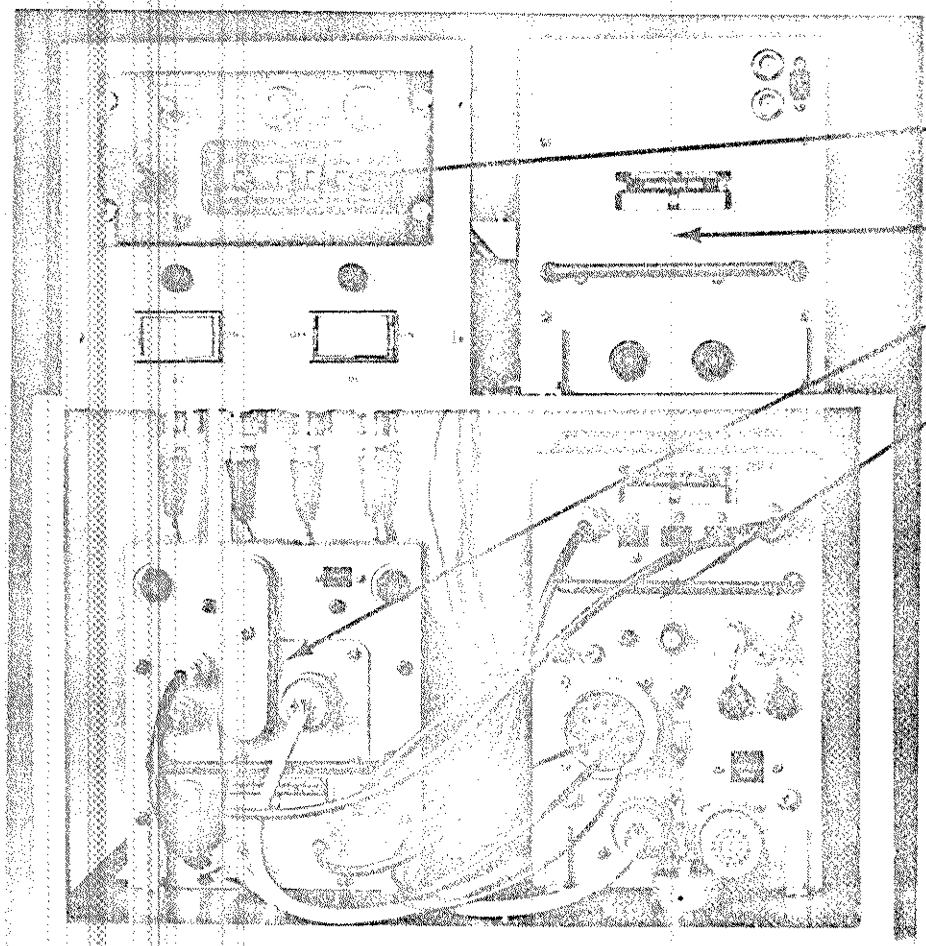
ANTENNA PATTERNS



AIRCRAFT SURVEILLANCE SYSTEM
GROUND INTERROGATOR-RECEIVER



NASA G-78-02280

RECEIVER: FREQUENCY- 1090MHz
SENSITIVITY- -83dBm

TRANSMITTER: FREQUENCY-1030±0.2 MHz
HIGH POWER- 2 KW
(33dBW) PEAK

INPUT POWER: 275 WATTS

CONCLUDING SUMMARY OF LASER SAFETY SESSION

Most of the stations have taken the necessary measures for preventing laser damages.

It most of the sites, there are local agreements to avoid striking aircrafts during tracking of satellites. The two papers presented at the session concerned that subject :

one, typically a radar system, is still experimental and requires the agreement from air traffic control authorities.

the other one has been experienced for two years now, and is used at Kootwijk station, on an optical basis.

Furthermore for some calibration methods requiring the use of a near target, a special component was designed for attenuating the beam.

Some discussions then occured and were devoted to probabilities of striking an aircraft : it seems that the chances can vary tremendously from an author to another and will bring more confusion than efficiency.

THE SATELLITE LASER RANGING STATION AT SAN-FERNANDO, SPAIN

J.L.HATAT : Centre d'Etudes et de Recherches
Géodynamiques et Astronomiques.

INTRODUCTION

The satellite ranging station at San-Fernando is the mobile station of the G.R.G.S.(Groupe de Recherche de Géodesie Spatiale).
It is in routine night time operation, in this site, since the summer of 1975.
It is an improved first generation laser station. The staff is formed by French and Spanish technicians.
The co-operation agreements between the G.R.G.S./C.N.E.S. and the Instituto y Observatorio de Marina de San-Fernando will permit a full management of this station by the I.O.M. by 1979.
The observing conditions at the present location are now threatered by construction of high buildings in the proximity. The station will be moved to the dome on the observatorio's main building.

