Mobile
systems
technology

Technical Aspects of the MTLRS#1 Upgrade

P. SPERBER, U. HESSELS, R. MOTZ

Institut für Angewandte Geodäsie
Fundamentalstation Wettzell
der Forschungsgruppe Satellitengeodäsie
D-8493 Kötzting, Fed. Rep. of Germany

Abstract. In this paper a conception for the upgrade of the Modular, Transportable Laser Ranging System MTLRS#1 is presented. The technical changes in the transmitting system, receiving system and some subsystems, which are necessary to increase the accuracy of the results and the reliability and automation of the system are shown.

1. Introduction

The Modular Transportable Laser Ranging System MTLRS#1 has operated successfully since 1984. Since 1985 the system has been in operation in the Central and Eastern Mediterranean area and in the U.S.A., contributing to the WEGENER-MEDLAS and the NASA Crustal Dynamics Project.

In order to improve the ranging accuracy and the system reliability it has been decided to perform a major system upgrade in 1991. For that time improvements are being planned for the following elements:

- Transmitting system
  - laser
  - start diode
  - cooling system
- Receiving system
  - new photo-multiplier
- Other subsystems
  - CCD camera
  - weather station with automatic readout

2. The transmitter

2.1. The laser

The duration and the energy of the emitted laser pulses are critical elements in the determination of the accuracy and the number of returns produced by the satellite laser ranging system. The temporal pulse-width limits the accuracy of the time interval measurement and the output energy influences the strength of the return signal. To improve these most important characteristics, the original Nd:YAP laser with a 370 ps pulse width will be replaced by a Nd:YAG System with 30 ps pulses.

Currently two lasers appear to be able to meet this specification:

The first alternative is an actively/passively mode-locked cavity dumped system. A detailed comparison of this system with its forerunner is given in Table 1 and the optical arrangement is shown in Fig. 1. The pulse is amplified (one single pass and one double pass amplifier) to increase

Typeset by $\mathcal{A}_{\mathcal{M}}\mathcal{S}$-TEX the energy to about 80 mJ at 1064 nm. The second amplifier is followed by a high efficiency second harmonic generator (SHG) to obtain a 30 mJ pulse at 532 nm. Expanding telescopes are used to reduce the risk of damage of the optical components. The two frequencies are separated through a dichroic mirror, only the green light would be used for tracking.

Several special features are included to facilitate remote control and adjustment of the laser:

- calibrated photodiodes to determine the dumping efficiency, the light amplification and the conversion rate of the SHG.
- motor controls to adjust selected optical elements without opening the laser and a CCD camera to monitor the spatial pulse shape of the green light.
- a 1 psec accuracy monitor to control the quality of the mode-locking, which is in turn governed by the modulation of the active mode-locker and the dye quality of the passive mode-locker. To achieve this accuracy a small part (about 1 %) of the pulse is split into two components. These two pulses are overlapped under a small angle in a non-linear crustal. The spatial shape of the output from this crystal is finally detected in a diode array to give the information on the pulse duration.

Alternatively, a new laser system - the self filtering unstable resonator (SFUR) described by R. Bianchi et al and by K. Hamal et al - is now available and there is some considerable chance that this design will finally be selected for MTLRS#1. With this very simple optical lay-out (Figure 1a) single pulses can be generated which meet the ranging specifications stated earlier. The advantages of this laser design are:

- very few optical and electronic components;
- no active mode-locking;
- no active cavity dumping or pulse selection;
- high stability and insensitivity to inaccurate adjustment;
- very good spatial pulse shape.

2.2 The start diode

To take full advantage of the short laser pulse it is necessary to use a start diode with a very fast rise-time to generate the start signal for the time interval counter. The HP 5082-4207 with a rise-time of 150 - 300 ps will therefore be exchanged for a diode with a 25 ps rise-time. Furthermore, to introduce high stability and the possibility to vary the pulse energy during tracking, the start diode will be placed before the last amplifier to detect the infra-red signal. Currently the diode detects the green light after the SHG.

2.3 The cooling system

A significant factor contributing to the stability of the output of the current laser arises from the fact that the actual laser system (optical elements and laser housing) is temperature stabilised. However, this has so far been achieved by using some proportion of the cooling capacity of the air conditioner for the cabin to cool the water for the laser. This has some obvious disadvantages:

- the laser can no longer be cooled if the air conditioner breaks down (this occurs at least once per year);
- the long heat-sheathed water tubes connecting the cabin and the laser (which is mounted on the base of the telescope mount) are continuously exposed to the sun. This results in inevitable heating of the cooling water and adds further to the load on the air conditioner;
- the capacity of the water reservoir required for this configuration is very large (200 l).

To improve this situation an independent air-cooled refrigerated recirculator will be added. This change will significantly reduce both the capacity of the water reservoir (about 30 l will suffice) and the length of the cooling tubes, thereby adding further to the overall system reliability

3. The receiver

Fig. 3 shows the current configuration of the receiver. Two modifications are necessary. A major improvement in the accuracy of the time interval measurement will result from the exchange of the RCA 8850 photo-multiplier tube (PMT) and the Ortec 934 constant fraction discriminator (CFD) for a better single photo- electron detection package. For this two options are available:

- a micro-channel plate (MCP) photo-multiplier coupled with a Tennelec TC 454 CFD;
- an avalanche diode.

The MCP has a significantly faster rise-time than the present PMT (300 ps compared to 3 ns) and, together with the new CFD, less jitter. To compensate for multiple photon events a received energy detector developed at OSG Kootwijk would also be included in the total package. This solution is comparable to that in use in most of the high accuracy systems currently in operation, but it requires careful tuning.

The avalanche diode has a very steep rise-time (about 100 ps) and a pulse shape and amplitude which is independent of the received energy level. The disadvantages here are that the diode needs to be cooled to -30^oC and it requires a gating pulse with a very low time jitter.

A further improvement in the receiving system would be possible if the correcting reflectors in the current receiver, which are used to reduce the 100 mm top-top range differences induced by the received signal impinging at different positions along the Echele monochromator surface, are replaced by a second Echele grating used in the opposite configuration.

4. Other subsystems

4.1 The image intensified CCD camera

To improve and speed up the adjustment procedures on the telescope an image intensified CCD camera will replace the former eyepiece (see left side of Figure 4). The eyepiece is currently used for two purposes:

- to perform star observations for the orientation of telescope;
- in conjunction with the He-Ne alignment laser, to adjust the Coude path and to check the orthogonality of the azimuth and elevation axes.

Both operations are presently possible with an accuracy of approx. +/- 4 arcsec. The use of the camera will improve this figure to about +/- 1 arcsec. This will result in improved acquisition, tracking and higher return rates.

A further advantage of this camera (Proxitronic PC-LL 2502) is, that it will make LAGEOS visible through the telescope. This offers additional control possibilities in the event of eventual sub-system failure.

4.2 The meteorological station

To obtain reliable meteorological information across the entire pass the current station, which requires manual registration of the data before and after the pass, with linear interpolation between, will be replaced by an automatic read-out and registration. A block diagramme showing the modifications is given in Figure 5.

With this technique the pressure is registered at the telescope at the level of the horizontal axis with an accuracy of +/- 0.15 mb; temperature and humidity are recorded at an altitude of 12 m above ground with a read-out accuracy of +/-0.15 K and +/-1.5 %. The control functions are performed by a Compaq SLT 286 laptop computer and the data is recorded discretely throughout the pass. The software supports the operator by providing a tracking protocol requiring little supplementary information.

4.3 Software

Only minor changes are currently being planned for the MTLRS#1 software. These include modifications to facilitate:

- tracking of Ajisai (already implemented);
- tracking of LAGEOS II, LAGEOS III; Etalon 1, 2, ...
- implementation of software recording the read-out from the received energy detector;
- on-site computation of normal points in the field.

5. Summary

The system up-grade for MTLRS#1 is planned to be completed by mid summer (July) 1991. It will result in a system with the following modified specifications:

- 30 ps pulse-width with 30 mJ/pulse at 532 nm;
- start pulse to the time interval counter from a diode with a 25 ps rise-time;
- a high quantum efficiency detector with a rise-time of 100 - 300 ps;
- high accuracy system orientation using an image intensified CCD camera;
- high resolution meteorological data to reduce the uncertainties of tropospheric refraction;
- improved tracking and performance monitoring software.

As a result of these modifications the system will be capable of tracking high and low satellites with a single shot r.m.s. of +/- 1 cm or better.

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A. Bianchi, A. Ferrario, P.G. Gobbi, C. Malvicini,G.C. Reali, SPIE 701, p.132, *1989.*

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Laser Specifications

	Old Laser	*New Laser*
	Kristalloptik YL143S	**Baasel Lasertechnik**
ACTIVE MEDIUM	ND:YAP	**ND:YAG**
WAVELENGTH	539 nm	**532 nm**
PULSE DURATION	370 ps	**30 ps**
MODE-LOCKING	active	**active-passive**
PULSE ENERGY	8 mJ at 539 nm	**30 mJ at 532 nm**
REPETITION RATE	1,2,5,10 Hz , ext.	**1,2,5,10 Hz , ext.**
DIVERGENCE	‹ 2 mrad	**‹ 2 mrad**

Table 1: Specifications of the MTLRS#1 Lasers

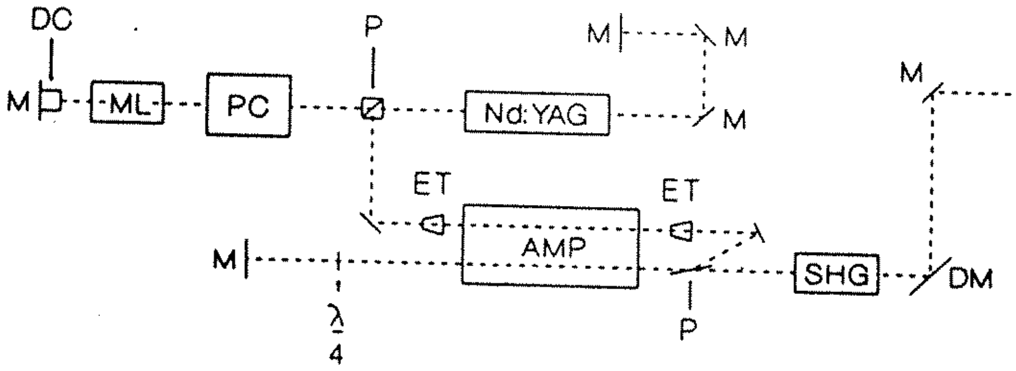
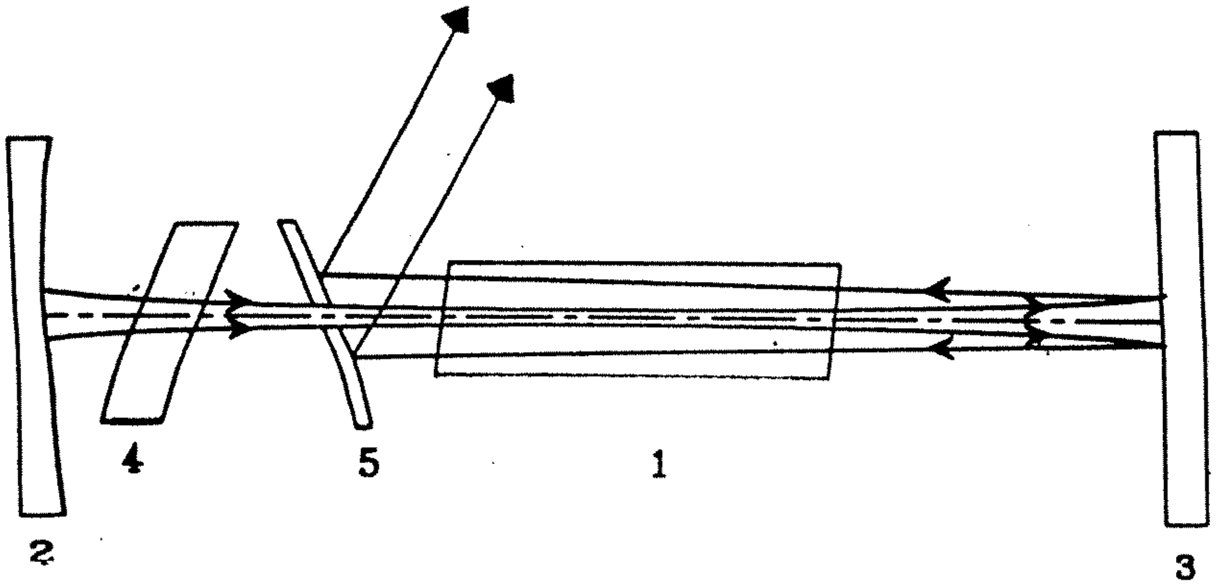


Fig. 1: Optical set-up of the new MTLRS#1 Laser

M : mirror
DC : dye cell
ML : active mode-locker
PC : pockels-cell
P : polarizer
ET : expanding telescope

AMP : amplifier
SHG : second harmonic generator
DM : dichroic mirror

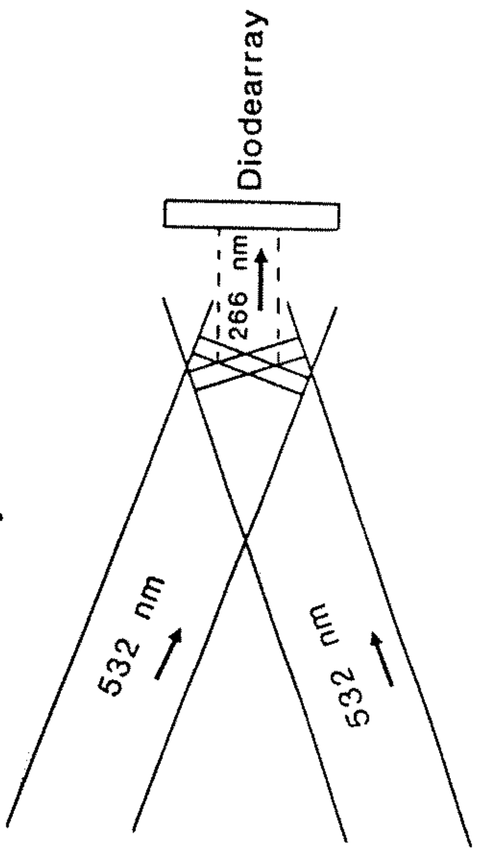


1 : Laser rod
2 : Mirror, 100 % reflectivity, curved
3 : Mirror, 100 % reflectivity, flat
4 : Cye cell
5 : Scraper mirror, 100 % reflectivity, flat

Fig. 1 a: Optical configuration of a modified SFUR Laser

Pulseduration Monitor

- Single shot autocorrelator
- Principle of operation:
  Second harmonic generation in nonlinear crystal



Pulse width resolution	< 1.0 ps
Maximum measurement range	60 ps
Accuracy	400 fs
Required input energy	300 µJ
	1 % of laserenergy

Fig. 2: Principle of operation and specifications of a single shot autocorrelator for MTLRS#1

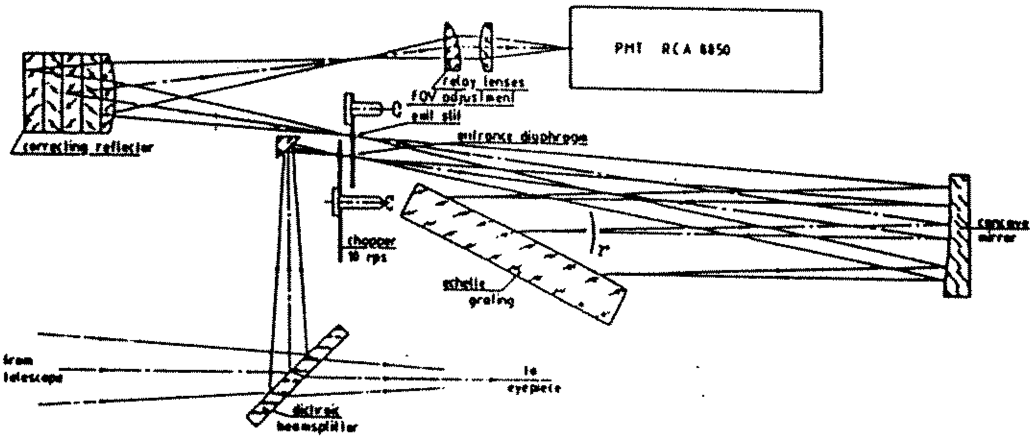


Fig. 3: Optical set-up of the detection package

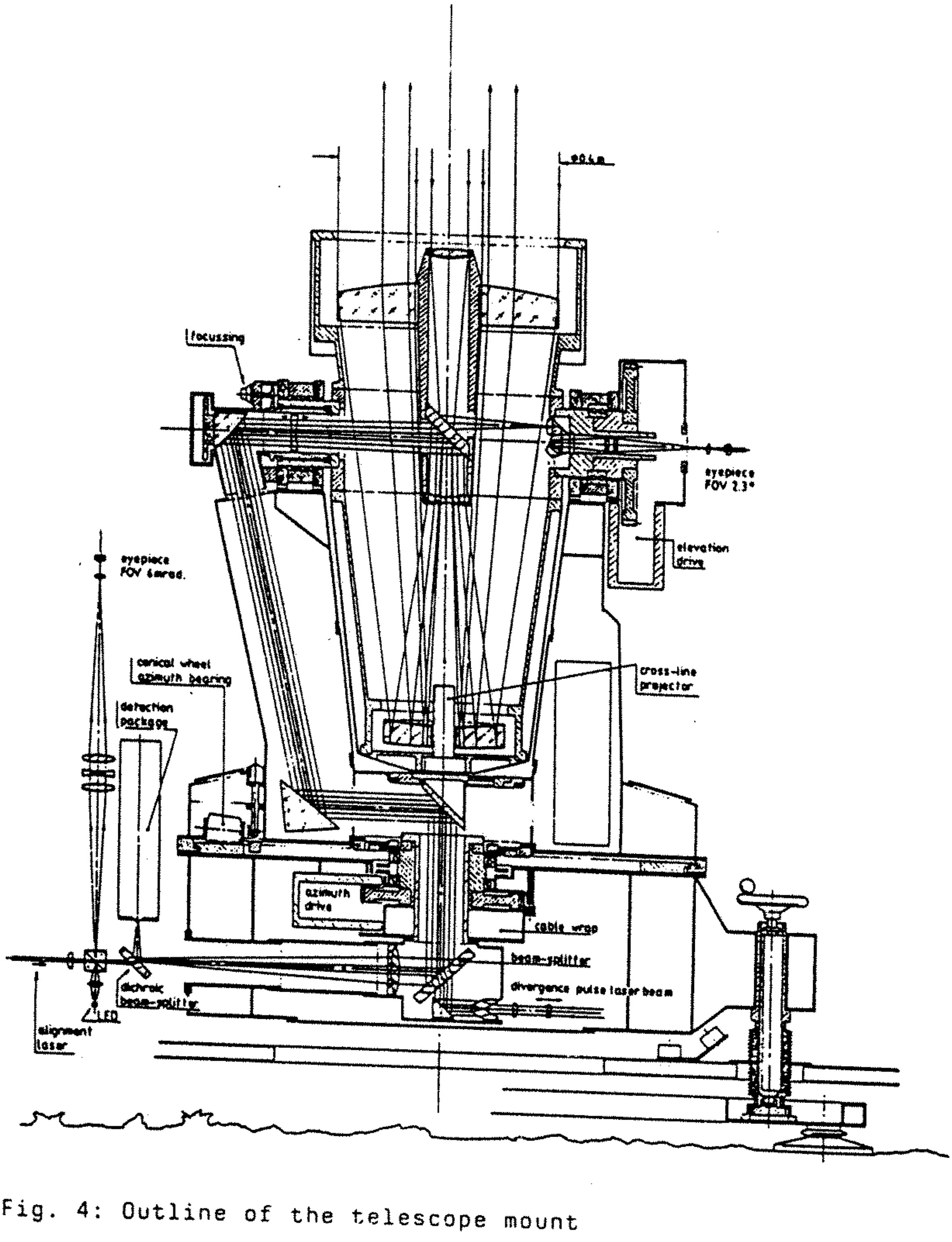
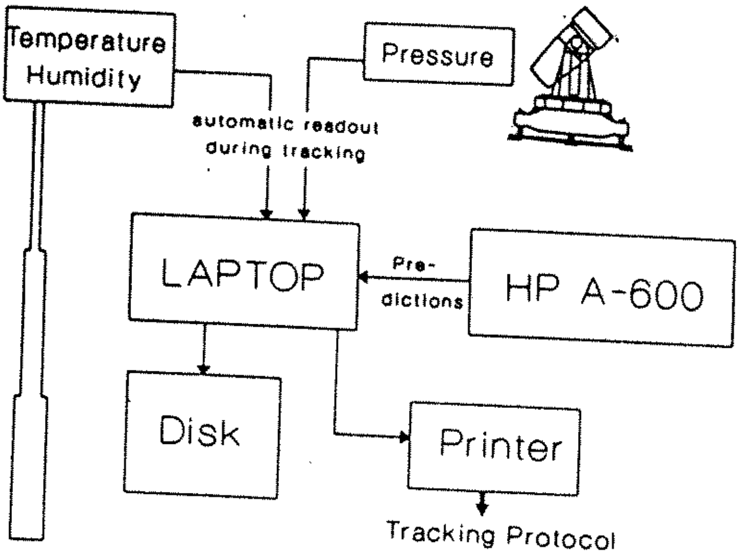


Fig. 4: Outline of the telescope mount

Automatic Meteorological System



SPECIFICATIONS

PRESSURE	*TEMPERATURE*	*HUMIDITY*
Paroscientific 760 16A	Driesen+Kern Squirrel Datalogger	
0.16 mb	0.15 K	1.5 %
RS232	RS232	

Quasi-continous record of the meteorological data during tracking

Computer aided production of the tracking protocol

Fig. 5: Block diagram of the automatic meteorological system

MTLRS-2 UPGRADE

W. Beek, K. Otten
Delft University of Technology
Observatory Kootwijk
PO BOX 581
7300 AN APELDOORN
NETHERLANDS

Tel: 05769-341
Fax: 05769-344

ABSTRACT

The MTLRS-2 upgrade of 1988 and for 1991 will be presented in this paper. Last years upgrade consisted of a signal strength measurement device which was added to the receiver system. Also we tried to add in 1988/89 a MCP-tube together with a switchable mirror box for switching between the PMT-and MCP-tube. The design aim was to use the MCP without loosing our internal calibration facility. Because of technical difficulties we had to switch back to the PMT and continued the MEDLAS-campagne in March 1989. The last part of this paper describes our upgrade for 1991 concerning the MCP (or solid-state detector) and Transputer realtime control.

