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OF THE INTERNATIONAL ASSOCIATION OF GEODESY

laser workshop

third international workshop on laser ranging instrumentation

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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

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THIRD WORKSHOP ON LASER RANGING INSTRUMENTATION

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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	Gravity Field, Tides, Positional Geodesy
BE-C	6503201	
GEOS-1	6508901	
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		Earth Dynamics, Polar Motion, Earth Rotation, Positional Geodesy, Lunar Science
A14		
A15		
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

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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

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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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The two figures and several paragraphs of the third part of this paper are taken from the report of the steering committee (J. Kovalevsky, P. Melchior, R. Sigl and G. Veis) published in "Space, Oceanography, Navigation and Geodynamics", E.S.A. publication SP-137, april 1978. I thank ESA and M. Hieber for having authorized me to do so.

FIG.1

Ⓐ SOLID EARTH PROGRAMME

(Tectonics Research and Positioning System)

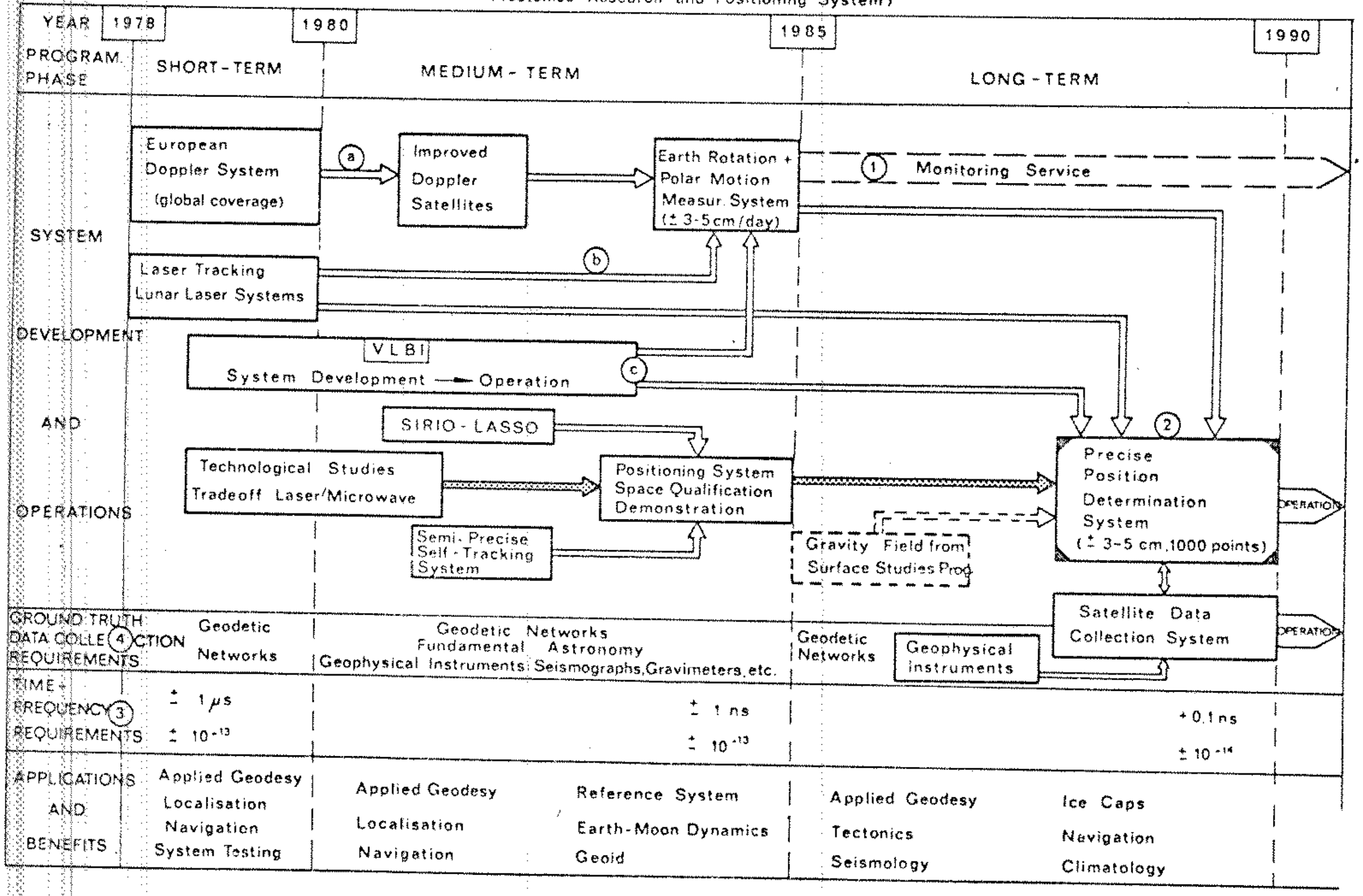
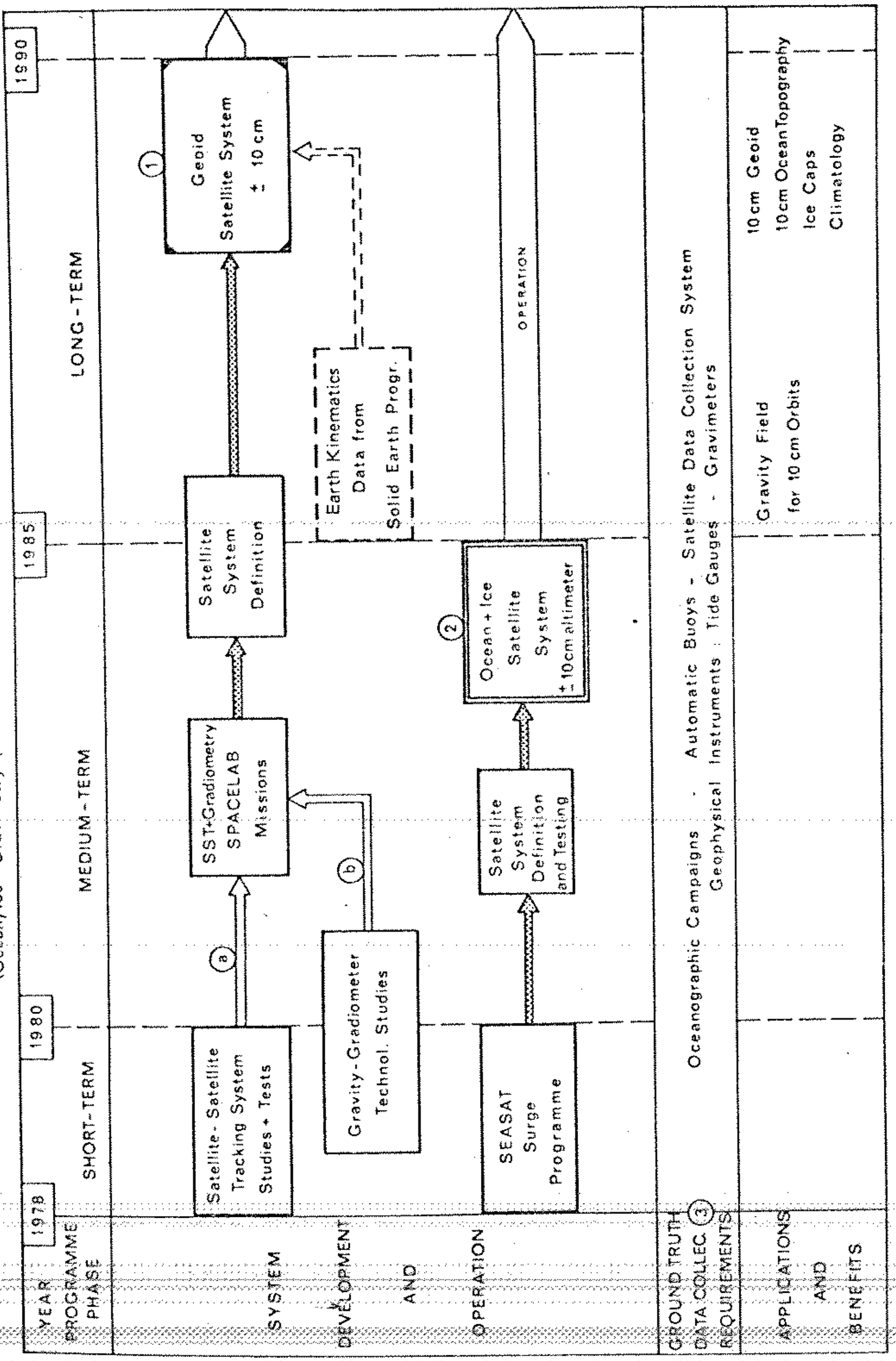