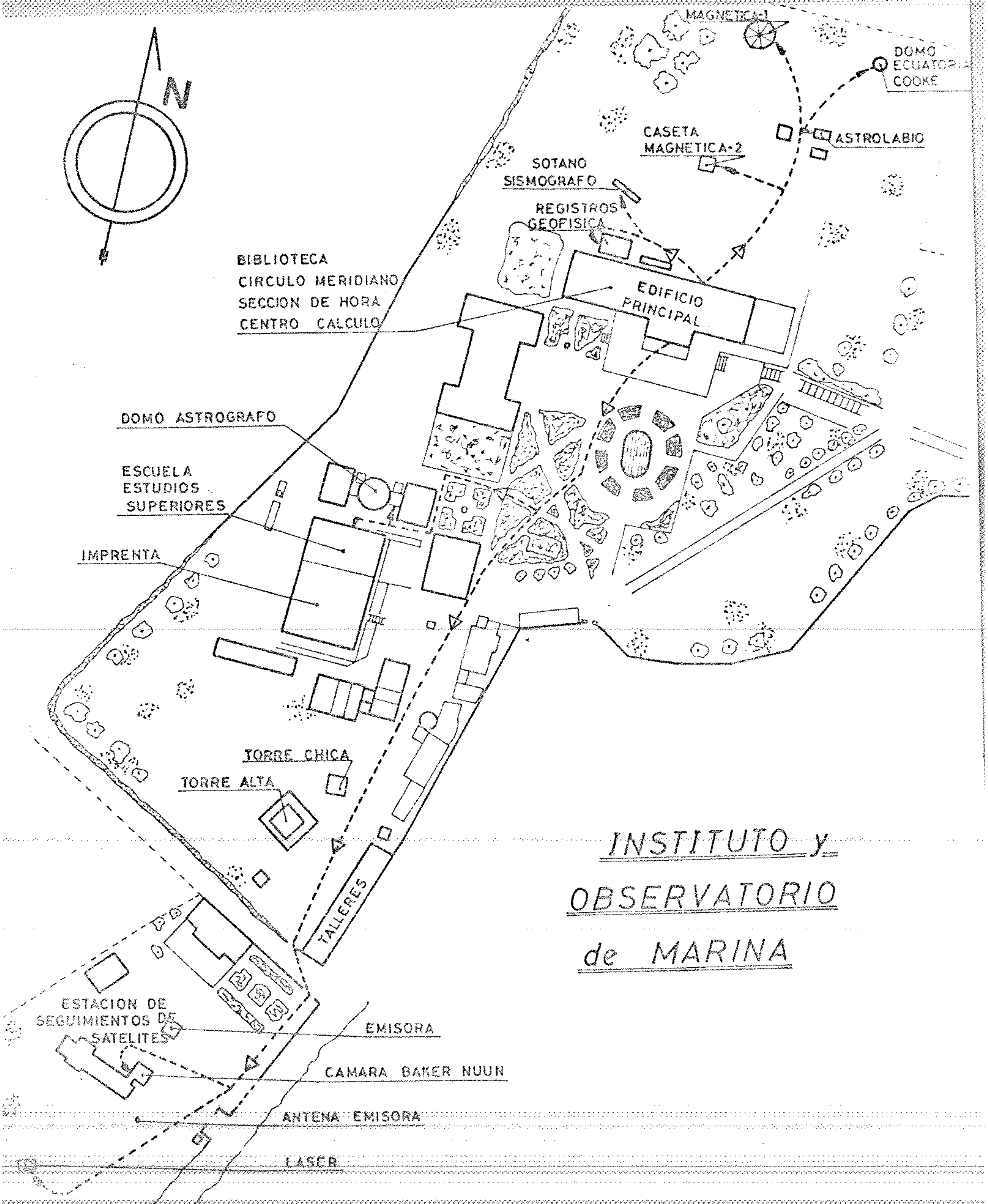
At the present time, the capabilities of this station are the following :

- Blind tracking by night.

- Visual optical tracking by television. (Both systems on GEOS I, GEOS 3, BEC and STARLETTE satellites.

- Ranging accuracy I - I,5 metre.

- Range capability 3800 Kms on GEOS I satellite type. Terrestrial ranging 200 Kms on retrorefletors.