DETECTOR SIGNAL STRENGTH

In FIG 1 the block diagram is drawn; most of the units are straight forward, the 2249 Single Gate unit from Le Croy needs separate gate and start signals which are generated by the gating circuit. This gating circuit consists of some ECL chips:2x 10116, 10124, 10104, 10135, 3 transistors BSX-20 for driving 50 ohm coax lines and 3x LM 723 for generating power supplies of +1.0 Volt, -2.0 Volt and -5.2 Volt. The circuit is built in a CAMAC module. Also a small modification was made to the Le Croy 2249 SG for extending the time between any two gates which originally was set to 2 microsec. If you will measure also the start signal strength you need about 70 ms between the two gates for LAGEOS ranges. We modified the monostable capacitor of the TD9602 from 10 nf to 12 microfarad. At the moment the unit is working very well but could not be calibrated so far because of the recent difficulties with our system in Italy and Greece.

MTLRS-2 ITT F4129-F MCP-Integration

In FIG 2 the simplified blockdiagram is drawn of the Micro Channel Plate set we obtained from Bendix-USA. Between the Power Splitter (PS) and the CFD a delay box is connected which is not drawn. The total set was tuned at Bendix laboratory under computer control for optimal performance and linearity of the CFD.

PMT signal strength measurement

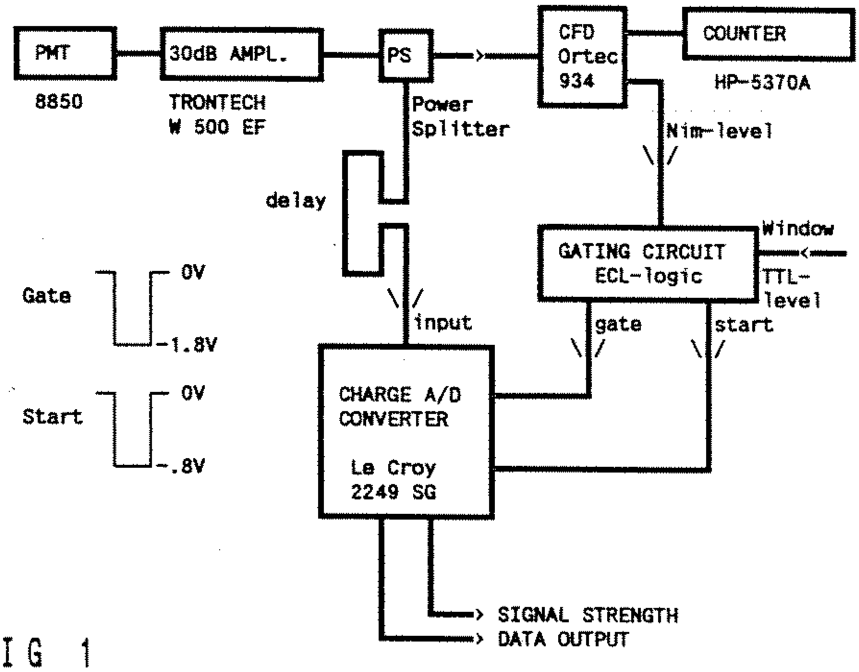


FIG 1

MCP-integration

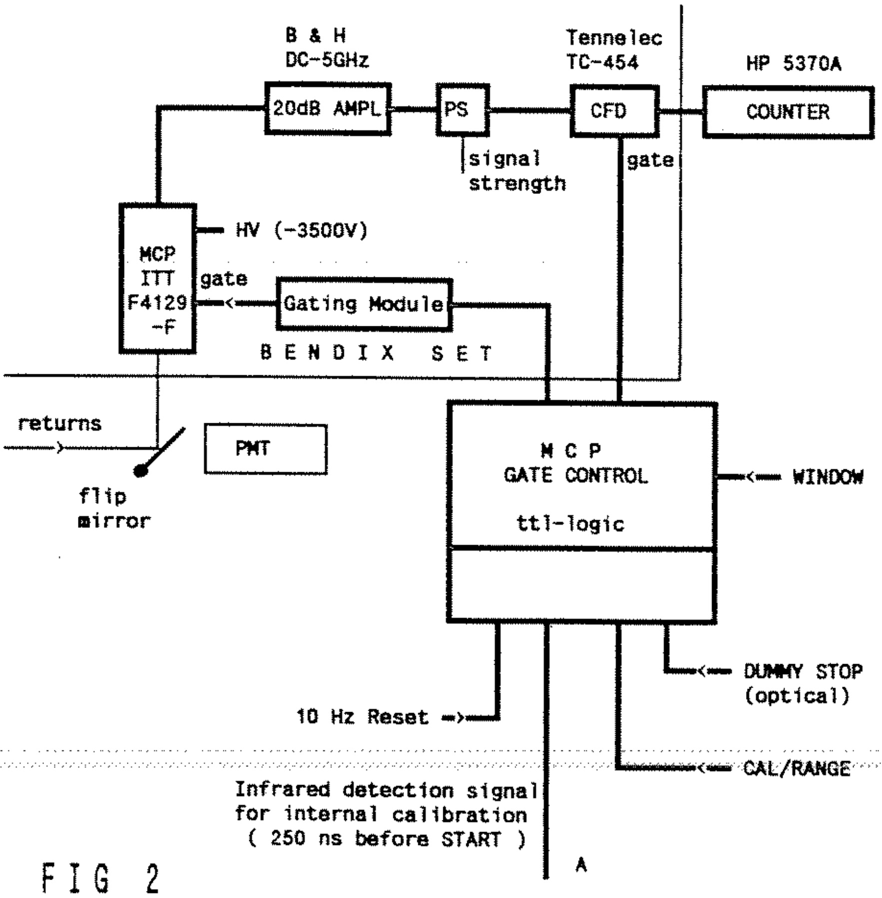


FIG 2

For internal calibration the signal A (FIG 2 and 3) is coming from inside the laser. Our laser is of the active/active type.
We need to gate the MCP 250 ns (a practical value determend by Bendix) before the return lightpulse arrives at the cathode of the MCP, because the output of the MCP gives a noise pulse due to the 600 V switching of the gate.
The cause of this noise pulse is the parasitic capacitance between the gate electrode and the output-anode. See the timing diagram in FIG 4.
We saw this noise pulse (with more amplitude than the return) at our Tektronix Digitizer and for our typical MCP this was about 200 ns before the output noise pulse decreased to 10%.

Without any modifications inside the laser the time-delay value between the signal at point A (FIG 3) and the moment the laser puls is generated at the laser output is for our laser about 100 ns.
The blockdiagram in FIG 3 shows the delay counter in ECL logic and we have to investigate if we can increase the existing counter delay value of 160 ns with an extra 150 ns to obtain a signal at point A which is 250 ns before the light-start pulse appears at the output of the laser.
If we cannot change this delay counter due to malfunction of the laser, we have to try a second IR-diode with more sensitivity so that it switches 150 ns earlier than the normal IR-diode.
We also tried laser-oscillator flashtube detection together with a monostable multivibrator for triggering the gate of the MCP but found it not reliable due to too much jitter.
The STOP-CFD has to be gated after the noise pulse but of course just before the return pulse.
For use of the MCP with external target calibration the gating is less complicated: the trigger for the MCP-gate and the STOP-CFD gate is generated by the normal START-detector in use and tapped (and delayed) from the output of the START-CFD.

We may state here, that it depends very much on the construction of the laser if we can use the MCP together with internal/simultaneous calibration.
At the beginning of 1989 we could not manage to solve this problem in time before the MEDLAS-campagne continued again and we had to switch back to the PMT-option and the system left Kootwijk in March 1989 for transport to Italy and Greece.

We also consider to use an Avalanche diode in our detection package but we then have to modify our Echelle Monochromator because this produces an image at the cathode of at best 1 mm diameter (private communication ir. H. Visser/ TPD-Delft). The Avalanche diode requires a limited area in the order of 100 microns diameter. The gating we expect will be much easier compared with the MCP.

REAL TIME TRANSPUTER CONTROL

From the beginning of 1990 our group will start with a new design of the electronics for controlling our total system. The main design will be made by three people in the field of hardware and software. The main philosophy is to minimize the hardware for improvement of reliability, and to automate the real-time process (see FIG 5 and 6). Other goals are: real time screening, automatic quick-look generation, multi-leaving of satellites and self diagnostic capability. To control these tasks one needs a flexible and powerful microcomputer.

Laser MCP-delay modification

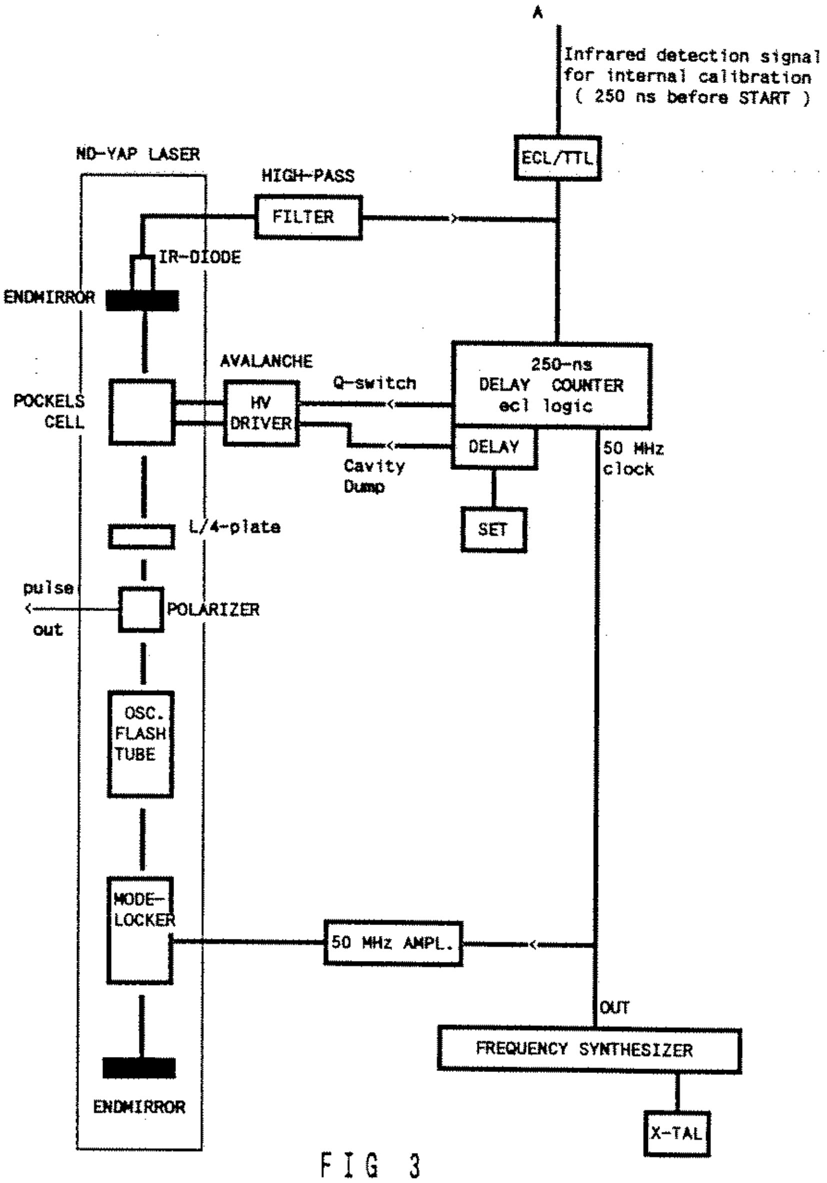


FIG 3

M C P timing diagram

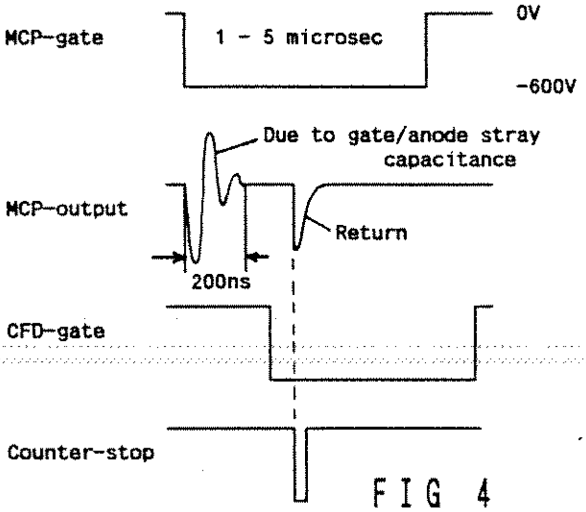


FIG 4

PHILOSOPHY

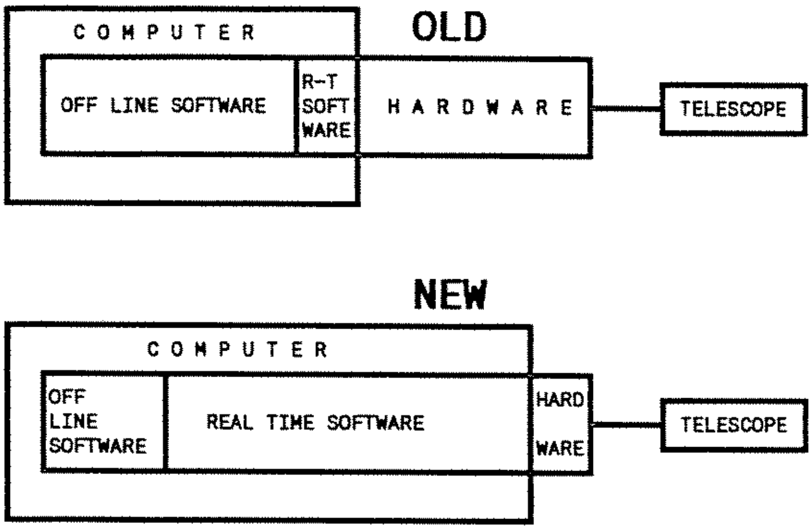


FIG 5

General Transputer Interfacing and new software tasks

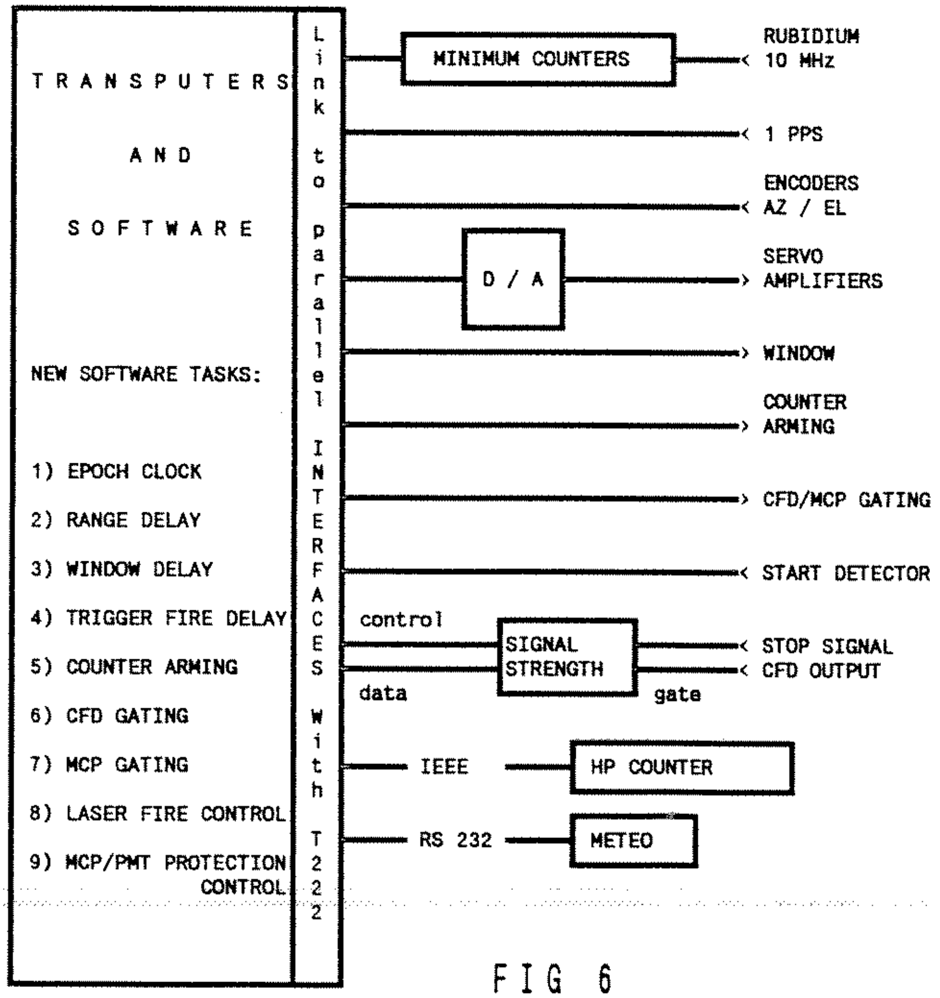


FIG 6

For the new design we will use Transputers which are flexible through their links and powerful through their high instruction rate per second. The serial-link-speed between each two Transputer-links is max 20 Mbits/s in both directions (one direction at a time). The T-800, T-414 and T-222 Transputers are 32- and 16 bit units which can do Multitasking and Parallel-processing.
At the end of 1989 a Transputer-development system was acquired, including software for use in a PC-80286-AT consisting of 3 full lengths slot boards each mounted on a PC-AT BUS-adapter. The Software language will be Parallel-C. Each Transputer will boot-up from the harddisk (see FIG 7) through their links, which means that we use no firmware in the total system.
As we see it now the final system will consist of a HOST-PC (from which the real time ranging will be controlled), with one or two Transputer PC-slot-boards for the overall control of the entire system.