FIG 2

Ⓑ SURFACE STUDIES PROGRAMME

(Ocean/Ice - Gravimetry, Vertical Motions Monitoring)



SCIENTIFIC GOALS OF LUNAR LASER RANGING

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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

$$\delta h/h = \delta n/n + 2\ \delta a/a \tag{1}$$

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 non-spherical 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

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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
UT0 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

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Wilson
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Hamal
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Aardoom /Zeeman
Fischer /Neubert
Johnson /Veis
Cugusi
Bauersima /Beutler /Gurtner /Klockler /Schurer
Halme /Paunonen /Sharma /Kakkuri /Kalliomaki
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reports from NASA, SAO, Wettzell, Kootwijk, Cagliari
Zimmerwald, Metsahovi, Helwan, Crimea, Dodaira

OPERATING SATELLITE RANGING SYSTEMS; INTRODUCTORY REMARKS

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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

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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/

-<u>Computer</u>: 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

-<u>Performances</u>: 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

-<u>Mount</u>: 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

-<u>Laser</u>: 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

-<u>Laser optics</u> : Variable afocal system with a focal ratios from 1 to 10

-<u>Receiver optics</u>: 1m Cassegrain telescope Al plated

- <u>Detection</u>: 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

-<u>Tracking scope</u>: 18cm refractor associated with a TV camera/Nocticon Thomson CSF tube/

Field 1°, 12 magnitude possibilities on a non-integrating mode

-<u>Electronics</u>: 100 ps resolution counter. Stop channel gated

-Computer: 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

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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% $\rightarrow$ 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 = $7{,}8\ 10^{-1}\ m^2$
θr = $5\ 10^{-5}$ 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 5A° 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} 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 Optique

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

I.2.2.2 Electronique

- 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 au-dessous 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 $T + \tau$

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(1) une note annexe traite du problème plus spécifiquement