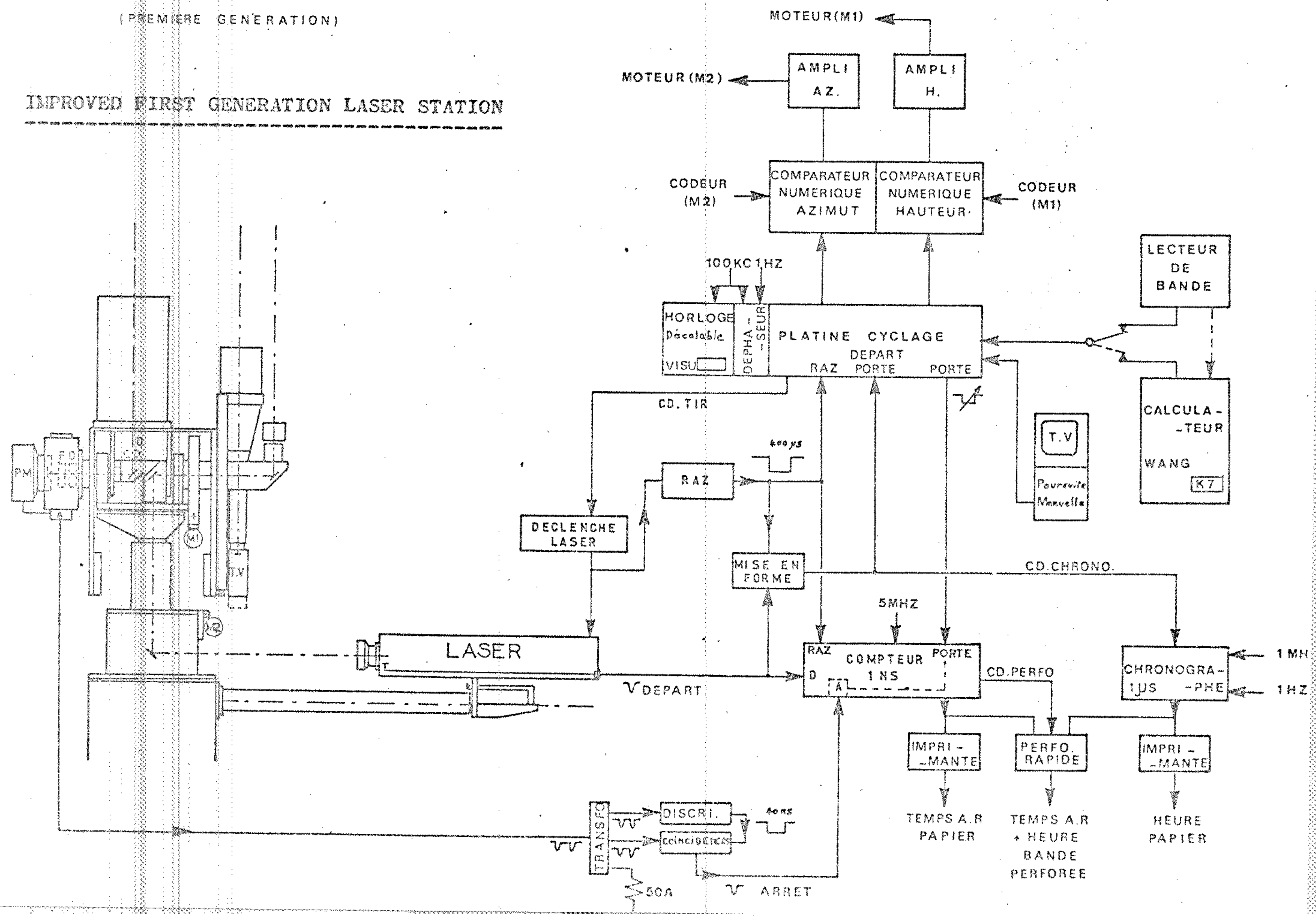


Location of the instruments

STATION DE TELEMETRIE LASER

(PREMIERE GENERATION)

IMPROVED FIRST GENERATION LASER STATION



Technical characteristics are the following :

LASER SYSTEM

Type rubis Compagnie Generale d'Electricité.
Pulse 27 ns 0,5 - 0,6 joule.
Repetition rate : max 60 ppm.
Beam divergence :4 mRad. With transmitting optic : 0,5 mrad.

Receiving telescope
Type cassegrain.
Aperture 36 cm F/IO

Visual tracking system

Television camera SOFRETEC type CF I22.Furnished with a Noticon tube.
Lens 200mm F/5
Limiting magnitude I3 - I4.
With this system,it is possible to track also STARLETTE and LAGEOS.

Detection PMT : R.C.A. model 3I034 A.

Amplifier : Avantek AV 9T, ampl.30 db.

Optical filters : 3 Å,7,5Å,I8 Å.

Range gate generador : GRGS design.

Time interval counter : Model CC 20,Ins. Centre de recherche de la C.G.E.

Receiving coincidences system (I) figure I
Discrimination : type VDI/II ref. SAIP DA/I2I.
Coincidences   : type VC 4 V /II ref.SAIP CR I33.

Epoch clock : GRGS design I µs.

Timing UTC : VLF (Baker-Nunn).

The positionning of the mount is performed in real time by a mini-computer WANG 2200 which uses magnetic cassettes.
Repositionning : I point every six secondes.

The mount is driven in both azimuth and altitude by two 250 W D.C motors.
Pointing accuracy : about 30 arcsec.

Optical coders are type MCB GI 076 B . 500 pts resolution.

The final results are punched on a paper tape ready for transmission by telex.
Tape punch : Tekelec airtronic model 34.
Punching speed : approx 70 ch/sec. Synchronous.

Aircraft detection,at this moment,is guaranted by visual television system.

The present staff is 6 persons operating only by night,7 days a week.

(I) R.BIVAS Thése de doctorat es sciences physiques : Télemétrie spatiale par laser.