In our observatory we will design a few different link-to-parallel interfaces, each build with a T-222 Transputer, which connect the remaining hardware through links to the Transputer boards inside the HOST-PC. We expect to run the T-222 link-to-parallel interfaces only from internal RAM-CASH of 4K so that no external RAM will be used.

Transputer Interconnection

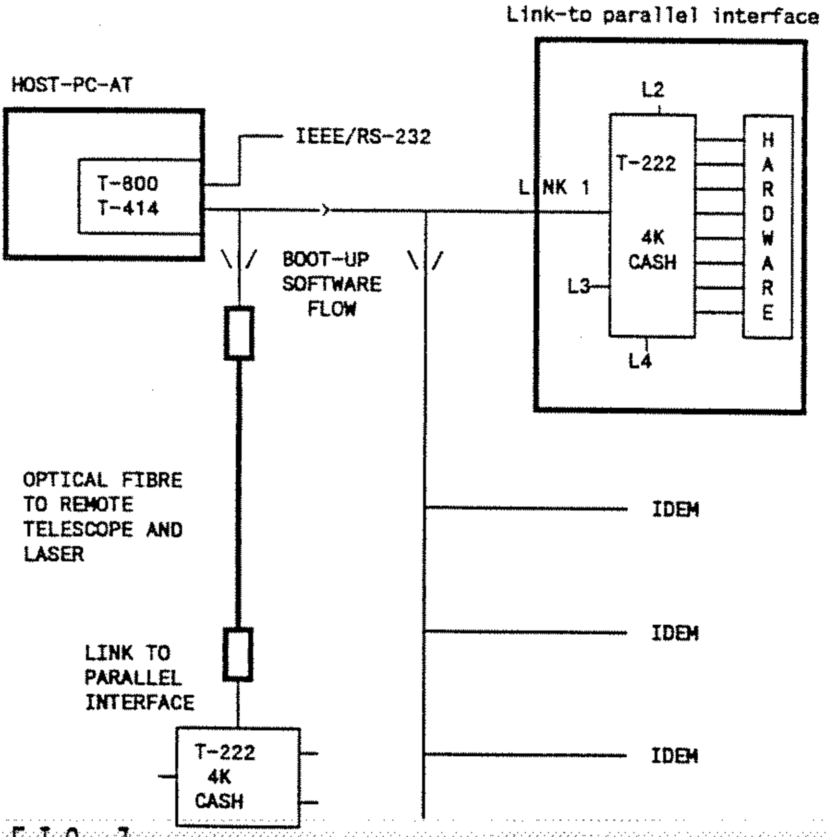
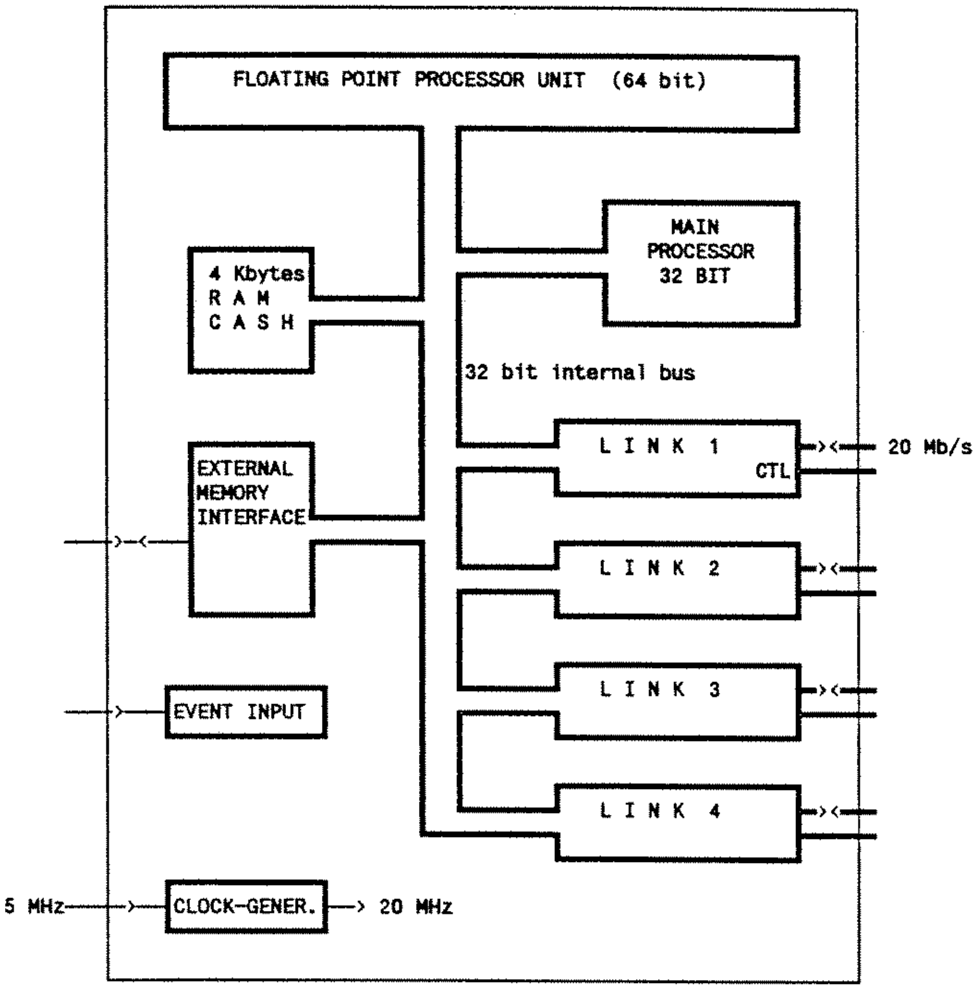


FIG 7

T 800 TRANSPUTER



1) Typ interrupt LATENCY in sub micro-seconds
2) Instruction throughput 10 MIPS (1.5 MFLOPS)
3) LINKspeed bidirectional max 20 Mbits/s for each link
4) Software support: OCCAM, C, PASCAL and FORTRAN
5) BOOTS from communication LINK or ROM
6) Pin compatible with T 414
7) Single 5 V power supply
8) Internal timers for real time processing
9) 32-Bit design

CONCLUSION

As soon as we have calibrated our detector-signal strengths unit and implemented a MCP- or Avalanche diode detection system, the pulse width of our laser will be the major limiting factor for the overall system-accuracy. Replacing the laser by a 30 to 50 mJ (30-100 ps) unit will be costly. The design of a new real time control system based on the Transputer will take a lot of man power. During 1991 we expect to implement these three items.

TELESCOPE FOR SATELLITE LASER RANGING TRANSPORTABLE STATIONS

M. Fibbi, A. Mariani
Officine Galileo S.p.A.
Space and Optics Division
via Albert Einstein 35
50013 Campi Bisenzio, Florence (Italy)

Telephone (39) 55 89501
Telex 570126 GALILE-I

ABSTRACT

A telescope design for Satellite Laser Ranging station, was developed by Officine Galileo, under Italian Space Agency (ASI) contract, for a transportable station (managed by CISE SpA) that, firstly, will operate at the Space Geodesy Center of Matera (Italy).

In the present paper the main features of the design are discussed. Mechanical, optical and servo-system aspects concur in the development of the design. The Telescope characteristics and a summary about the technical choices, the analyses and the final results of the design, are illustrated.

Introduction

In the last years the Satellite Laser Ranging (SLR) metodology has reached a primary position for the geodetical measurement thanks to the very high accuracy that can be obtained with the progress in lasers, electronics and optics.

In the new SLR station an optical telescope powered on two axis (elevation and azimuth) is used as beam-expander for the laser beam and as receiver for the return radiation from the satellite.

The mechanical, optical and servo-system performances of the telescope are therefore very important in performing the geodetical measure.

In this context, could be very interesting to carry out a SLR transportable station, so that geodetical measurement could be performed in points otherwise not accessible for this kind of technique.

1. GENERAL DESCRIPTION

The telescope system for SLR has three principal function: a) beam expander for the laser of the station (532 nm; 50 mJ;100 ps;10 Hz); b) receiver of the return radiation from the satellite; c) pointer and tracker of the satellite taken as reference of the measurement.

The system in object consists of a very stiff aluminium mechanical structure that supports the optical components and assures the precision pointing requirements. The structure has two degree of freedom: elevation (+- 110 deg) and azimuth (540 deg).

The principal optics of the telescope is utilized both for the laser shot (as beam expander) and to receive the return radiation from the satellite.

The telescope is in afocal configuration and is provided of a Coude' path that allows the optical interfacing with the other optical components of the station. The primary mirror has a diameter of 400 mm and is made in pure aluminium, both to minimize the effects of the thermal expansion in the range of - 20 + 50 °C and for optical stability. Furthermore the instrument is provided of a parallel finder telescope.

Each of the two rotation axis of the mechanical structure are powered by mean of a brushless motor (pancake type) that lead directly the rotation axis without any gear reductions. Each motor works in close loop with two angular position detectors in order to assure the dinamic and static precision requirements.

1.1 General Characteristics

In the following paragraphs the general characteristics and performances are shown.

1.1.1 Phisical Characteristics

- Configuration : - GIMBALED AFOCAL COUDE' TELESCOPE
  - PARALLEL FINDER TELESCOPE
- Overall dimensions : Heigth : 157 cm
  diameter: 153 cm
- Mass : 790 kg
- Moment of inertia : AZ axis: 45 - 58 kg m^2
  EL axis: 23 kg m^2
- First natural frequency : > 40 Hz
- Power consumption : 1000 W max
- Operating thermal range : - 10 °C + 40 °C

1.1.2 Optical characteristics

- type : - AFOCAL TELESCOPE
  - TWO CONFOCAL PARABOLIC MIRRORS
- magnification : 8 x
- primary parabolic mirror : material : aluminium + Ni
  focal length: 800 mm
  diameter : 400 mm
  coating : Al-enhanced
- secondary parabolic mirror : material : aluminium + Ni
  focal length: -98.50 mm
  diameter : 49.25 mm
  coating : Al-enhanced
- effective receiving area : 1100 cm^2
- overall optical efficiency (532 nm) : 72 %
- averaged " " (visible): 72 %
- beam collimation (532 nm) : 80% of the energy in 4 arcsec
- Finder telescope : FOV : 3 degree
  diam. : 50 mm
  magnif.: 12 x

1.1.3 Mechanic and servos characteristics

Charact. / Axis	range [degree]	pointing accuracy static - dynamic [µrad]	velocity max [deg/s]	acceler. max [deg/s²]
A Z	0 - 540	50	10	5
E L	+- 110	50	4	2

1.1.4 Thermal control

- passive telescope thermal compensation in the range -20 +50 °C
- forced air circulation
- heating system

2. DESIGN

To evaluate the attitude of the design to meet the characteristics above mentioned several analyses have been performed. In the following sections the most significant analyses and results of the mechanical, optical and servo system design are presented.

2.1 Mechanical design

The mechanical and structural design has been implemented by means of Finite Elements Analysis. The most important components have been analysed and a trade off among the best solutions was made. In the fig. 1 the general section of the instrument is shown.

In this paragraph are presented, as example, the results about the static load analysis of one important component: the Primary Mirror.

2.1.1 Primary Mirror

The Primary Mirror characteristics are directly related to the optical performances of the whole Telescope. So that a big effort in the design of this components was made, in order to

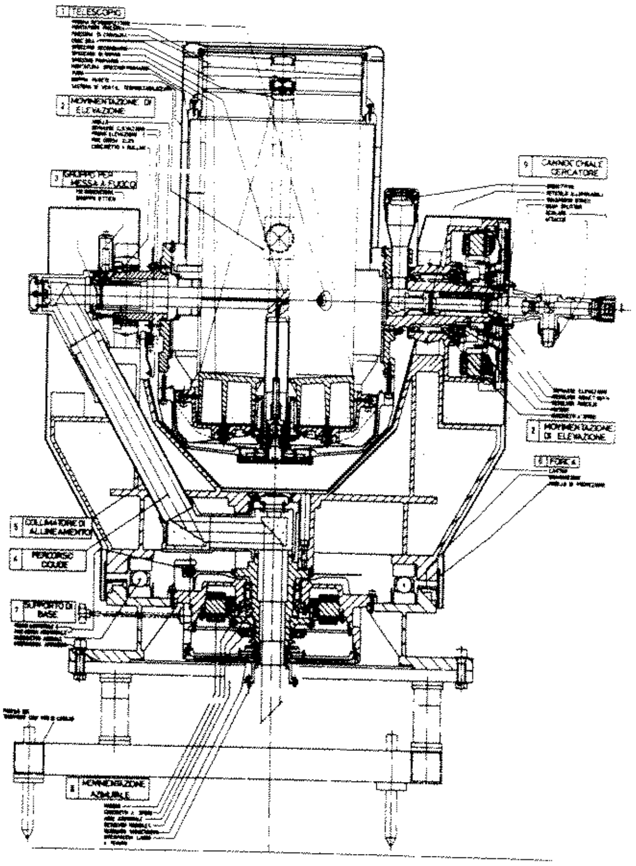


Fig.1 - Section view

maintain the deformations of the mirror surface within the range inposed by the optical design (λ/10).

The design of the mirror had to take in account the following basic requirements:

- minimize the effects of thermal expansion on the optical performances;
- use of a material with good optical stability.

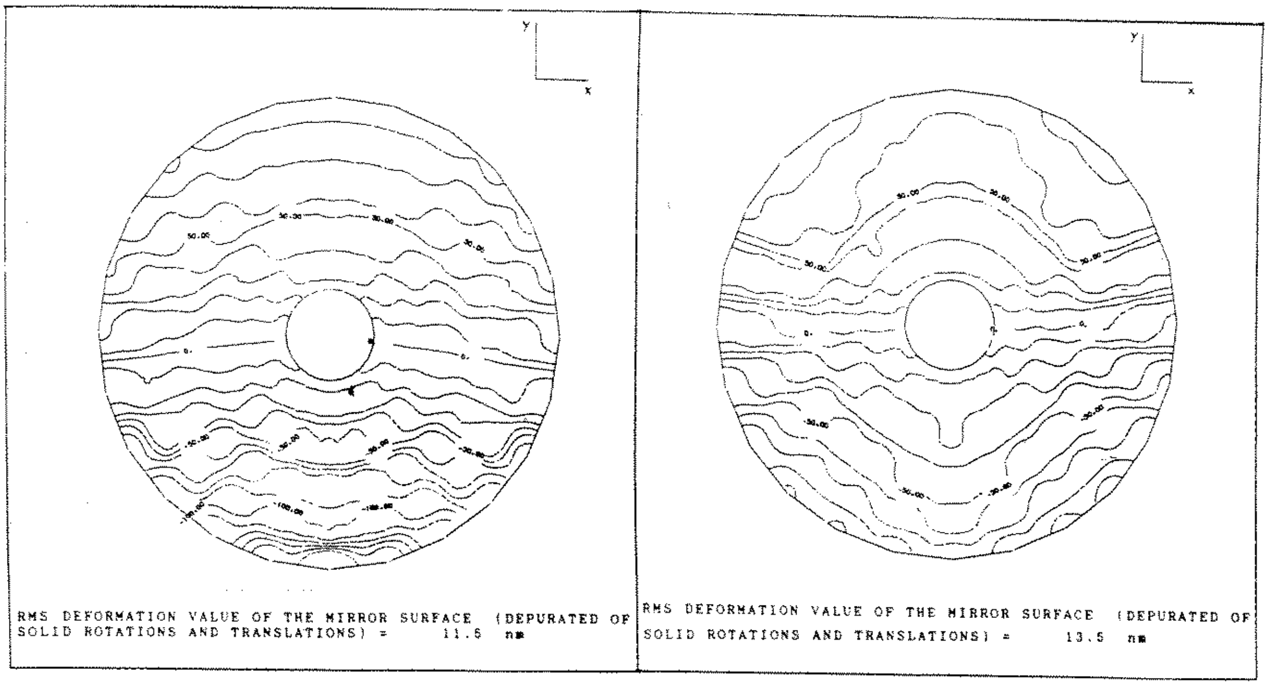
A pure aluminium (at 99.5 %) mirror meets as well as possible these requirements.

The special mirror fixture guarantees that the stresses induced by the structure are not transmitted to the mirror.

2.1.2 Mechanical analysis results

The figure 2 a) and b) shows the mirror surface for two static load conditions: Telescope vertically and horizontally positioned, (i.e. mirror horizontally and vertically).

The deformation RMS values, for the two load conditions, are contained in about λ/40.



(a) (b)

Fig.2 - Primary mirror: constant deformation curves [nm]

2.2 Optical design

The Telescope, from the optical point of view, consists of two aluminium confocal parabolic mirrors arranged in the afocal configuration with magnification 8x (see par. 1.1.2 and fig.3). The Coude' path,that interfaces directly the laser of the station, is equipped with a motorized focousing group able to eliminate any eventual loss of the afocality condition.

All the optical components of the telescope present an enhanced surface coating in order to increase, as much as possible, the optical efficiency at 532 nm (wave lenght of the laser).

The optical path is completly sealed and the entrance window is tilted to avoid retroreflections.

2.2.1 Optical analysis results

In the following fig.4 are shown the Diffraction Encircled Energy Function and the relative spot diagram. It can be seen that the requirement of 80 % of the energy in 4 arc-sec (see par.1.1.2) is satisfated with good margin.

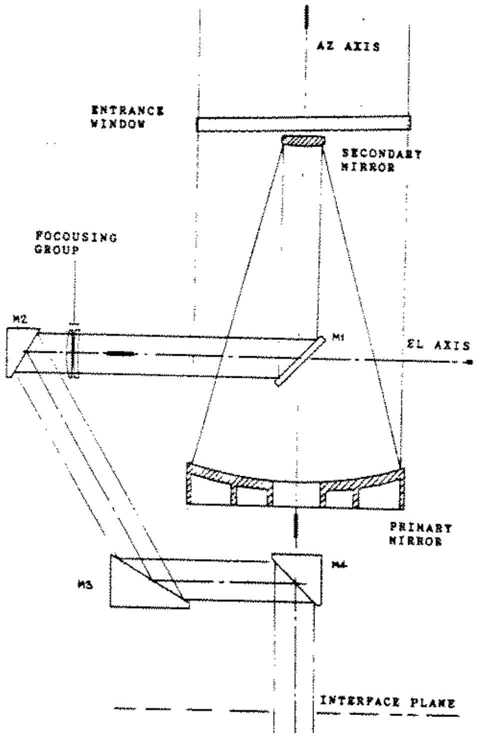


Fig.3 - Optical overall view

This results are valid if the mirrors are manufactured and maintained stable within λ/10. We note that the results of the mechanical analysis on the primary mirror (see par. 2.1.1) are compliant with this requirement.

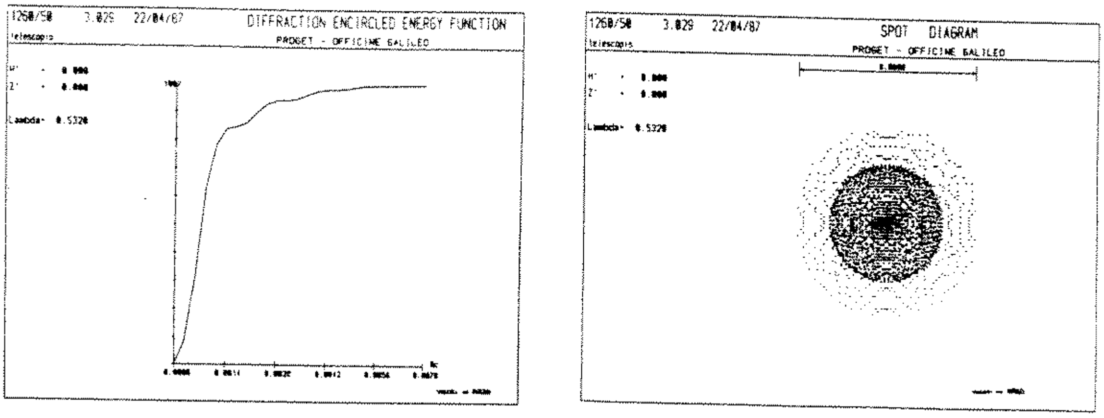


Fig. 4 - Optical analysis results [mrad]

2.3 Servo-system design

The instrument actuating system consist of two closed loops servos one for each axis (elevation and azimuth).

To achieve the required accuracy (see par. 1.1.3) each axis utilizes one motor (pancake type, brushless) and two angular transducers. Motors and transducers work directly on the own axis, without any mechanical reduction in order to avoid backlash. The couple of transducers consists of one resolver (accuracy 1 arc-min) and one inductosyn (accuracy 1 arc-sec). The coarse transducer (resolver) avoids ambiguity in the intrpretation of the signal of the inductosyn in the revolution. The two loops are controlled by means of a microcontroller that interface the main computer of the station.

3. CONCLUSIONS

The principal choices of the above described telescope design could be resumed as follow:

a- parabolic aluminium mirrors (primary and secondary) in confocal configuration supported by an aluminium alloy structure in such a way to minimize the thermal effects on the optical quality. So that an active thermal control has not been necessary;

b- motors that lead directly the axis and inductosyn angular transducers, for controlling the axis with the required accuracy.

The finite element analysis performed on the instrument shows the validity of the design: the deformations of the primary mirror surface and of the structure do not reach values that could compromise the optical results. Furthermore modal analysis shows a lowest natural frequency larger than 40 Hz that assure the stability of the instrument.

At the present, the Telescope is in the construction phase at Officine Gallileo S.p.A. that has already reserved a special clean room with anti-vibrating floor (5 m x 5 m) for the mounting and testing activities.

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H.Hurnik, J.Offierski, J.Osiński

Sending-receiving telescope for the mobile Laser.

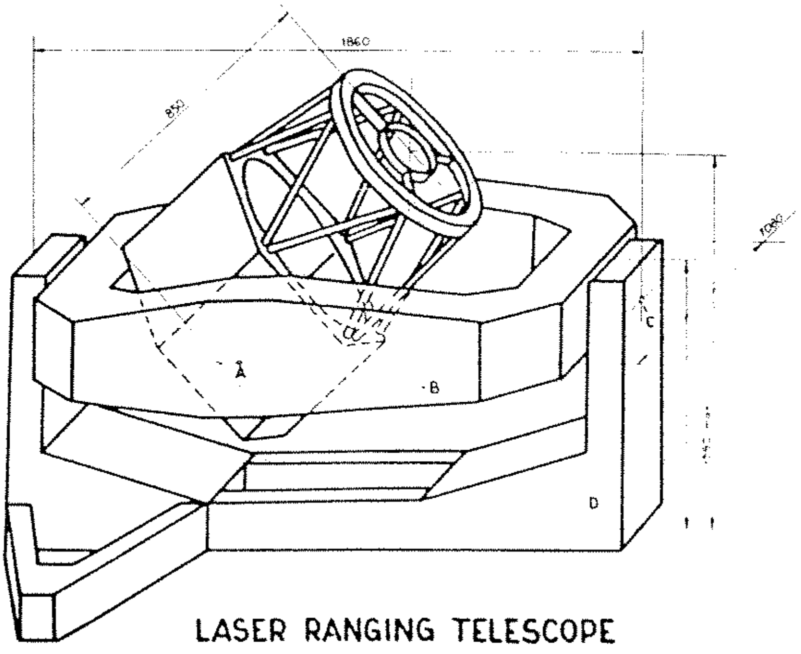
Astronomical Observatory of A.Mickiewicz University, Poznań

Astronomical Latitude Observatory Polish Academy a Science, Borowiec

Institut of Physics of Technical University, Wrocław

1. Telescope.

Following the results of our experimental research we have designed a single telescope instrument with the axis system according to Abelle and equipped with a Coude system. A general idea of its construction is illustred in Fig.1.



- Fig.1. -

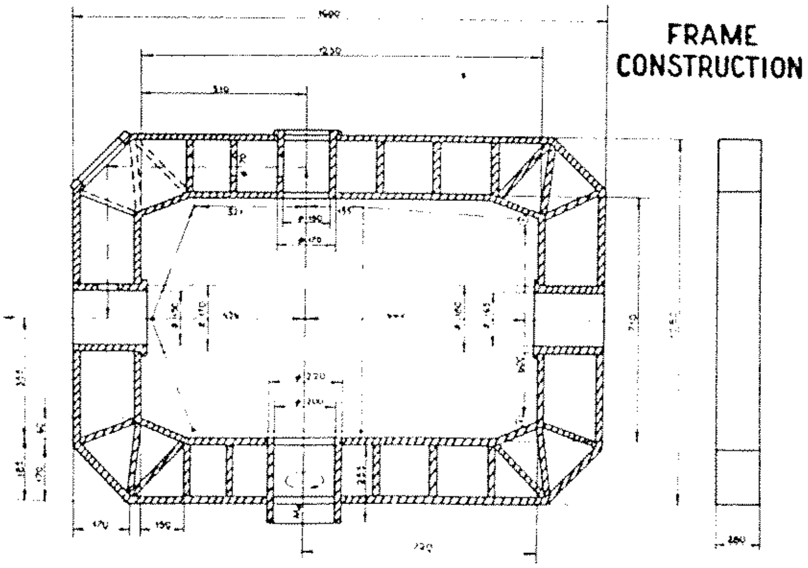
A Cassegrain telescope with the main spherical mirror of 500 mm in diameter rotates along the A axis in the frame B which makes the main horizontal axis C and rotates in the bearings mounted in the footing D. In this double-axis instrument its main horizontal axis is analogous to the vertical axis in the horizontal system.

An artificial horyzon, which is a mercury mirror placed in the foting,

enables the determination of autocollimation zero points in the scales of both axes when directed vertically downwards.
From the observations of star transitions we determine the position of the main axis or the vertical plane which is the plane of movement of the rotation axis of the telescope.
The parameters of the instrument:

footing length 1860 mm
footing width 1800 mm
rotary frame width 1080 mm
folded instrument height 1590 mm

The construction is to be made of bending plate elements. A cross-section of the frame is shown in Fig.2.



- Fig. 2. -

2. Optics.

The optics of the sending-receiving telescope making a part of a ranging laser station includes the following:

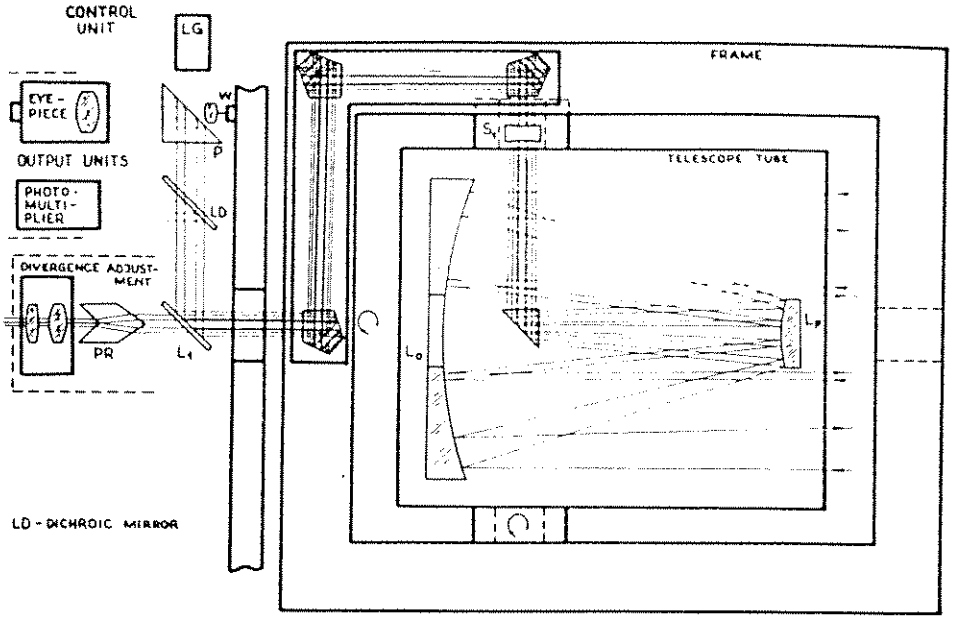
a) Cassegrain telescope system

a main spherical mirror of 500 mm in diameter a convex mirror od 150 mm in diameter which at the same time corrects the image because its bach sufrace is sputtered with aluminium so it also works as a correction lense.
The distance between mirror is 695 mm
The focal length is 5000 mm

b) Coude system

The laser light from the telescope input system, laser echo and the satellite image from the telescope pass through three pentagonal prisms

mounted in the instrument frame, a negative lense in the rotation axis of the telescope and the fourth rectangular prosm in the optical axis of the telescope to the output system.
The pentagonal prisms are mounted in one plate. The fourth rectangular prism is mounted in special mechanism, which provide possibility of regulation in all deprees of freedom. Fig.3. present a schematic diagram of optical system of the telescope.



- Fig.3. -

c) The input and output optical systems
The main elements of the input system are two lenses SO1 and SO2 which are responsible for the initial broadening of the laser beam. This is a no focus system of the Galileo telescope type of the angular magnification of 2,5 which provides the laser beam broadening from 4 mm to 10 mm. A shift of the lenses relative to each other produces a change in divergence within ± 1 mrd. Another element is a prism which divides the beam into two which pass through the windows in the mirror L1 and then come to the Coude system and the telescope which in this phase functions as a transmitting telescope. In this phase the negative lense S1 broadens the beams and causes their greater divergence. The laser echo and the satellite image follow the same optical path but in the reversed direction up to the mirror L1.
There they are reflected and pass through a focusing and correcting lense S2 onto a beam-splitter. The beam-splitter deflects the laser part in perpendicular to the diaphragm and photomultiplier and lets the satellite image into a control eyepiece with a ficusing plate with a cross. In this

phase the telescope functions as a receiver and controller.

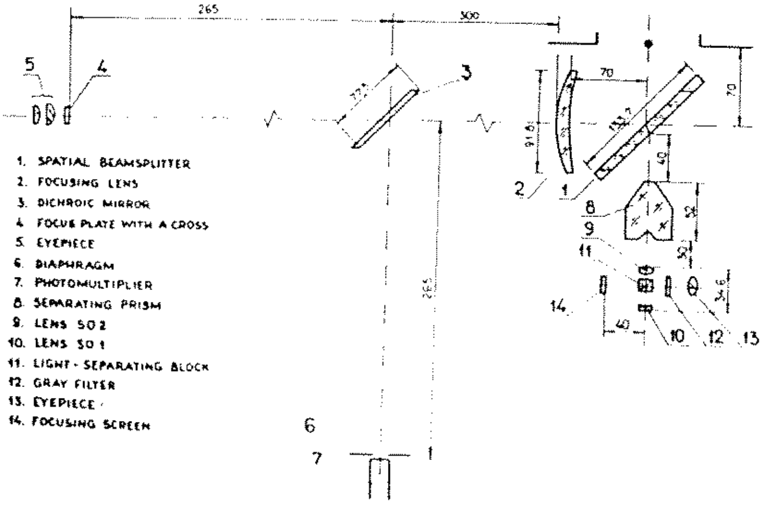
d) Adjustment system

Adjustment of the telescope with the Coude system ist performed using levelling instrument conected with the autocollimator.

Adjustment of the working system is performed with the help of four elements mounted in perpendicular to the laser beam between the lenses SO1 and SO2 which provide preliminary broadening of the beam. These four elements are beam splitter K1, a neutral filter F, adjustment eyepiece OK and a ground glass M. The beam splitter K1 used in adjustment procedure is replased by neutral K2 during ranging laser operation.

The input, output and adjustment systems are shown in Fig.4.

The optics of the ranging laser station has been designed and worked out at the Institute of Physics at Wrocław Polytechnics, Wrocław Technical University.

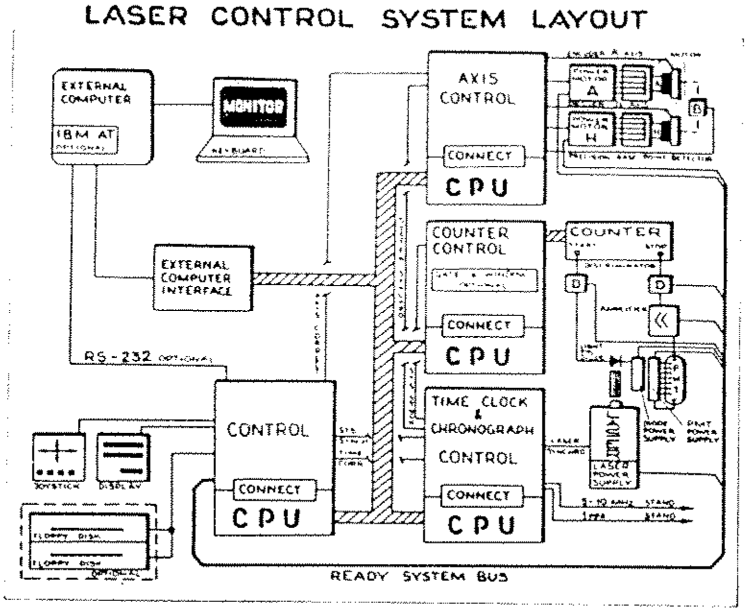


- Fig.4. -

3. Automatics

As the possibility of the ranging laser work in certain conditions when the measured satellite is not visible should be ensured, the automatic system must provide the possibility of the telescope control according to the satellite ephemeris within the accuracy of ± 10". At the same time the work of the laser transmitter and detection system should also be automatically controlled. The telescope motion is driven by wobble plate engines PTT 16 of the power of 300 W and provinding from 1 to 2000 revolution per minute. The engines are joined to the instrument axes with a three-degree roll-worm gears of the ratio 1:10000. The instrument motion is controlled with rotary induct of the minimum stroke of 1"4. Such a system

ensures that a telescope is ready for work in 3 minutes and provides the possibility of observation of satellites at 600 km above the Earth Surface. The automatic control system of the engines ensures their continuous work according to the ephemeric and provides the possibility of introducing corrections by the observer.
The electronics of the instrument has been designed similar as for the Astronomical Observatory Station in Borowiec and its block diagram in shown in Fig.5.



- Fig.5. -

The control system is composed of the following elements:
3 CPU charts based on a processor Z80B6 MHz, including 256 kB memory
1 CPU chart based on the same processor or a single microcomputer;tree special interface
a) interface of the assembly control which includes:
 - digital to analog convertes (12 bit) for setting the velocity of satellite motion
 - two-direction counters for continuous assembly control
 - a system for detection of direction of motion
 - an absolute reset system
 - control programs, programs for correcting the positions in the axes A and H and programs for calculating the transversal correction
b) a clock and chronograph interface including:
 - a clock driven by an external frequency of 5MHz supplied by the frequency standard
 - a chronograph able to record time moments with an accuracy to 100 ns
 - counters for the system synchronization
 - control program and program calculating the longitudinal correction
c) counter interface including:

- the system anabling reading the counter data
- optional systems generating a gate and a window
- control program.

All three CPU charts are coupled via a special fast data bus for transfering data and programs. This but is also connected with a CPU chart "Supervisor" which controls the work of the other charts as well as the operation of all units in the system. In the case of the system failure this chart is responsible for intermediate data storage. The chart of the interface with an external computer is used to connect an external computer which calculated the ephemeris and stores all observations. This chart may by replaced with a series transmission line RS-232.

An observer controlling the assembly will be equipped with a throttle lever (joystick) to correct the positions and a projector displaying the present state of the system.

FRENCH HIGLY MOBILE LASER SYSTEM

****

by

F.PIERRON and M. KASSER

CERGA-GRGS-CNES

SUMMARY

General specifications
Laser System
Mount
Software

MATERA LASER WORKSHOP

SEPTEMBER 1989

OBSERVATOIRE DU CALERN
CAUSSOLS
06460 SAINT VALLIER DE THIEY
FRANCE
TELEX:461402F
SPAN:29211::PIERRON

GENERAL SPECIFICATIONS OF THE MOBILE LASER SYSTEM:

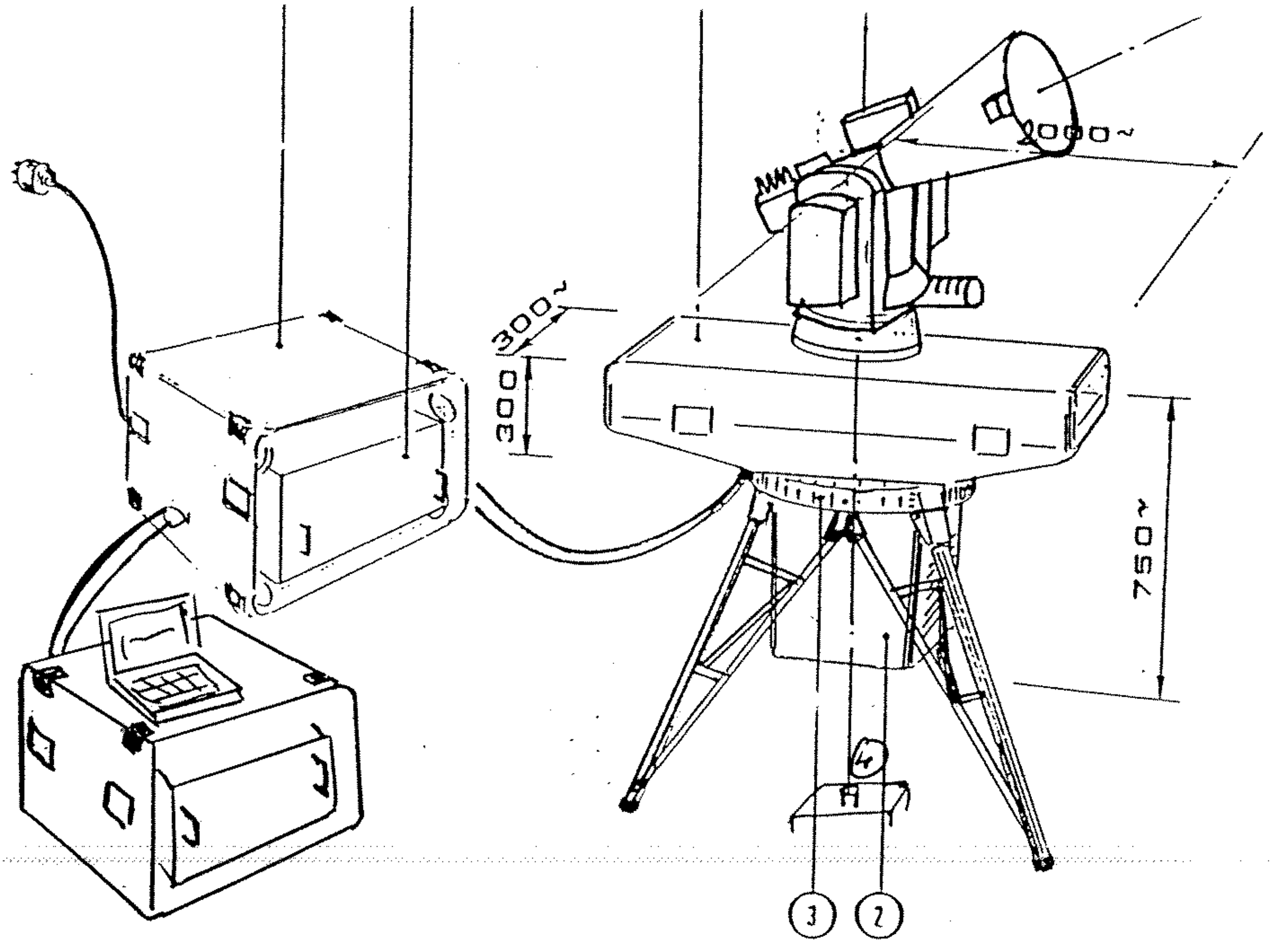
- Very compact
- Easy to transport by plane or car
- Weight: 200 Kg maximum packaged in containers of 40 Kg max.
- Very reliable, especially the laser system (In design actually to Quantel,...)
- Operational cost weak

======>two technicians only to operate.

- Accuracy at the centimeter level
- Capability to track a satellite very close of the zenith.