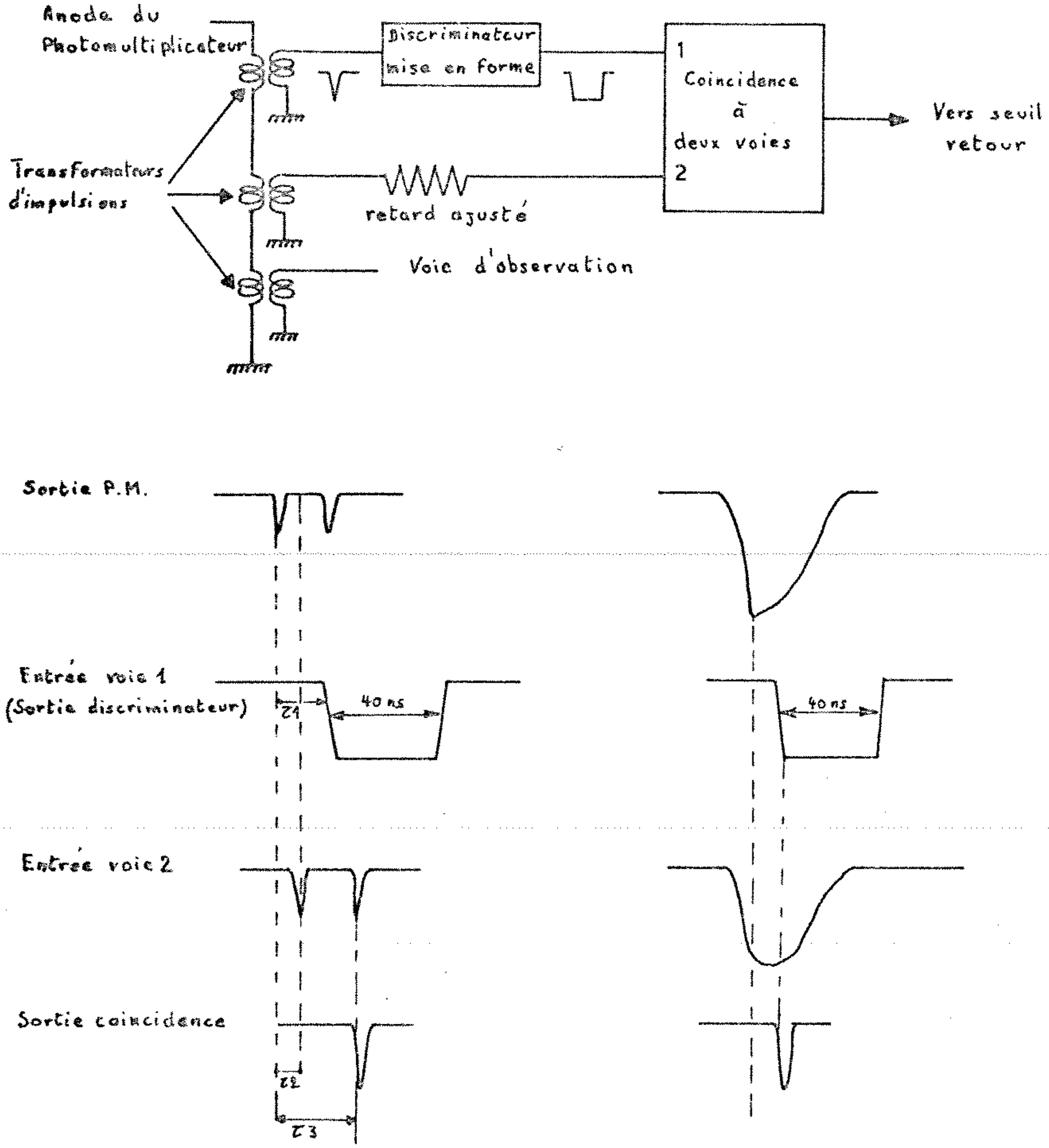
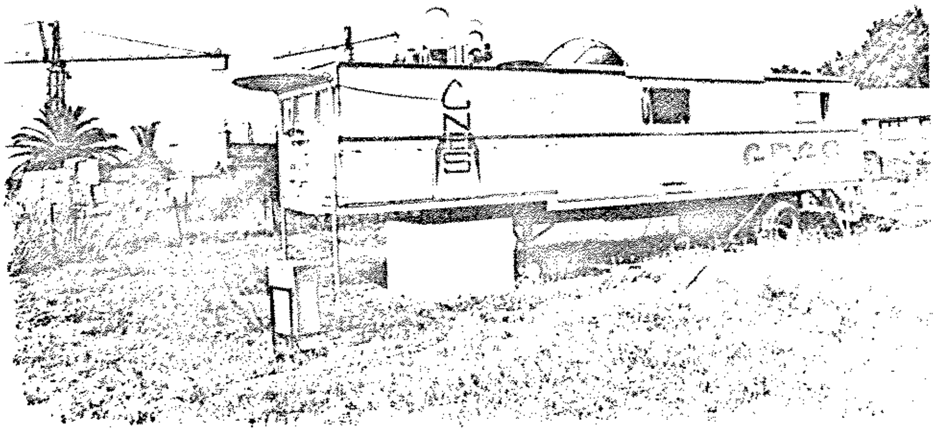
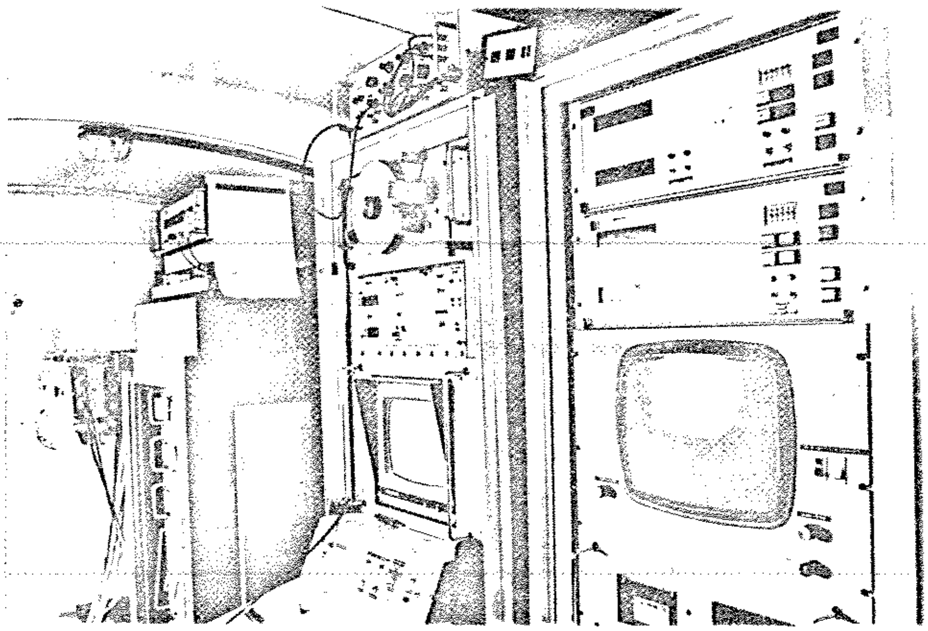


Schéma de principe du discriminateur de coïncidences.

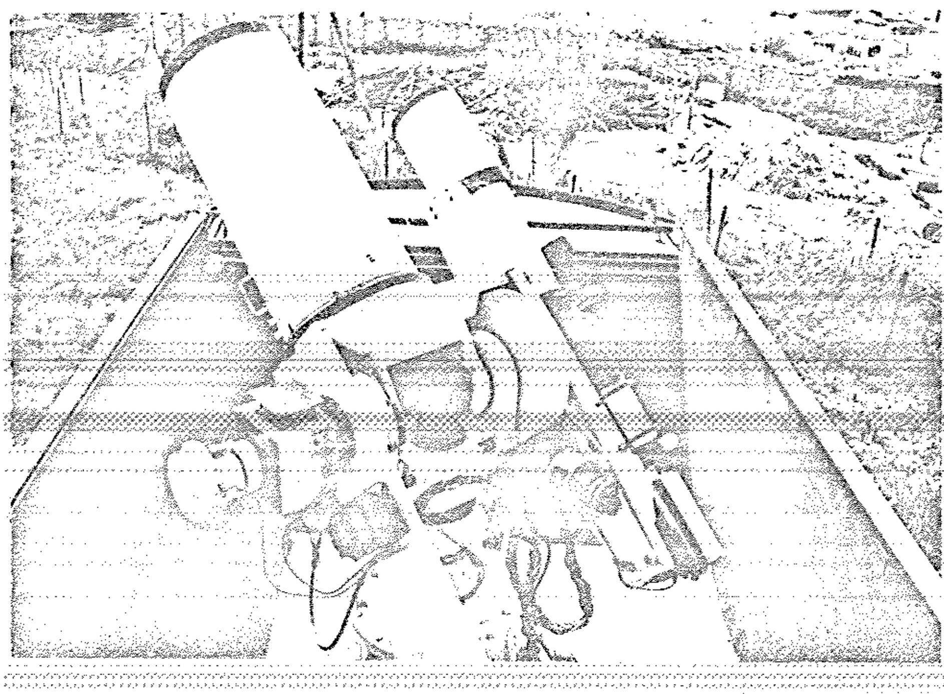
figure I



General view of the station

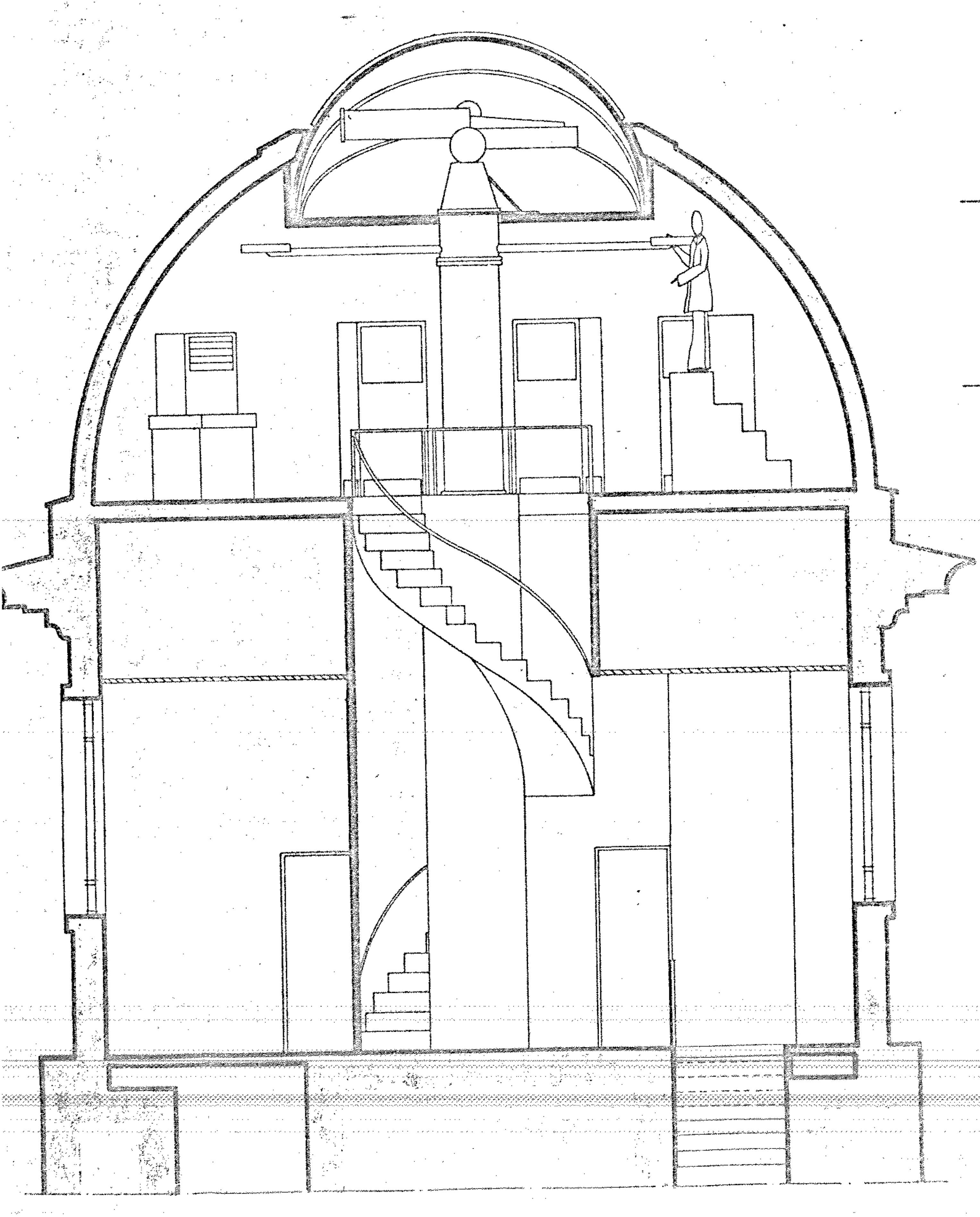


- The electronics



The laser mount

Architect plan project of the new laser site



SECCION-X X'

CALIBRATION

The calibration of the system is by using one ground target at 830 m. This calibration, approximately 60 points of range data, is performed before and after each satellite pass.
It was impossible to find another farther target.

FUTURE IMPROVEMENTS

- A new laser will be fitted. Possibility to operate with pulses of 5 - 10 ns and 2 - 3 joules.

- Increased ranging accuracy.

- Blind tracking by day.

- Possibility to get regular ranging data on LAGEOS.