Particularly TOPEX-POSEIDON at an elevation of 89 Deg with an azimuth speed of 50 Deg/sec during some second of time.

*Operating date predicted: Early 92 forTOPEX-POSEIDON launch



LASER EMITTER SPECIFICATION

****

MANUFACTURER: QUANTEL FRANCE

-ND-YAG LASER IN ACTIVE-ACTIVE MODE

-ONE DOUBLE PASS AMPLIFIER

-ENERGY PER SHOT: 100 milli Joules at 1064 nm

-REPETITION RATE: 10 HZ

-Pulse Width: 200 ps to 300 ps with a 7 % stability

-Cooling System: Air water exchanger

Operating temperature: -10 deg c to 35 deg c

-Total Weight not exceeding 37 Kilogrammes.

-Packaging in two pieces: *The head

*The power supply

COMPACT LASER HEAD:

****

Composition of the laser head:

-Optical components fixed on a carbon fiber bench and included in a presssurized enclosure.

-Oscillator cavity

-One double pass amplifier

-One pulse selector

-No harmonic generator for doubling frequency to the green color

-Cooling system and capacitors banks are fixed just under the bench.

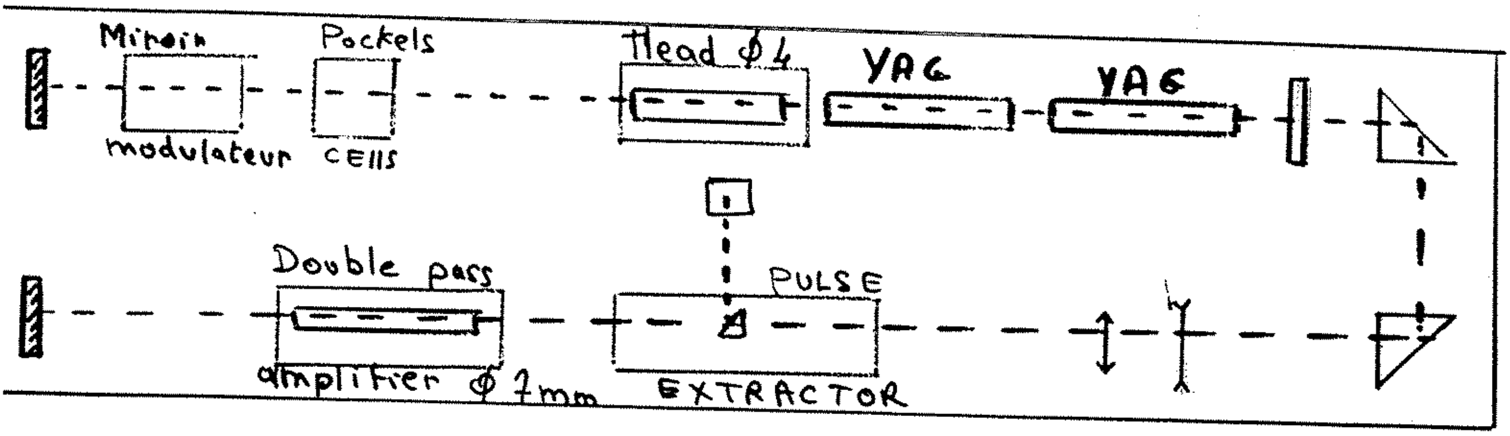
-Rotating contacts for electrical connections with the mount.

-Size of this head:

-1.00 m by 0.30 m for the bench by itself

-0.700 m by 0.30 m for the capacitors and cooling system under.

Weight: no more than 25 Kg



Compact laser bench(Project)

POWER SUPPLY OF THE LASER:

-Fully designed in order to minimize the size, the reliability and the weight .

-Size: typically 40 liter

0.40 m by 0.40 m by 0.30 m

-TOTAL WEIGHT: 15 KG

RECEIVING DEVICES, DETECTION PACKAGE

****

*DIAMETER OF THE RECEIVING OPTIC: 20 Centimeters

*Infrared detector: Avalanche photodiode in test actually at the Cerga LLR station but very promising in term of link budget.

-The emitted energy is twice.

-Atmosphere transmission better

-Quantum efficiency of the detector at least 50 % instead 20%

-Very interesting cost

MOUNT:

****

*In design actually in the swiss company KERN on the base of an existing electronic theodolite.

*Especially designed to be operated in the land.

TEMPERATURE

WEIGHT

RELIABILITY

STURDINESS

*MAXIMUM SPEED DURING THE TRACKING: 60 DEG/SEC

in order to calibrate oceanographic satellites

*VERY GOOD TRACKING ACCURACY(Some arc seconds)

*SUITABLE FOR ACCEPT THE RECEIVING SYSTEM WHITH A TOTAL WEIGHT OF 6 KG.

SOFTWARE:

****

BASE: The packages of the Grasse station

IMPROVMENTS: Automatisation and communications links

Multi-satellite satellite tracking: capability of moving from a satellite to an another very quikly.

Satellite Laser Radar Electronics Based on IBM PC Computer

Miroslav Čech, Antonin Novotný

Czech Technical University, Prague
Faculty of Nuclear Science and Physical Engineering
115 19 Prague 1, Břehová 7
Tel.: +42 2 848840, telex 121 254 FJFI C

Abstract

This paper deals with fully computer controlled system for satellite laser radar operation. The system is based on IBM PC/AT computer, microprocessors controlled compact laser radar electronics (LRE III) and corresponding software package for IBM PC and LRE III (firmware in EPROMs of LRE III). The software package, hardware and firmware of LRE III has a modular design. The system has been installed in Helwan, Egypt, and it's used for full blind tracking and satellite laser ranging from August 1989.

1 Introduction

The development of the computer controlled laser radar for the Helwan satellite laser radar station started in 1979. The satellite position prediction, satellite laser radar control and ranging data analysis, software package was developed for HP 2100 and HP 1000 computers [1].

The satellite laser radar in Helwan has been operating from 1981 with full computer control without visual checking of tracking. The experimental radar in Helwan has been continuously improved including software package [4], [5], [6], [7], [8].

In the period 1987–1989 the satellite position prediction and ranging data analysis programs were improved and were implemented on IBM PC/AT, the world-wide used computer. The developed compact laser radar control electronics LRE III and control software has been installed in Helwan SLR at the beginning of August 1989. The control system based on Hewlett-Packard computer was completely removed.

2 Hardware Configuration of the Control System

2.1 IBM PC/AT Computer System

2.1.1 The computer consists of:

2.64 MB RAM, 40 MB hard disc, 2 floppy drives 5.25″; 1.2 MB/360 kB, math co-processor INTEL 80287, graphic adapter, EGA/VGA color monitor, 2 serial/1 parallel ports, mouse, internal async. modem 1200 Bd

2.1.2 The computer system is attached to:

- LRE III electronics
- printer Epson LQ 850
- FACIT paper tape puncher (for telex)

2.2 Laser Radar Electronics LRE III

The LRE III is based on three INTEL 8080 microprocessors with 30 kB firmware stored in EPROMs. These control routines were written in *C* language and ASSEMBLER language. All the commands are sent from PC/AT as ASCII characters (2 letters & number, for example command *LP*4 sets laser period 400 ms).

2.2.1 The LRE III consists of:

- 1 equipment mainframe with power supplies (dimensions: 50 × 40 × 40 cm)
- 5 printed circuit boards connected by modified multibus on the backplane
- I/O ports on the front panel

2.2.2 The LRE III is attached to:

- IBM PC/AT using serial port 9600 Bd
- step motor drivers — azimuth & elevation
- time interval counter HP 5370B, IEEE 488 interface & arming signal
- laser transmitter (laser trigger, laser epoch [start])
- receiving electronics (PMT gate)

- station clock (time setting in LRE III, LORAN C timing)
- sensors on various laser radar parts

2.2.3 LRE III parameters

- **Time gate:** 100 ns - 1 s with the resolution 100 ns
- **Time window of PMT:** 100 ns - 1 ms with the resolution 100 ns
- **Time epoch of ranging:** the precision is determined by external 10 MHz frequency standard; time resolution is 100 ns
- **Step motor controller:**
  - ⋆ *Independent control of two axes (100 ms interval)*
  - ⋆ *Smooth movement between positions*
  - ⋆ *No overshoot*
  - ⋆ *Manual pointing movement*
  - ⋆ *Velocity, acceleration and resonant frequencies are soft programmable in 100 ms steps*
- **Laser trigger period:** 100 ms - 1s, with the resolution 100 ms

2.2.4 LRE III commands (I/O serial port)

- **Satellite tracking commands:**
  - ⋆ *Calibration, satellite ranging*
- **Time epoch commands:**
  - ⋆ *Time set, set input multiplexer for time, read time of external event, read internal current time*
- **Step motor commands:**
  - ⋆ *Motor clear, set and read motor position, move to absolute and relative coordinates, manual move, set maximal velocity, update acceleration and resonance frequency table*
- **Counter commands:**
  - ⋆ *Send counter commands, counter initialization, set time pause between commands, set clear command for counter, read counter data*

- **Time gate commands:**
  - ⋆ *Set gate window and delay*
- **Miscellaneous commands:**
  - ⋆ *Set default parameters, set laser trigger period, laser trigger ON/OFF, PMT (photomultiplier) enable/disable*

3 Software Package

The satellite laser radar software package includes:

- The system of programs for satellite position prediction and ranging data analysis written in **FORTRAN 77**, independent on hardware of a satellite laser ranging station and running on any IBM PC compatible .
- The programs for control of satellite laser radar ranging activities written in *C* language.
- Firmware routines at LRE III written in *C* language and **ASSEMBLER**.
- General programs for IBM PC: *Compilers, editors, word processors, communication programs, utilities.*

3.1 Satellite position prediction

AIMLASER program is based on the SAO algorithm [2] and the Royal Greenwich Observatory implementation. **ORBIT** program is the modification of the CSR of the University of Texas algorithm based on the integration of range/rate vectors [3]. Both mentioned programs compute the geocentric position (x, y, z) of satellites during the pass in 1 minute interval. The computed results are used for:

- satellite ranging data analysis,
- interpolation for 1 second intervals (geocentric position is converted into topocentric for mount position control).

Performance

- Accuracy: LAGEOS – better than 0.5 arcmin / 1 μs,
  low orbit satellites – 1 arcmin / 2 μs
- Routinely full blind tracking of LAGEOS, STARLETTE and AJISAI
- Computation time for position prediction of 1 satellite: 1 min

3.2 Radar control

The control programs consists of programs running on PC/AT and firmware routines (2.2.4) running on three microprocessors of the LRE III.

The control programs in IBM PC are:

- **MOUNT** — *absolute and relative mount movement, setting and reading of the mount position,*
- **TIME** — *internal time setting and reading, checking of time functions of LRE III,*
- **RCAL** — *radar calibration program,*
  - ⋆ *creates histogram of calibration,*
  - ⋆ *computes mean and sigma of the calibration,*
- **SMP** — *satellite laser ranging program,*
  - ⋆ *on-line color graphic display ,*
  - ⋆ *on-line correction of the azimuth, elevation, tracking time delay and time window,*
  - ⋆ *the possibility of the stars tracking for the service purpose*
  - ⋆ *the area selecting of valid points on the graphic screen by a mouse,*
- **STARS** — *stars position calculation, tracking data preparing for SMP program),*
- **FVT** — *receiver field of view test, graphic output,*
- **LORAN** — *time base correction program.*

The LRE III commands are described in 2.2.4.

3.3 Ranging Data Analysis

The ranging data are evaluated in Station. The analysis software has been periodically updated since 1981 [1], [4]. The last version of these programs (1988) on HP1000 computer has been implemented on IBM PC/AT [8].

The analysis of results is based on calculating range residuals, i.e. the differences between observed and predicted ranges. The main feature of the analysis software are:

- running on any IBM PC compatible with the mentioned hardware specification;

- complete ranging data analysis in SLR Station;
- noise rejection;
- ranging jitter evaluation;
- ranging data corrections corresponding to used instruments;
- processing of multipulse character of laser ranging data;

3.4 Ranging data transmission

- The quick-look data:
  - ⋆ by telex *(Facit puncher)*
  - ⋆ by telephone *(internal modem card)*
- Full data rate (MERIT2 format):
  - ⋆ by mail *diskettes*

4 Conclusion

This article describes compact, ineexpensive and reliable SLR control hardware and the SLR software suitable for transportable Stations.

The software package may be used on generally spread computers in present time, i.e. IBM PC compatibles. It may be easily installed at any satellite laser ranging facilities. The LRE III laser radar electronics, because of its conception of microprocessor controlling, may be also modified for any hardware configuration of a SLR station.

The system is used in SLR Helwan, Egypt. During the period August—October 1989 more then 200 passes of the satellites were succesfully measured.

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Recent software developments

THE DILUTION OF PRECISION (DOP) TECHNIQUE

Alberto Cenci, Marco Fermi, Cecilia Sciarretta

Telespazio S.p.A., Roma

Alessandro Caporali

Dipartimento di Fisica, Universita′ di Bari

Abstract

Instrumental resolution in laser ranging is still unmatched by dynamical models of the range data. But even if one had a "perfect" model of the observations, still the recovery of the station coordinates would depend on the data set and on the details of the estimation algorithm. It has become somewhat customary to judge a data set on the basis of the number of passes. We argue that this criterion is unreliable and may be misleading. We rather suggest that purely geometrical concepts, such us the dilution of precision, are much more reliable indicators of the "robustness" of a data set. The computational overhead is negligible even with the limited computing resources avalilable at a mobile site. We analyse the dilution of precision in a number of actual occupations of mobile sites during the Wegener 1987 campaign finding that 40-50 passes, if well distributed in the sky, are a lower limit for a data set, in the sense that the dilution of precision can still significantly decrease as more passes are added. Simulations are reported indicating that the determination of height with centimetric accuracy may require a substantially longer stay time.

INTRODUCTION

The intrinsic precision of Satellite Laser Ranging (SLR) measurements is only a necessary, certainly unsufficent condition for an accurate estimation of station coordinates, Earth rotation parameters and orbit perturbations. Especially when working with mobile stations, the analyst would like the data set be such that the station coordinates can, though not always will, be recovered with an accuracy matching the precision of the ranging data. It is very sad to discover "a posteriori" that a mobile station has acquired to few passes, or even too many, perhaps at the expenses of another scheduled site.

Although it is clearly impossible to full process the data in real time at the observing site, we think it should be possible to do at the station, in nearly real time, simple calculations which can at least give an idea if the acquired set of passes is adequate for the scientific analysis.

For these reasons we have done a number of occupation studies and developed means to quantify the information content of a data set for a given station. In the following we will examine two simple algorithms: one is based on the calculation of the Dilution of Precision (DOP), defined as the square root of the sum of the variances od the station coordinates of one station as a function of the set of passes. The larger the DOP, the weacker the geometry and viceversa. The second algorithm is based on a sequential correction of station coordinates and orbit (in the sense of range and time biases). Using simulated data, thus free of model errors, we shall examine the recovery of known coordinate offsets, as passes are sequentially acquired. In this connection we discuss on computationally simple algorithms, such as Kalman filters, to be used at the station for a "quick look" data analysis.

DOP, SKY COVERAGE AND STAY-TIME

Figures 1 and 2 (from Cenci et al., 1989) refer to the WEGENER 1987 campaign and give an excellent example of two limit situations. The Roumeli site has a peculiar sky coverage: nearly all passes are aligned in the same direction and most are at a low-mid elevation above the horizon. Had the effective number of passes be one half of that effectively tracked, the sky coverage would have become extremely poor (figure 1.b). Inspection of the plots in figure 1 leads to some simple but meaningful consideration. First, the tendency of the passes to have the same direction implies that only a linear combination of the station latitude and longitude can be recovered, not both separately. The estimated uncertainty of a positional correction in the direction of the pass will, in general, be lower than in the orthogonal direction. Thus a data set containing many passes (in this case 58), but nearly all in the same direction, will in general be poorer than a data set with fewer but more randomly oriented passes. The second consideration concerns the height of the station, which is best determined by zenithal passes. In our cases we note that doubling the number of passes (from one half to all) brings in the data set only one additional pass with elevation greater than 60 degrees and the total number of passes above this elevation is a modest five.

By contrast figure 2 indicates a far better sorted pass distribution over Dyonisos during the same 1987 Campaign. The full data set contains 152 passes. It is clear that the first third (figure 2.c) of these passes provides a considerably better geometry than the full data set (figure 1.a) for Roumeli. In summary, figures 1.a and 2.c contain the same number of passes and such number is -according to common belief- considered acceptable and sufficent. Yet our simple examples indicate that the two data sets are very different from each other as to their potential for unbiased and uncorrelated recovery of station coordinates. Figure 2 also indicates that tripling or doubling the data set at Dyonisos was not really worth the effort, as most ground tracks tend to repeat themselves, thus lowering the random noise but not removing systematics due to pass geometry. A longer occupation would instead have been beneficial to Roumeli, for reasons discussed above.

If the number of passes alone is by itself a not too reliable indicator of the "robustness" of the associated solution for station coordinates, we need some more informative parameter. We have identified the dilution of precision (DOP) as a better criterion than the pass number for assessing the geodetic potential of a data set for a given station. DOP is simply the square root of the trace of the variances of the station coordinates. Thus DOP is the factor by which the nominal precision of the ranging measurements is multiplied to obtain the 1 sigma spherical error. To compute the DOP one has to accumulate the partial derivatives of the range relative to the three coordinates, generate a 3x3 matrix by multiplication of a 3xn matrix of the partials and its transposed (n being the number of accumulated data points), invert the matrix and compute the square root of the trace. Although this calculation is not as immediate as counting the number of passes, it is a very straightforward by-product of the off-line software at the station and thus can be easily implemented and operated.

Figure 3 gives the plot of the DOP of each mobile WEGENER station in the 1987 Campaign as a function of the passes. The plots clearly indicate that the 40-50 passes figure only defines a minimum requirement for stay time, at least from the point of view of the formal error. It rather appears that a safer figure is 100 or more passes, a region where the DOP curve has lost most of its slope.

MONITORING SEQUENTIAL UPDATES OF STATION COORDINATES

The calculation of the dilution of precision outlined in the previous section is useful in the sense of an estimate of the formal error. It does not tell whether the solution for the station coordinates, as the passes are acquired, will eventually stabilize at an unbiased value. Even detatiled analyses using full-size kinematical and dynamical models of the range data cannot give an answer to such question with a confidence better than ± 5 rms (this is the typical noise of the post-fit range residuals, mostly systematic and with non zero mean on a pass-by-pass basis). This fact is simply a consequence of model uncertainties. However one can simulate range observations with a known model from a station with assigned coordinates, process the simulated data introducing known offsets in the station coordinates and orbit and monitor how the true coordinates and orbit biases are recovered, as passes are accumulated. Figures 4 and 5 show the result of such simulation where the range data have been simulated for the Matera station in the period March 1-31 1986. The simulated data have been processed assuming an offset of 30 mas (1 mas = 0".001) in latitude and longitude and 1 m in height, relative to the coordinates used to generate the simulated data. The LAGEOS ephemeris used in the analysis phase was time-biased of 1 msec relative to that used in data generation mode. The solve for parameter set consists of the three station coordinates, a range bias (no offset) and a time bias. All day and night time passes above 20 degrees elevation are used to estimate the solve for parameters using an adaptive Kalman filter, in the sense of Jazwinski (1970) (see also Schutz et al., 1975,1976 and Wakker and Ambrosius, 1982). The updated values of the parameters were back substituted every three hours.

Figures 4 and 5 depict the recovery of the five parameters.

Figure 4.a shows the convergence of the post-fit residuals to zero as the model parameters are sequentially updated. Figure 4.b indicates that the 1 msec time bias is almost immediately recognised by the filter and compensated to zero in a few days of tracking. Figure 5.a contains a comparison of the estimates of height and range bias. Initially the two quantities are strongly correlated, due to insufficent geometry. Then, as more passes are acquired, they decouple and converge to the known values of 0.00 m and 1.00 m for range bias and height respectively. Finally, figure 5.b shows the recovery of the known offsets (30 mas) in latitude and longitude. Note the greater "speed" of latitude convergence, due to the highly inclined LAGEOS orbit. Note also that latitude and longitude offsets can be recovered considerably faster than height. The 40-50 passes lower limit predicted by looking at the DOP is then confirmed for planar coordinates but appears marginal, in most cases unadequate, for the recovery of height.