COMMUNICATION INFORMATION

The postal adress of San-Fernando is :

Station Laser

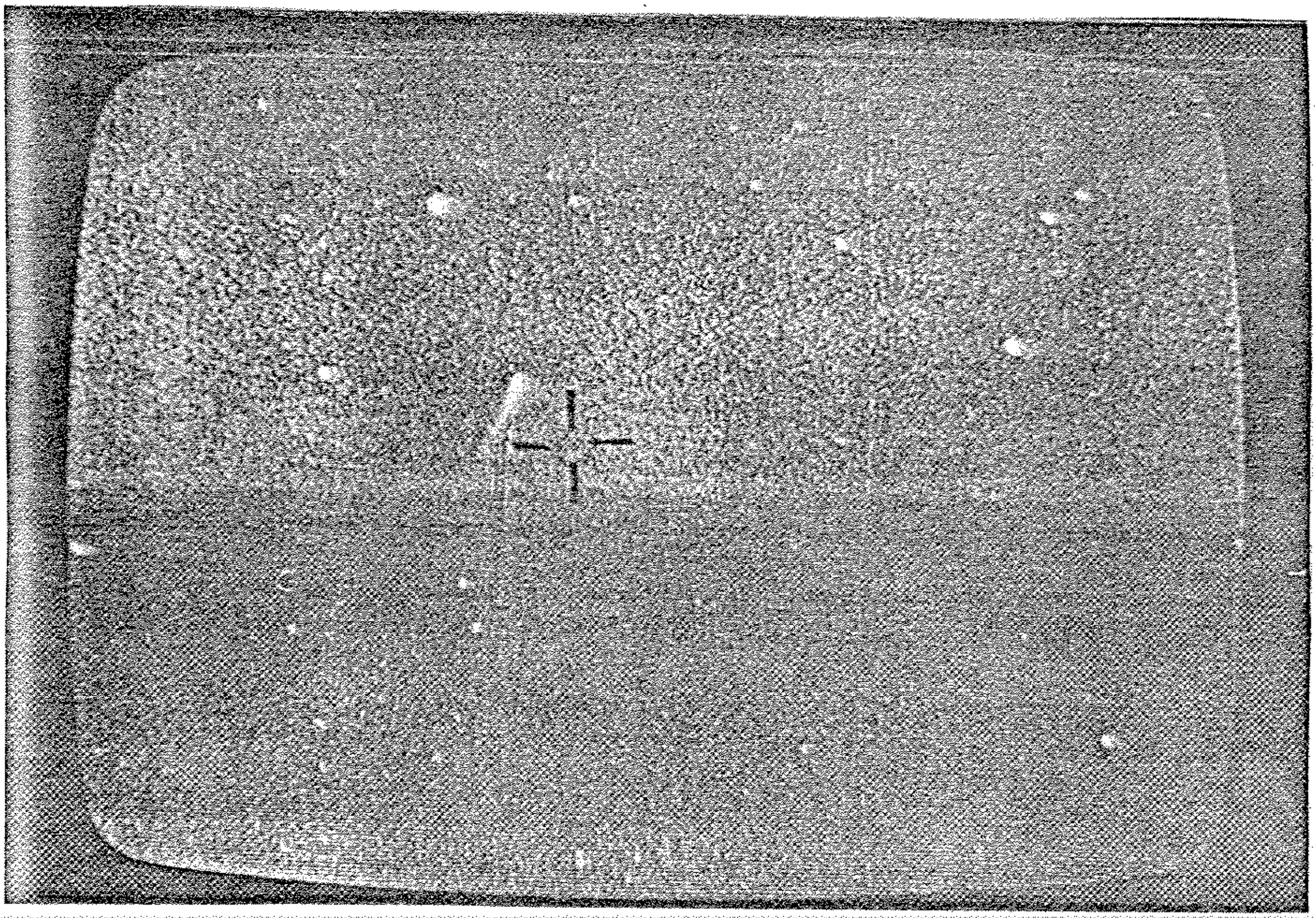
OBSERVATORIO DE MARINA

SAN FERNANDO

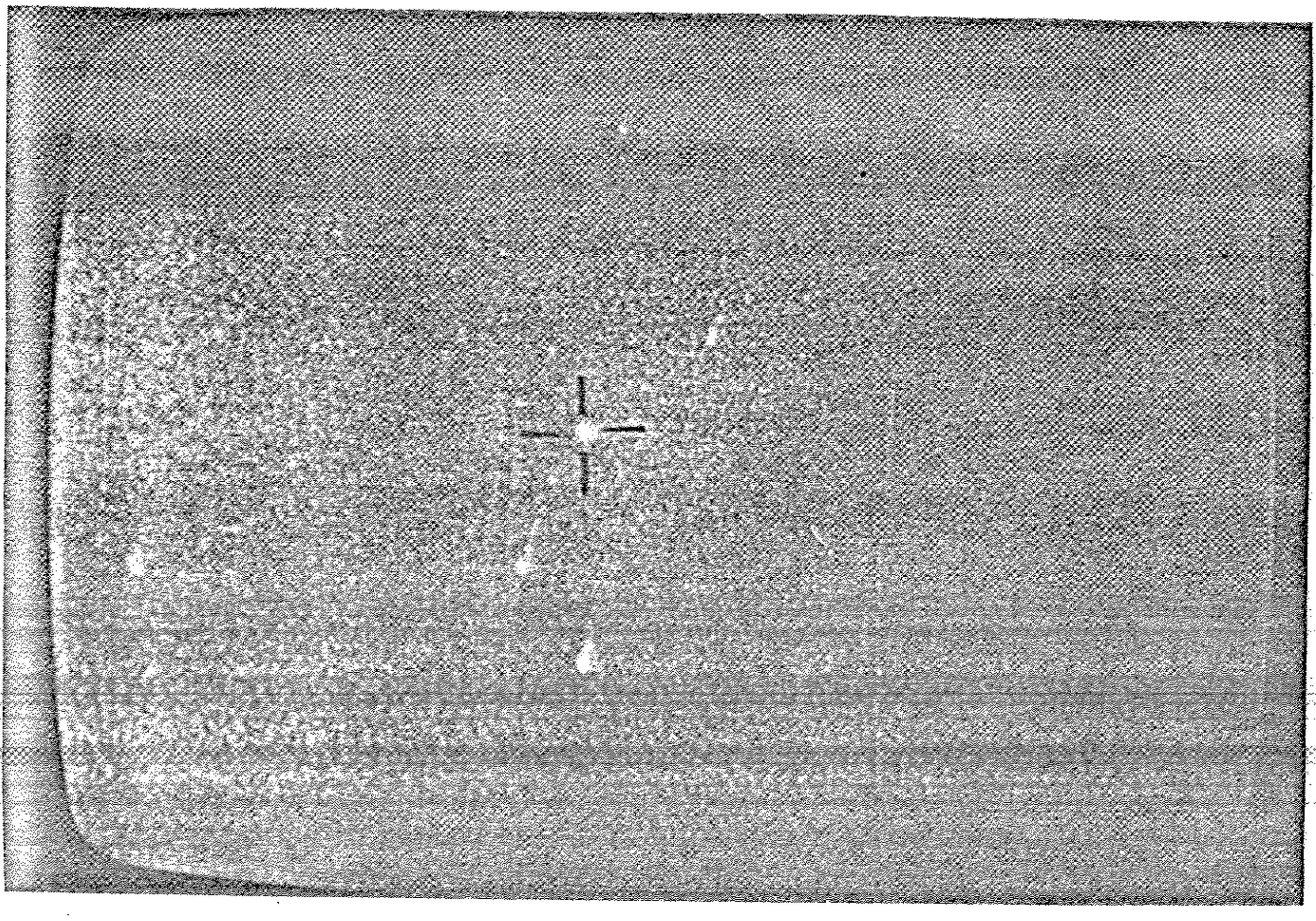
CADIZ (España)

Telex number :

76108



I - Stars are fixed.The satellite pass on the left of the reference reticle. Film 400 ASA - 1/30 sec.



II - Manual tracking.The satellite is kept in the reticle.

SUMMARY STATISTICS STATION - 7804 SAN-FERNANDO YEAR I977

	GEOS I (650890I)		GEOS 2 (680020I)		GEOS 3 (750270I)		BEACON C (650320I)		STARLETTE (750I00I)		TOTAL		BAD WEATHER CONDITI (lost pass. percenta
	OBS	PAS	OBS	PAS	OBS	PAS	OBS	PAS	OBS	PAS	OBS	PAS	
AN	0	0	0	0	54	5	0	0	0	0	54	5	90 %
EB	I08	4	75	3	24	3	48	3	0	0	255	I3	77
AR	5I	3	284	9	52	3	93	5	I3	I	493	2I	52
PR	48	4	0	0	I9	I	0	0	0	0	67	5	--
AY	I45	8	0	0	67	2	I24	5	0	0	336	I5	3I
UN	227	8	0	0	78I	2I	837	24	284	I6	2I29	69	39
UL	499	I6	0	0	560	2o	I7	I	5	I	I08I	38	20
UG	348	8	0	0	884	I9	685	23	I85	I0	2I02	60	I0
EP	I78	3	0	0	39	5	47	2	I49	I4	4I3	24	I4
CT	0	0	0	0	I46	4	8I	3	2I	4	248	II	42
OV	84I	I9	0	0	25I	4	I35	4	48	II	I275	38	44
EC	80	2	0	0	I73	4	I3	I	25	I	29I	8	84
OT	2525	75	359	I2	3050	9I	2080	7I	730	58	8744	307	

- **Time interval counter failure in april.**
- Total blind tracking : 696 returns.

SUMMARY STATISTICS STATION 7804 SAN-FERNANDO, YEAR I978

(For the first four months)

	GEOS I		GEOS 3		BEACON C		STARLETTE		BAD WEATHER CONDITIONS (lost passages percentage)
	OBS	PAS	OBS	PAS	OBS	PAS	OBS	PAS	
JAN	I24	3	0	0	68	2	I9	2	78 %
FEB	429	7	0	0	76	2	I03	8	65
MAR	703	22	776	I3	458	I4	49	5	35
APR	240	5	I9	2	III	4	3I4	I6	6I
TOT	I496	37	795	I5	7I3	22	485	3I	

- NUMBER OF RETURNS 3489
- MANUAL TRACKING 25I9
- BLIND TRACKING 970

session 7 ranging software and data preprocessing

chairman P. Wilson /co-chairman R. Schutz

Wilson
Thorp /Latimer /Campbell /Pearlman
Novotny
Greene
Nouel /Brossier
Vermaat
Carpenter
Sinclair
Shelus /Ricklefs
Schutz

Ranging Software and Data Pre-processing

Chairman's Summary

The primary purpose of this session was to delineate software characteristics and needs at various levels, particular emphasis being placed on the relationship between software and hardware. The pre-processing of data by various organisations was reviewed; the main features of both satellite and lunar software were dealt with and the corrections applied to the data were identified by each group.

Discussions centred mainly on the following topics:

- data compression and data handling, with particular reference to possible implications on system (hardware) design;
- the weighting of observations;
- look angle computations and satellite ephemerides;
- the modelling of systematic errors;
- data filtering and corrections.

A lively discussion followed the provocative statement that 50 error-free measurements would contain all the information on the orbit and related field parameters that can currently be modelled.

The diversity of the software described reflects on the one hand the various levels of sophistication of the hardware in use, and on the other, the need for a standardisation of concepts, particularly with respect to the quantities of data now being accumulated. Although no agreement could be reached on the best ways of dealing with the masses of data which can be foreseen with the developing systems, it was recognised that this question impacts data management at all levels from collection through analysis and archiving. Some agreement was reached on the need for a central data bank and the need was expressed to identify the appropriate parameters which can lead to a compaction of the data and can effect overall system design.

SOFTWARE IN THE SERVICE OF THE LASER RANGING MEASUREMENT PROCESS

INTRODUCTORY REMARKS TO SESSION 7

Peter Wilson
Institut für Angewandte Geodäsie (Abtlg.II, DGFI), Frankfurt and
Sonderforschungsbereich 78, Satellitengeodäsie, der TU München
Fed. Rep. of Germany

This is the first session of a Laser Workshop designed to address software problems. In proposing the framework of the papers and discussions which will follow, I have tried to direct the attention of the speakers towards software considerations directly associated with the measurement processes. However, since with improved accuracies it becomes increasingly important for the observer himself to make a preliminary assessment of the relevance of his observations and the degree to which his equipment is performing satisfactorily I have also suggested that on-site postmission analysis and the preliminary off-site screening of the observations be considered. At this point however I consider that we enter the realms of other users and the subject-matter to be addressed in the following symposium. To summarise then, I propose to restrict the discussions here to subjects pertaining directly to

a) range and look-angle predictions
b) system and data flow control during the measurement process
c) on-site post mission analysis
d) initial screening of the observational data.