CONCLUSION

The minimum data set for station positioning should contain at least 40-50 passes, yet a deeper analysis must be done to verify that the overall geometry is adequate. Having in mind the minimum stay time of a mobile laser station, we have investigated two types of calculations simple enough to be done off line on the local computer. One is the DOP, that is the geometrical scale factor for the formal error in position. The second is the sequential updating of the station coordinates using a simple Kalman filter and a five parameter model. This last approach in particular indicates that a reliable estimate of the height of the station will require about twice as many passes as those required for latitude and longitude .

ACKNOWLEDGEMENT

This research is supported by Agenzia Spaziale Italiana

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Shutz, B.E. and B.D. Tapley: Sensitivity Analysis of Short-Arc Station Coordinate Determinations From Range Data. The Journal of Astronautical Sciences, Vol. 24 n. 2, pp. 111-136, 1976.

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Figure captions

figure 1: sky coverage over Roumeli according to different partitions of the data set.

figure 2: same as figure 1 for the Dyonisos station.

figure 3: decrease of the formal error in positioning for various WEGENER 1987 sites occupied by mobile laser systems, as passes are acquired.

figure 4: range residuals (a) and time bias recovery (b) using simulated range data for a total of one month.

figure 5: recovery of height and range bias (a) and latitude and longitude (b) as LAGEOS passes are acquired.

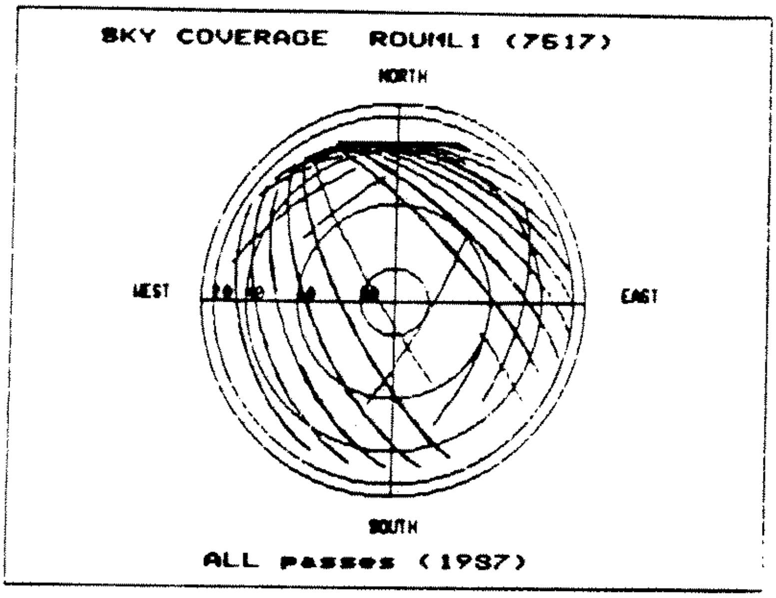


FIG. 1 /a

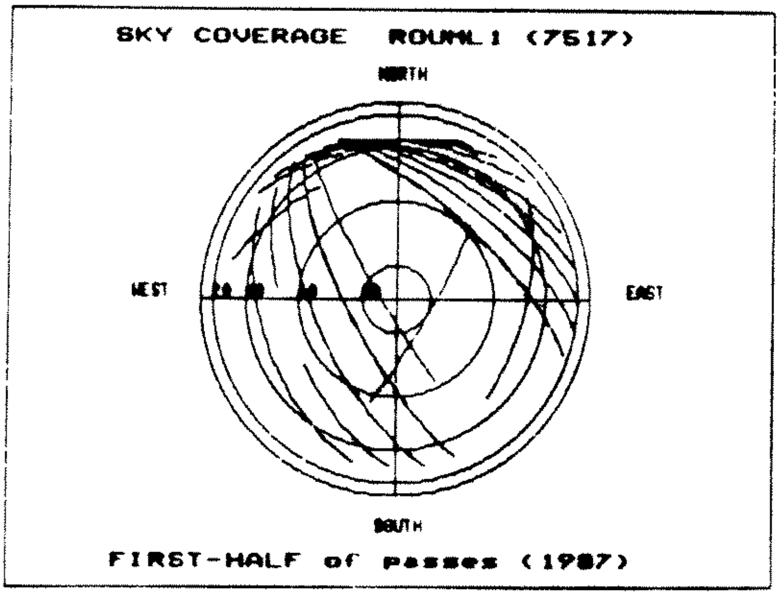


FIG. 1 /b

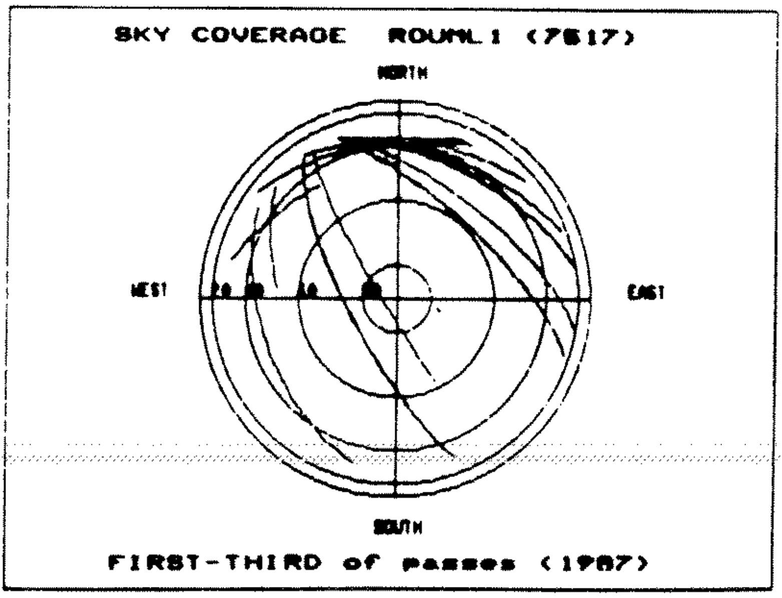


FIG. 1 /c

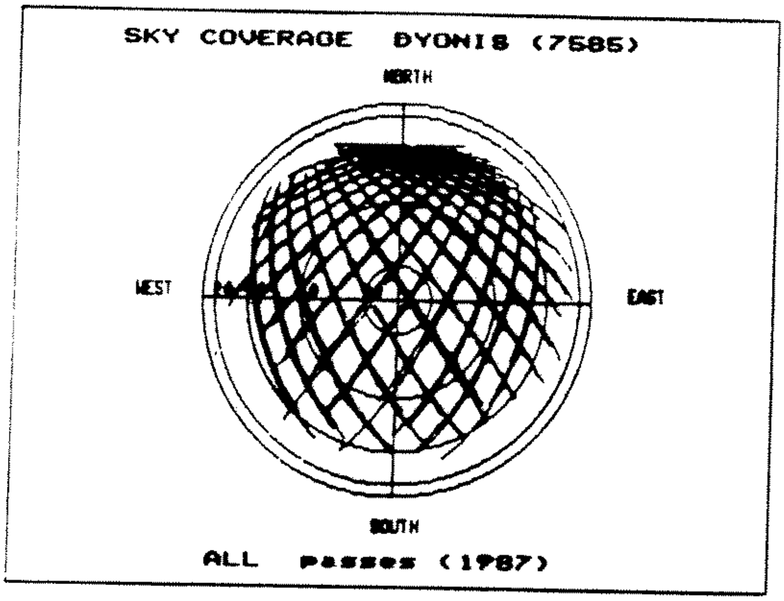


FIG. 2. /a

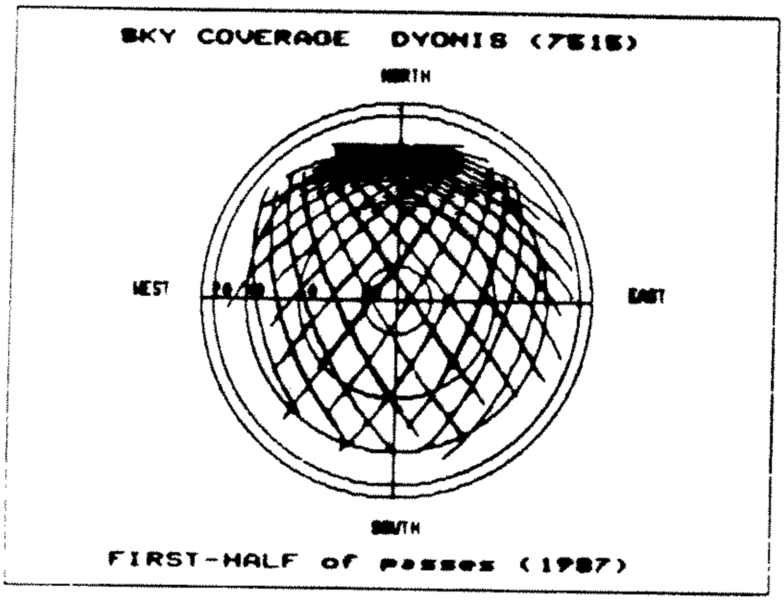


FIG. 2. /b

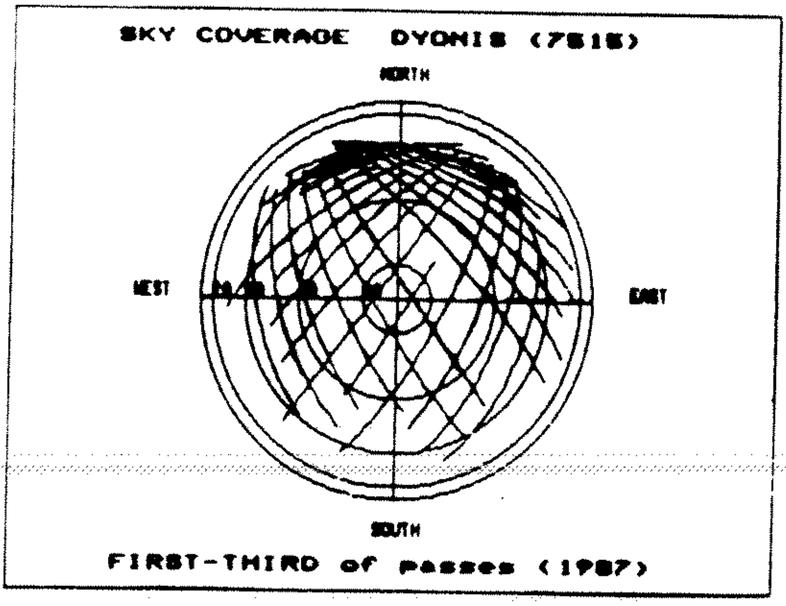
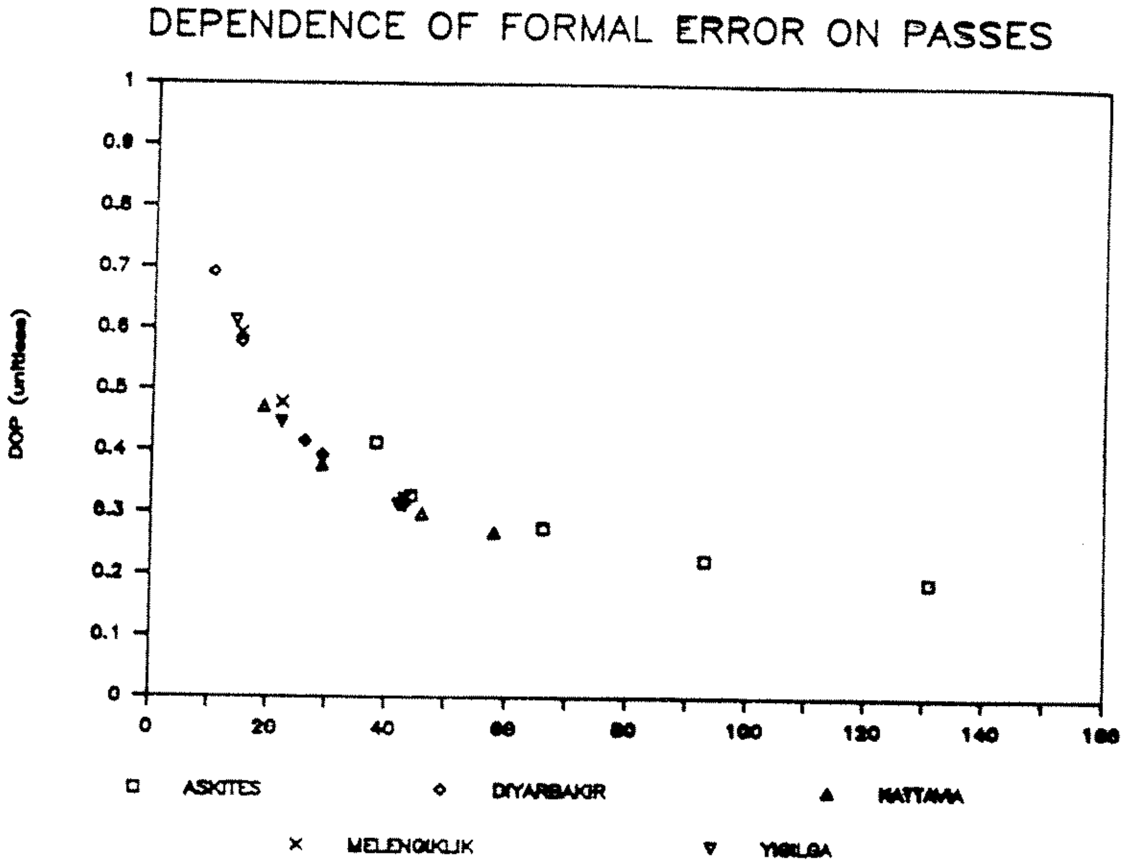
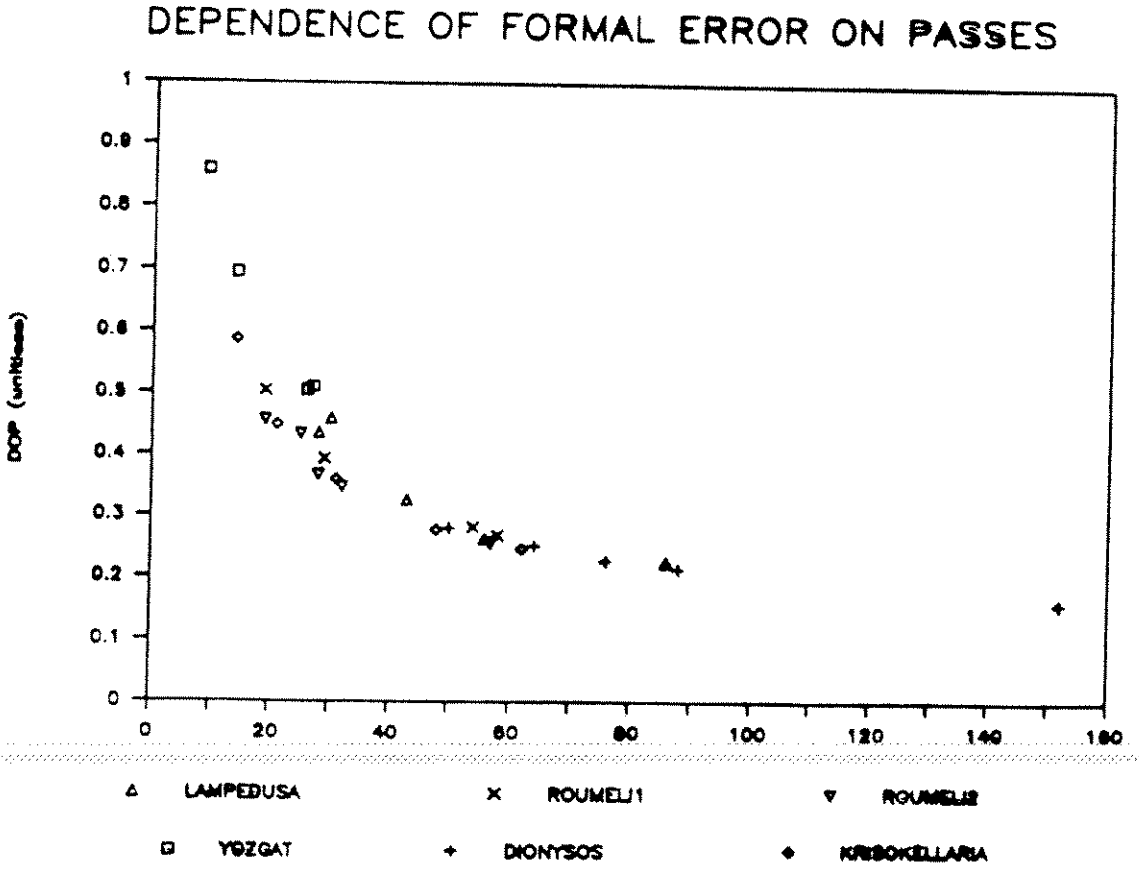


FIG. 2. /c

FIG. 3


DEPENDENCE OF FORMAL ERROR ON PASSES


DEPENDENCE OF FORMAL ERROR ON PASSES

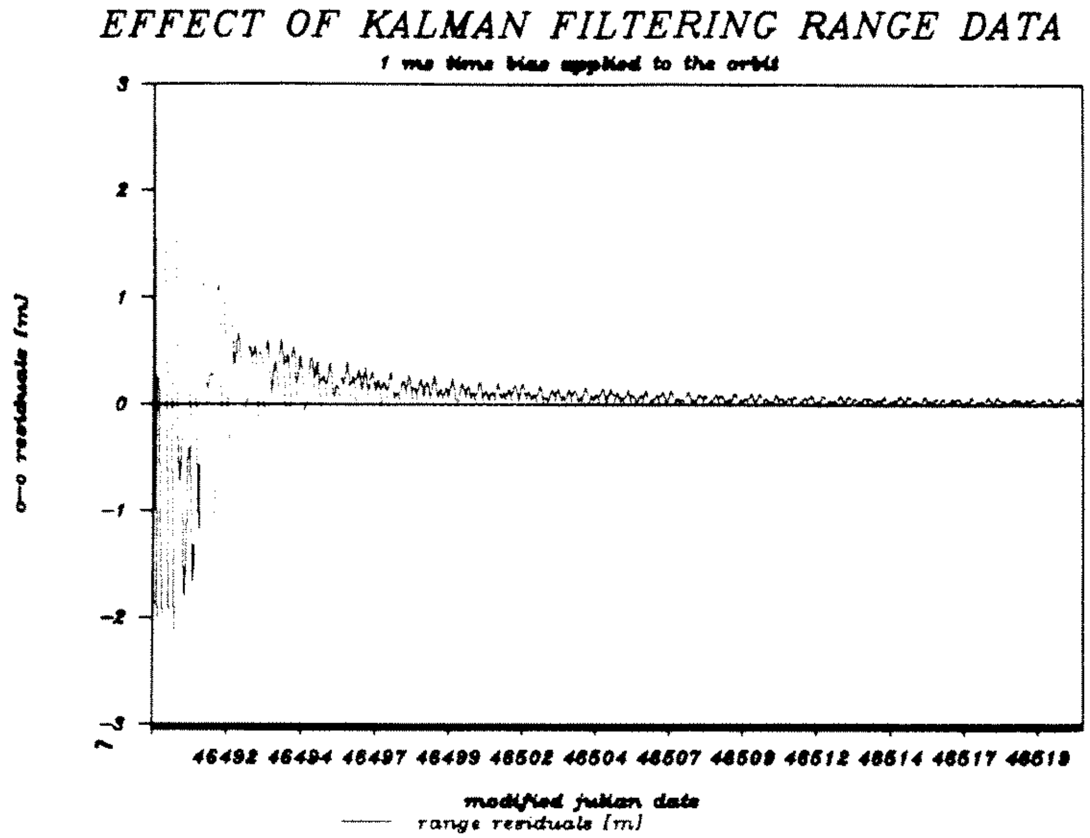

EFFECT OF KALMAN FILTERING RANGE DATA
1 ms time bias applied to the orbit
o-c residuals [m]
3
2
1
0
-1
-2
-3
46492 46494 46497 46499 46502 46504 46507 46509 46512 46514 46517 46519
modified julian date
range residuals [m]