It is my hope and anticipation that this session will serve not only as a record of the current status of software application , but will also demonstrate the trends and provide useful reference information for those groups updating or introducing automated tracking procedures as well as cataloguing the scope of these problems for newcomers to the laser tracking community. Whereas not all stations are similarly equipped with respect to computer hardware, it is worth bearing in mind that the computer is the most versatile and compact-major hardware component of the ranging system and the software the cheapest to duplicate, an important consideration for the design of future systems, for which the advent of micro-processors may have a significant impact.

SAO RANGING SOFTWARE AND DATA PREPROCESSING

J. M. Thorp, J. Latimer, I. G. Campbell, and M. R. Pearlman
Smithsonian Astrophysical Observatory
Cambridge, MA

MINICOMPUTER FIELD PROGRAMS

The SAO laser stations have a software package to handle satellite ranging from input quick-look orbits to final data preprocessing. The former system of paper-tape recording of data has been eliminated except for quick-look elements and quick-look data for orbital maintenance.

1. Prediction Program

A compact Fortran program that produces pointing predictions from Keplerian elements, rates, and long-period perturbation terms has been developed for use in the field. This software, which is based on the SAO Aimlaser program, operates with the standard SAO laser orbital-element messages, which are sent out each week. Using an abbreviated gravity-field model selected for each satellite, the program generates geocentric vectors 2 min. apart for those periods in which the satellite is visible at the station. The program then interpolates between these vectors to produce topocentric predictions at the laser firing rate and stores them on magnetic tape for use during operation. A short summary of the passes for each day is printed during the prediction calculation.

2. Pulse-Processing Program

The pulse-processing program receives the incoming laser data, including the reference pulses, the precalibration and postcalibration data, and general housekeeping information, in real time. The pulse centers for both the calibration and the satellite data are calculated by means of the cross-correlation technique. Start- and stop-channel calibrations are determined for each return, including the influences of internal system settings. The data are then written on a reduced data tape for shipment to SAO.

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

3. Calibration Programs

Programs to calibrate the system electronics (start calibration) and to process extended target calibrations are available on the field minicomputers and are used routinely. These programs calculate all necessary corrections and apply them to the data, giving the field station a fully reduced analysis. From these calibration analyses, start-calibration parameters are determined and electronic and optical system response is examined.

4. Quick-Look Program

The quick-look program scans the reduced data file and prepares a quick-look message of 12 to 15 points for each satellite pass to be teletyped to SAO for orbital maintenance. The program disregards low-level returns in this process in an attempt to eliminate noise stops. The 12 to 15 points are chosen uniformly over each pass.

5. Direct-Connect Program

The direct-connect program provides the interface between the laser equipment and the minicomputer. The program is interrupt-driven with core-memory buffers assigned to each device. Prediction information stored on magnetic tape is read into the core buffers, where it is available for delivery to the laser on demand every 7.5 sec. Incoming raw data are recorded on magnetic tape and also sent to the pulse-processing software for on-line reduction. In addition, the program provides real-time data for the operator, including a graphic display of the return-pulse shape, the satellite and calibration range data, and general housekeeping information.

The process described above takes 3 to 4 sec to accomplish. At the end of each pass or calibration sequence, a summary of the data is printed for the operator.

DATA PROCESSING

1. Final Data

Raw laser data are received from the four SAO field stations on block-addressable magnetic tape. In addition to the range, epoch, system calibration, and housekeeping information, the raw data also include predicted range, azimuth, and elevation to permit geometry-dependent correction and screening to be carried out before orbital analysis is undertaken. The pass constants, such as temperature, atmospheric pressures, humidity, electronic and optical system settings, and calibration data, are examined immediately. Then the system calibration constant is computed from the average of the pre- and postcalibrations by using tabulated values of surveyed target-calibration distances corrected for atmospheric refraction. The calibration constant is applied to the data, along with the atmospheric refraction (Marini and Murray, 1973) and center-of-mass reductions (Arnold, 1972, 1974, 1975a, b, 1978 a,b).

The data are next screened on the basis of internal consistency by using observed-minus-predicted range differences. The technique "tentatively" selects good points by examining the consistency of slopes between each point and its seven predecessors and seven successors. By including only the good points, a least-squares solution for range and time offsets is obtained, and the slope-clustering screening is repeated. Overlapping 12-point local least-square fits are performed to eliminate the occasional bad points still present. Finally, least-square fits are done for the pass by using serial correlation coefficients to control the degree of the polynomial employed. The root-mean-square residual from this fit is used to characterize the data noise component.

Next the epoch of the observation goes through a sequence of steps: 1) conversion to the time of return-signal reception, 2) correction for station-clock offsets to United States Naval Observatory time, and 3) conversion to the International Atomic (A1) time scale.

Following this, the data are pooled and processed through a differential orbital improvement (DOI) program to determine the orbital elements and to check for systematic time and range biases. In order to save computation time, the DOI program uses an abbreviated gravity field specifically selected by sensitivity analysis for each satellite. A post-DOI processor explicitly computes the best-fit epoch timing error and range bias for each pass. Any significant values obtained are used as flags to indicate possible systematic errors for further examination.

2. Quick-Look Data

A selection of 10 to 15 observations per pass is transmitted from the laser sites to SAO for ephemeris updating on a weekly basis. The process is similar to the final data processing, except that the screening and precise timing reductions are omitted and a simplified version of the DOI program is employed. Orbital elements are generated weekly for a complex of retroreflector satellites and distributed to the laser ranging community for predictions.

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