FIG.4./a

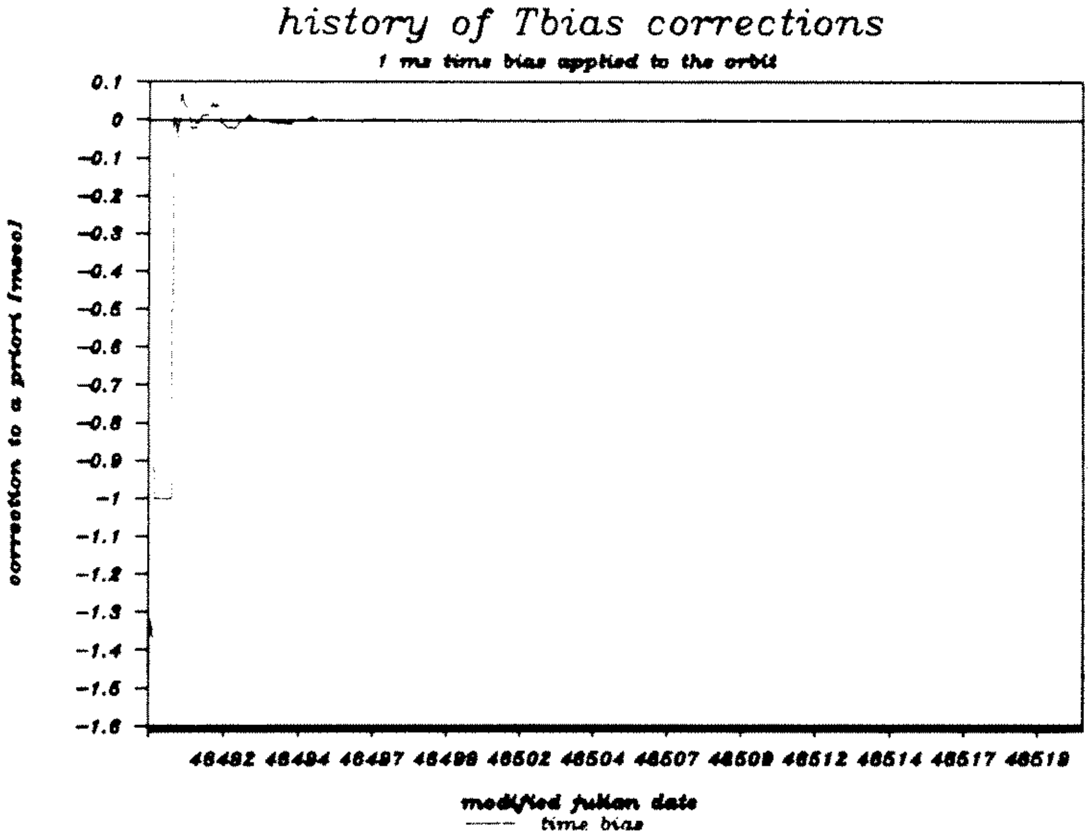

history of Tbias corrections
1 ms time bias applied to the orbit
correction to a priori [msec]
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
-0.9
-1
-1.1
-1.2
-1.3
-1.4
-1.5
-1.6
46492 46494 46497 46499 46502 46504 46507 46509 46512 46514 46517 46519
modified julian date
time bias

FIG.4/b

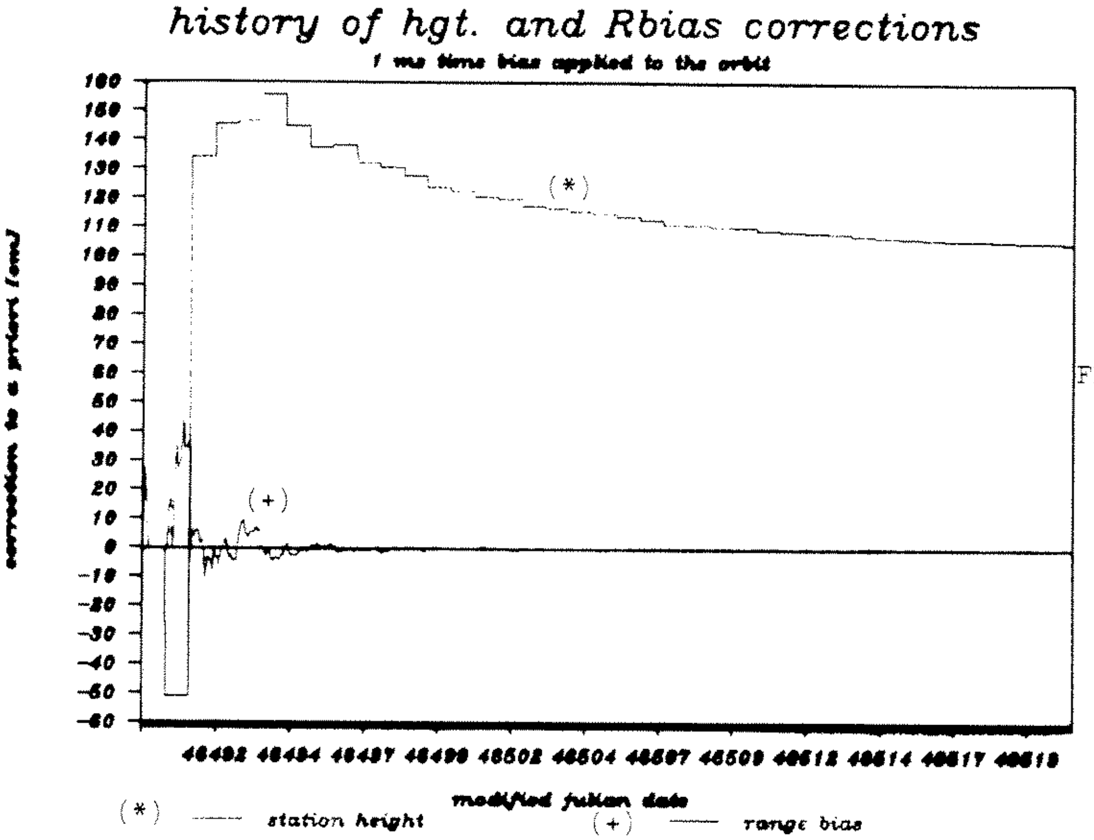

history of hgt. and Rbias corrections
1 ms time bias applied to the orbit
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
correction to a priori [cm]
(*)
(+)
48492 48494 48497 48499 48502 48504 48507 48509 48512 48514 48517 48519
modified julian date
(*) station height
(+) range bias

FIG.5/a

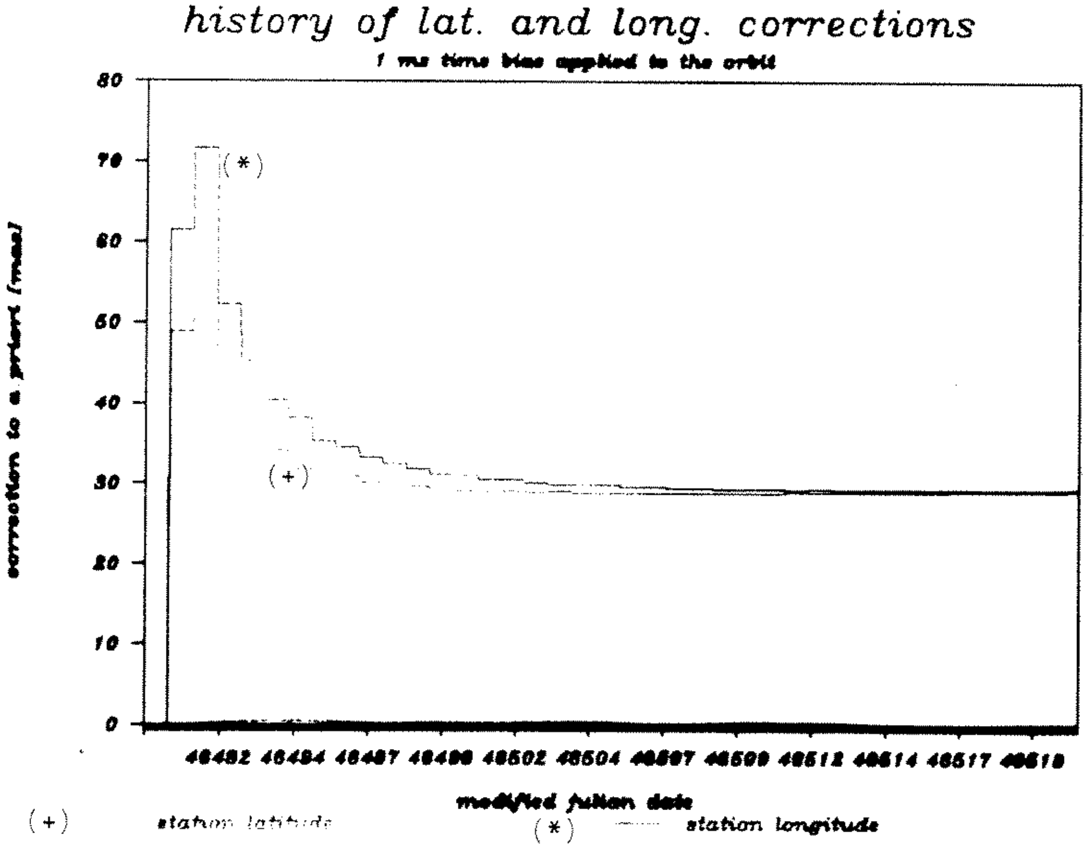

history of lat. and long. corrections
1 ms time bias applied to the orbit
80
70
60
50
40
30
20
10
0
correction to a priori [mas]
(*)
(+)
48482 48484 48487 48489 48502 48504 48507 48509 48512 48514 48517 48519
modified julian date
(+) station latitude
(*) station longitude

FIG.5/b

SOFTWARE OF BOROWIEC LASER RANGING STATION

S. Schillak, E. Butkiewicz, J.W. Offierski
Space Research Center of
Polish Academy of Sciences
Astronomical Latitude Observatory
Borowiec
62-035 Kornik - Poland -

Telephone 61-170187
Telex 4121623 aos pl

Abstract

The Satellite Laser Ranging Station at Borowiec is operating from May, 1988. The software system of the station is described. System is divided on four main parts; prediction, real time, data analysis and handling, and stars programs. It gives possibility for full blind tracking. Hardware that affects programming is outlined.

1. Introduction.

This paper describes BORLAS, satellite laser ranging software used at Astronomical Latitude Observatory in Borowiec. The system consist of several programs which run on minicomputer MERA-400. Minicomputer has 128k-16 bits words memory. The Real-time, Multitask, Multiuser SOM-3M operating system is used to execute the tasks. Programs have been written in FORTRAN-IV and Assembler. All programs and subroutines were written by Borowiec laser group. The programs are divided into catalogue type programs, real-time programs and programs used before and after satellite pass. Overall view of hardware of the system is shown in Fig.1. Description of the system is presented in the papers; Schillak, 1989, 1) and 2). Minicomputer MERA-400 is connected with the system through the PI interface.

Inputs to the computer:
- mount azimuth and altitude positions from encoders (±0°.0005),
- ranges from the time interval counter (±150 ps),
- epochs from laser clock (±1 μs),
- actual time (±1 ms).

Outputs from the computer:
- mount azimuth and altitude to motors,
- firing start to laser,
- range gate to time interval counter.

Software of the system is presented in Fig.2.

2. Catalogue programs.

a) KEL - orbital elements catalogue.
Program has the following commands for operations on the catalogue: read in orbital elements in SAO format from telex and write them into the disk to the elements file (once per week), calculate the matrix of long-periodic lunisolar and tidal perturbations for next 10 days and write them to elements file (once per week), list of head-lines of elements catalogue, delete elements set, display or print elements set, operations on subcatalogue of satellites.

b) KEF - ephemeris catalogue.
This program gives possibility to realize operations with scheduled head-lines and ephemeris file. The routine performs the following commands: list head-lines of schedule and ephemerides, delete ephemeris, display or print ephemeris with arbitrary step, calculate ephemeris for LASSO experiment.

c) KOB - observation catalogue.
This program is used for operations on observations data and pre-processing of the results. It has the following main commands: copy the results of the pass, initial filtering of the pass, plot residuals, input time correction of laser clock to UTC, list and delete head-lines, display of results of the

pass, display of residuals, eliminate erroneous points, operations on subcatalogue of stations.

d) KKA - calibration catalogue.
Program KKA is designed for operations on calibration file and its head-lines. The commands are similar to the KOB program and also perform operations described in KAL program.

e) LOG - reports catalogue.
The short program for displaying or printing of one page of the main parameters and additional information about the satellite pass.

f) KBO - clean range data catalogue.
This is special program for handling of the results of satellite passes. The head-lines and range data are written in the format which gives possibility for transformation to quick-look SAO format and MERIT-2 full rate format. The main commands of this program are as follows: write range data in the new format from observation file, calibration file and reports file, punch the telex tape in quick-look format, write to magnetic tape results in the full rate MERIT-2 format, write results to the observation file for use them by other Borowiec programs.

3. Prediction Programs.

a) PRO - schedule calculation program.
This routine calculates time of the beginning of satellite passes, maximum altitude, minimum range and duration of the pass for the introduced minimum satellite altitude of arbitrary station. It enables the setting-up of the daily passes or night passes only, including information about beginning and end of the Earth's shadow. Program have three modes of operation: 1) write all satellites to KEF catalogue on the disk in time order, 2) print all passes of one satellite (long-period schedule, once per half year), 3) print daily schedule for all satellites (once per week).

b) EFE - ephemerides calculation program.
Calculates for one second step azimuth, altitude and range from the KEF data up to 10 ephemerides and writes the results into the disk (once per day).
Program EFE performs the following operations:

- read in from KEF file previous data calculated by PRO program,
- calculate secular Earth gravitational field perturbations on the basis of elements set,
- calculate semi-major axis from the perturbed mean motion,
- calculate the matrix of short-periodic tesseral harmonics perturbations of the degree and order up to 6x6 for the entire pass (11 values),
- calculate long-periodic Earth gravitational field

perturbations on the basis of elements set,
- calculate short-periodic J_2 perturbations,
- interpolate luni-solar perturbations,
- interpolate the tesseral perturbations,
- calculate satellite rectangular coordinates,
- calculate station rectangular coordinates,
- calculate range, azimuth and altitude of a satellite,
- correct the altitude for refraction,
- write epochs, ranges, azimuths and altitudes into the disk in ephemeris file.

4. Real-Time Programs.

a) STE - main satellite tracking program.
Program performs the following sequences of operations, initial part:

- read ephemeris for a given pass from ephemeris file,
- display satellite tracking and calibration parameters for acceptance by operator, change the parameters if necessary,
- change azimuth and altitude to mount coordinates including mount model errors,
- read in weather parameters,
- start calibration subroutine,

*- read ephemeris point,

- display information about satellite pass,
- write range gate to the time interval counter,
- write mount position to motors and check it with mount position from encoders (100 ms before start),
- wait, if the current time is less than the prediction time.

Main loop:

- fire the laser,
- read mount position from encoders,
- read epoch from laser clock,
- read range from the time interval counter,
- calculate and display residuals and actual mount position,
- write epoch, range, azimuth and altitude to the observation file on the disk,
- check of the last point of ephemeris,

**- read next ephemeris point,

- compute cross correction if necessary,
- check of the pointing possibility to the next position (zenith part), if not go to **,
- calculate and write range gate to the time interval counter,
- write mount position to motors and check it with mount position from encoders (100 ms before start),
- read commands from keyboard,
- wait, if the current time is less than the prediction time.

The list of available commands for parameters change and control of the system work in the real-time cycle is as follows: start to fire laser, stop laser firing, input azimuth correction, input altitude correction, input cross correction, input epoch correction (up to 30 sec), input new repetition rate (max. 1Hz), input new range gate window, wait for operator decision (the next start will be 20 sec after operator's command from the point designed by *), absolute end of the pass.

The last part of the program STE:

- write head-line of the pass to the disk,
- read in weather parameters,
- start calibration subroutine,
- write parameters and information about the pass to the LOG file.

b) KAL - calibration program.
Program performs up to 10 calibrations to the ground targets. Program KAL has similar main loop as STE routine. Loop is realized up to the moment when assumed number of good measurements is obtained. The same commands are also available from keyboard without corrections in mount position and time, but with possibility to change the number of shots and value of system delay.
After calibration program performs the following operations: calculate the mean calibration and its standard deviation, display histogram of residuals, eliminate erroneous points, calculate calibration correction, write additional data to the head line of calibration file.

c) MON - mount pointing program.
This program drives the mount under computer control. Program includes mount model errors. It has several main modes of operation: pointing to ground target No 1 (1295.42 m), pointing to ground target No 2 (302.90 m), pointing to the under roof position, directs the mount to the input azimuth and altitude position, changes position of the mount for arbitrary step in azimuth and altitude.

5. Data Analysis Programs.

a) FIT - main filtering program.
This program is used when number of noise points is bigger than normally. It gives the possibility to reject erroneous points in the range of ±50 cm from residuals curve (Offierski, 1986, 2)).

b) EPA - data analysis program (Schillak, 1982).
The routine EPA is used after satellite pass for data processing. Program performs the following sequences of operations: read in of data set from observation file, calculate time bias and range bias, plot the residuals, compute polynomial fit and standard deviation of the pass, display histogram of residuals, eliminate erroneous points, write accepted results to the observation file.

6. Star Programs.

a) ROZ - distribution of stars.
Program calculates azimuth and altitude of stars from STAR catalogue (300 stars from FK-4 catalogue). Stars are distributed in four ranges of azimuth and eight ranges of altitude. This program is used for control of the mount pointing and mount model errors determination. The accuracy of star position is about 1 arcsec.

b) MOD - determination of mount model errors.
Program is used for mount model parameters determination immediately after stars observations. From readings of the positions of the mount and computations of azimuth and altitude, 7 parameters are calculated by the iteration, using least squares method. Accuracy of the mount position after including this parameters is equal to ±10 arcsec. Program determines the following parameters: correction of azimuth zero point, correction of altitude zero point, tilt of basic plane x and y, inclination of altitude axis, flexure of the telescope tube, collimation of optical axis.

7. Conclusions.

After two years of systematical satellite ranging the BORLAS software system described above showed very good usefulness in practice and easy for operators. In connection with future planned third generation system, real-time programs will be changed to the new multi-processor system. Other programs will be rewritten for IBM PC/AT microcomputer in C language but idea of the system will be this same.

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Schillak S., E. Butkiewicz, J. Offierski, 1989, 2),"Borowiec Laser Ranging System", Observations of Artificial Earth Satellites, preprint (Presented at the 18th Intercosmos Symposium "Use of Artificial Satellite Observations for Geodesy and Geophysics", June 12-17, 1989, Cracow, Poland).

BOROWIEC
LASER
RANGING
SYSTEM

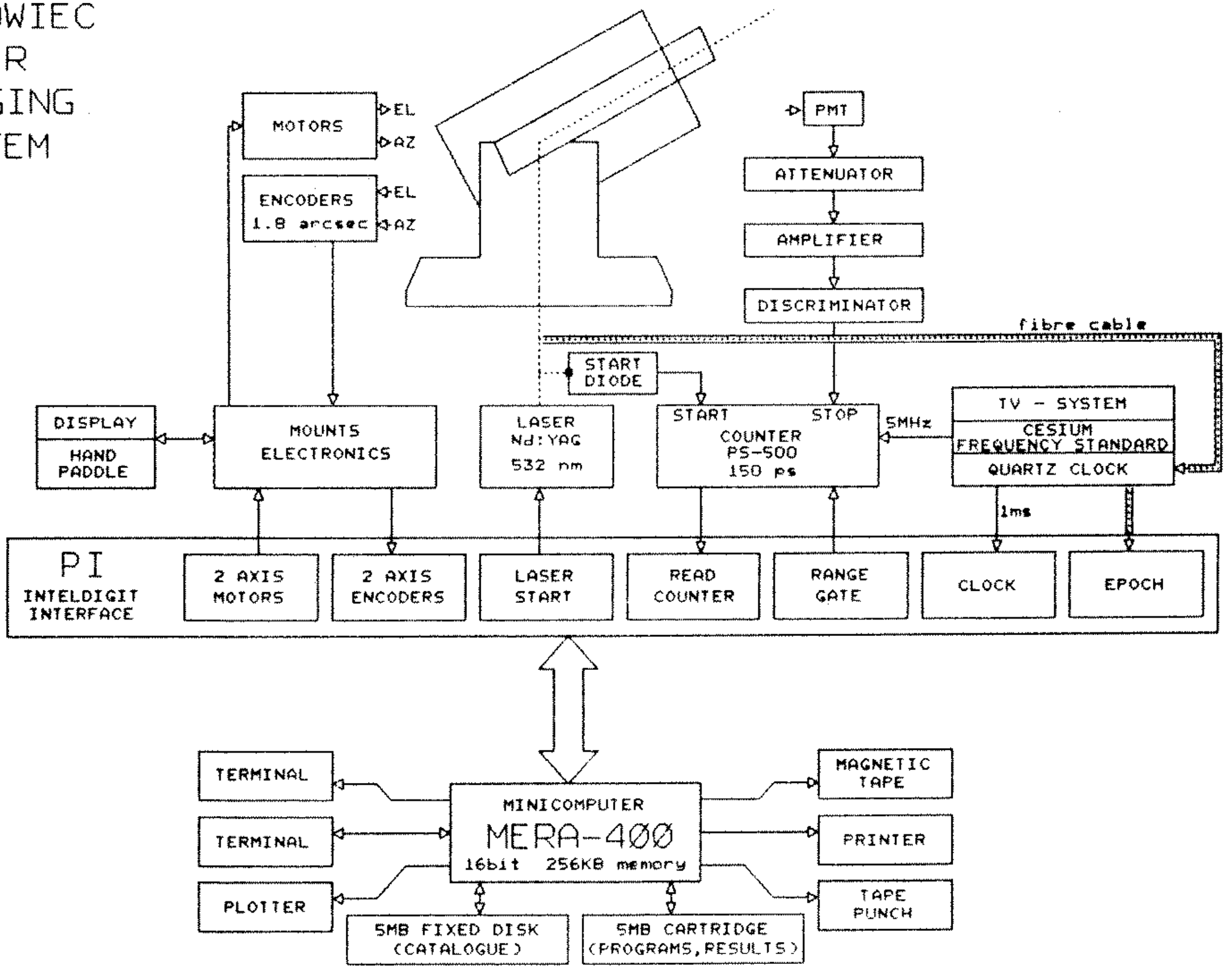

Fig.1

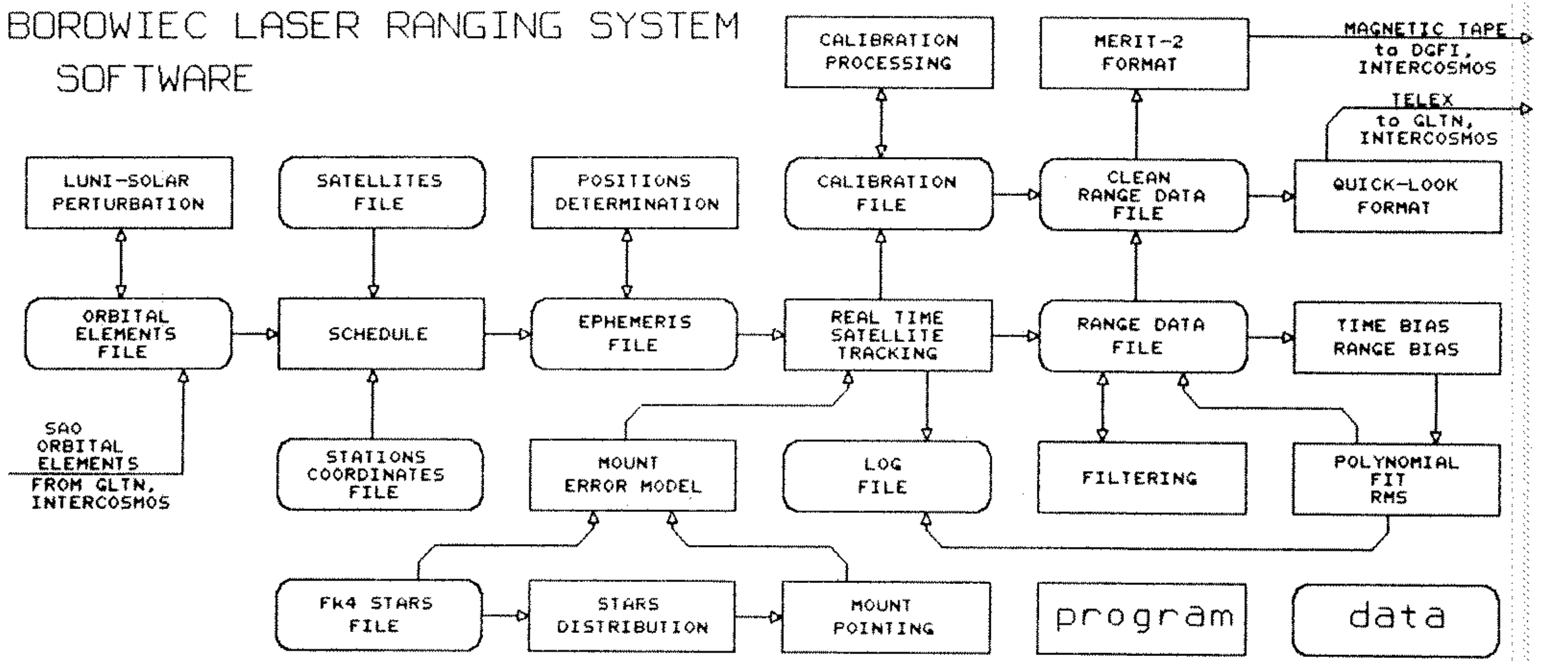
BOROWIEC LASER RANGING SYSTEM
SOFTWARE
LUNI-SOLAR PERTURBATION
SATELLITES FILE
POSITIONS DETERMINATION
CALIBRATION PROCESSING
MERIT-2 FORMAT
MAGNETIC TAPE to DGFI, INTERCOSMOS
TELEX to GLTN, INTERCOSMOS
CALIBRATION FILE
CLEAN RANGE DATA FILE
QUICK-LOOK FORMAT
ORBITAL ELEMENTS FILE
SCHEDULE
EPHEMERIS FILE
REAL TIME SATELLITE TRACKING
RANGE DATA FILE
TIME BIAS RANGE BIAS
SAO ORBITAL ELEMENTS FROM GLTN, INTERCOSMOS
STATIONS COORDINATES FILE
MOUNT ERROR MODEL
LOG FILE
FILTERING
POLYNOMIAL FIT RMS
FK4 STARS FILE
STARS DISTRIBUTION
MOUNT POINTING
program
data

Fig.2

Predictions for ERS-1

Rolf König
Deutsches Geodätisches Forschungsinstitut, Abt.I (DGFI)
Marstallplatz 8
D-8000 München 22

presented at the
7th International Workshop on Laser Ranging Instrumentation
October 2-6, 1989
Matera, Italy

Abstract

For the ERS-1 mission, orbit predictions shall be forwarded to the Laser tracking stations and to the PRARE system as well. Form and generation of the predictions are described. Also attention is paid to the accuracy of the various types of predictions.

1. Introduction

ERS-1 is the first European Remote Sensing satellite to be launched in December 1990. It will carry a radar altimeter, the PRARE (Precise Range and Range Rate Equipment) space segment (*WILMES, H., REIGBER, Ch.*, 1987) and a Laser retroreflector among other instruments. The primary tracking system for precise orbit determination will be the ground-based Laser tracking systems. Additional tracking will be performed by the PRARE experiment. To support the tracking activities, the D-PAF (German Processing and Archiving Facility, DGFI being part of it and responsible for precise orbit, altimeter products and the PRARE products) will provide the SLR (Satellite Laser Ranging) stations and the PRARE system with predictions of the orbit of ERS-1.

2. Form of Predictions

The generation of orbit predictions will take place daily. For the SLR sites IRVs (Inter-Range Vectors) and SAO (Smithsonian Astrophysical Observatory) elements are produced, for the PRARE system PRARE elements. IRVs (format see f.i. *VERMAAT, E.*, 1985) are positions and velocities in the pseudo body-fixed reference frame. The SAO elements (*PEARLMAN, M. R. et.al.*, 1979) are composed of Brouwer mean elements, their secular rates of change and coefficients of long period terms in the modified equatorial reference frame (*VEIS, G.*, 1963). The D-PAF offers diverse communication links for data distribution such as Telex, MARK III, SPAN or X.25 Network (*MÜLLER, H.*, 1989). The process of generating orbit predictions is schematically shown in Fig.1.

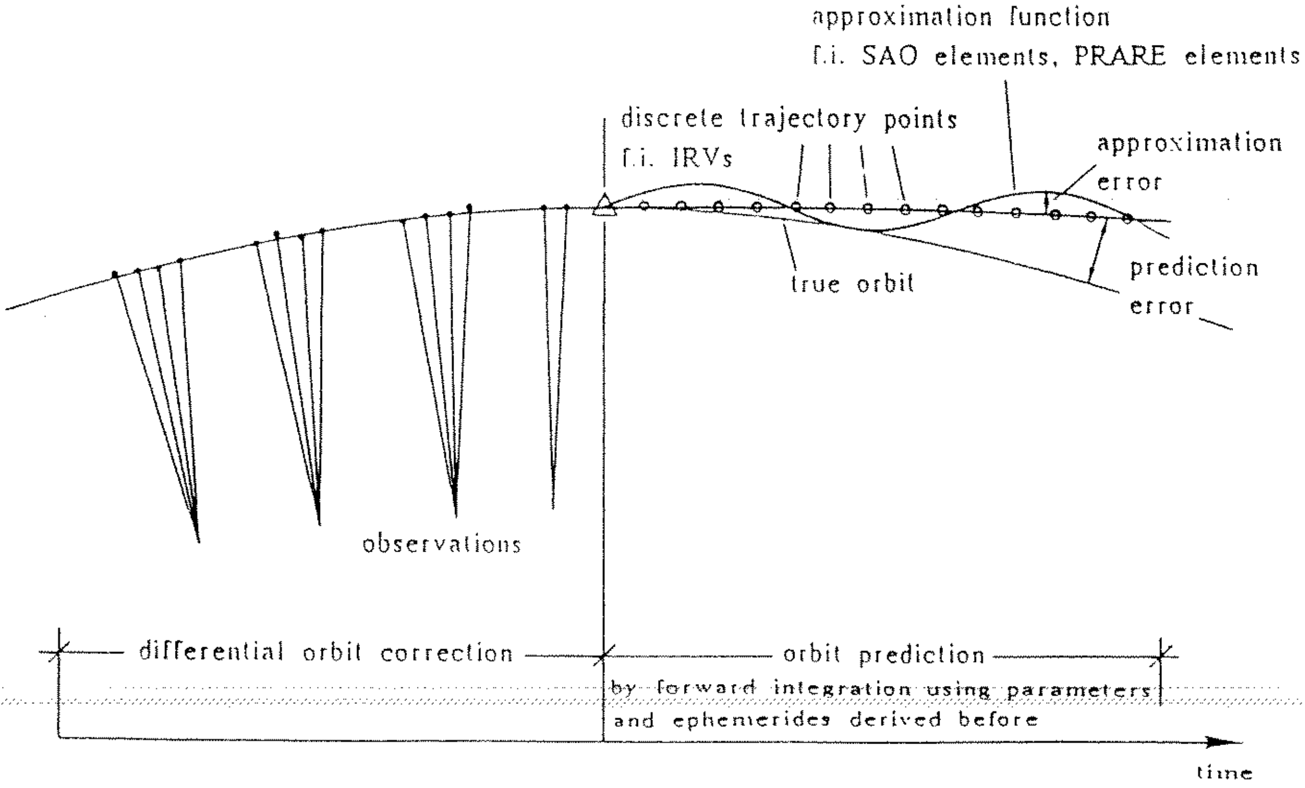

Figure 1 Generation of orbit predictions

The result of the orbit prediction is a set of state vectors (positions and velocities), in this case minutely spaced and given in the true equatorial reference frame. In order to get IRVs, three-hourly spaced states are selected and transformed to the pseudo body-fixed reference frame.

For the SAO elements all states of the prediciton period are transformed into the modified equatorial reference frame and converted into Kepler elements. From these osculating elements Brouwer mean elements, secular rates of change and long period effects are determined (*BROUWER, D.*, 1959; *LYDDANE, R.H.*,1963). Then a least squares solution is used yielding one prediction set only.

The idea underlying the PRARE element set is quite similar to that of the SAO elements. That is to get a short message valid over a certain period. The states are converted into the Keplerian typ elements a, $e\times\cos\nu$, $e\times\sin\nu$, i, Ω and $\omega+\nu$, where a stands for semimajor axis, e for eccentricity, ν for true anomaly, i for inclination, Ω for longitude of ascending node and ω for argument of perigee. Also a least squares solution follows leading to the coefficients of a dedicated approximation function.

3. Generating the Prediction Message

3.1 Least squares solution for SAO elements

For input to the least squares procedure several observations are available:

$$a_{0_i},\ e_{0_i},\ i_{0_i},\ \omega_{0_i},\ \Omega_{0_i},\ M_{0_i};\quad \dot{\omega}_i,\ \dot{\Omega}_i,\ n_i;\quad \delta e_i,\ \delta i_i,\ \delta\omega_i,\ \delta\Omega_i,\ \delta M_i,$$

where M is mean anomaly. Index 0 refers to Brouwer mean elements, $\dot{\omega}$ and $\dot{\Omega}$ are secular changes of perigee and node, n is the mean motion and δ indicates long period effects. All of these quantities are derived using Brouwer's theory. Index i covers the number of all states of the prediction period.

The SAO element message consists of the set

$$\omega_0,\ \dot{\omega},\ \Omega_0,\ \dot{\Omega},\ i_0,\ e_0,\ M_0,\ n,\ \dot{n},\ \ddot{n};$$

$$B_{1,k}(\delta\xi),\ B_{2,k}(\delta\Omega),\ B_{3,k}(\delta i),\ B_{4,k}(\delta\eta),\ B_{5,k}(\delta\chi);\ k=1,3;\ \Delta\eta_0,$$

where the $B_{m,k}$ are the coefficients of harmonic functions modelling long period perturbations. The nonsingular Keplerian type element set is

$$\xi = e\times\cos\omega,\ \eta = e\times\sin\omega,\ \chi = \omega+M;$$

with the first order approximations

$$\delta\xi = \delta e\times\cos\omega,\ \delta\eta = \delta e\times\sin\omega,\ \delta\chi = \delta\omega+\delta M.$$

The applied solution can be seen from the observation equations where the dashed lines indicate separate adjustment problems:

$$e_{0_i} + v_{e_{0_i}} = e_0$$

$$i_{0_i} + v_{i_{0_i}} = i_0$$

$$\begin{aligned} \Omega_{0_i} + v_{\Omega_{0_i}} &= \Omega_0 + t_i \dot{\Omega} \\ \dot{\Omega}_i + v_{\dot{\Omega}_i} &= \dot{\Omega} \end{aligned}$$

$$\begin{aligned} \chi_{0_i} + v_{\chi_{0_i}} &= \chi_0 + t_i \dot{M} + t_i \dot{\omega} + t_i^2 \dot{n} + t_i^3 \ddot{n} \\ \dot{M}_{0_i} + v_{\dot{M}_{0_i}} &= \dot{M} \\ \dot{\omega}_{0_i} + v_{\dot{\omega}_{0_i}} &= \dot{\omega} \end{aligned}$$

$$\begin{aligned} \delta\xi_i + v_{\delta\xi_i} &= B_{1,1} \times \cos\omega + B_{1,2} \times \sin 2\omega + B_{1,3} \times \cos 3\omega \\ \delta\Omega_i + v_{\delta\Omega_i} &= B_{2,1} \times \cos\omega + B_{2,2} \times \sin 2\omega + B_{2,3} \times \cos 3\omega \\ \delta i_i + v_{\delta i_i} &= B_{3,1} \times \sin\omega + B_{3,2} \times \cos 2\omega + B_{3,3} \times \sin 3\omega \\ \delta\eta_i + v_{\delta\eta_i} &= B_{4,1} \times \sin\omega + B_{4,2} \times \cos 2\omega + B_{4,3} \times \sin 3\omega + \Delta\eta_0 \\ \delta\chi_i + v_{\delta\chi_i} &= B_{5,1} \times \cos\omega + B_{5,2} \times \sin 2\omega + B_{5,3} \times \cos 3\omega \end{aligned}$$

3.2 Least Squares Solution for PRARE Elements

Following observations are available for input:

$$a_i,\ \xi_i,\ \eta_i,\ i_i,\ \Omega_i,\ \chi_i,$$

where

$$\xi = e \times \cos v,\ \eta = e \times \sin v,\ \chi = \omega + v.$$

For the PRARE prediction message a solution for the coefficients of a special approximation function is needed. The type of this function can be seen from the observations equations:

$$\begin{aligned} a_i + v_{a_i} = a_0 + t_i \dot{a} &+ \cos(\chi_0 + t_i \chi)\, c_{1\,rev} + \sin(\chi_0 + t_i \chi)\, d_{1\,rev} \\ &+ \cos 2(\chi_0 + t_i \dot{\chi})\, c_{2\,rev} + \sin 2(\chi_0 + t_i \dot{\chi})\, d_{2\,rev} \\ &+ \cos(t_i \omega_e)\, c_{1\vartheta} + \sin(t_i \omega_e)\, d_{1\vartheta} \\ &+ \cos 2(t_i \omega_e)\, c_{2\vartheta} + \sin 2(t_i \omega_e)\, d_{2\vartheta} \end{aligned}$$

$$\xi_i + v_{\xi_i} = \xi_0 + t_i \dot{\xi} + \cos \ldots$$

$$\chi_i + \ldots ,$$

where:

ω_e ... earth rotation rate.

The c and d coefficients are equivalent to phase and amplitude of the adjacent harmonic terms. In contrast to the SAO elements the PRARE set mainly models short period effects.

4. Accuracy

4.1 Requirements

One criterion used for the accuracy of orbit predictions for Laser tracking is the maximum beam divergence of the SLR system. For instance, in case of ERS-1:

	max. position error:
new Wettzell Laser: max. 30 arcsec	60 m,
old Wettzell Laser: max. 50 arcsec	100 m.

For PRARE the demands into position accuracy of the orbit predictions are less stringent and are related to two limiting criteria:

criterion:	max. position error:
antenna pointing 0.5 deg	3500 m,
doppler shifted frequency 1000 Hz	3000 m.

The accuracy of the different prediction messages varies. The accuracy of IRVs is simply that of the predicted orbit. In case of SAO elements and PRARE elements the accuracy of the approximation has an additional impact.

4.2 Accuracy of Predicted Orbit

In order to estimate the accuracy of predicted orbits, a differential orbit correction was applied to a STARLETTE arc, 1980, with 10 days of Laser range observations. This orbit was considered to be the reference orbit. A comparision with a orbit computed from the first 5 observation days only and predicted 5 days ahead yielded a loss of accuracy in position of ~10 m/d.

Covariance analyses and simulations for ERS-1, 3 day repeat cycle (*WILMES, H. et.al., 1984*) yielded a similar result of ~15 m/d. The conclusion for Laser tracking is that if the position error would totally be distributed across-track direction the valid period of the predictions can be 4 days. Infact normally the major part of the position error is an along-track error. So for the initial phase of the ERS-1 lifetime the predictions shall be distributed twice a week. As soon as the valid period is confirmed to be longer the interval of distribution can be increased. On the other hand ERS-1 is a frequently manoeuvred spacecraft and in turn additional messages will be distributed.

4.3 Accuracy of Approximation

4.3.1 SAO Elements

The least squares adjustment results in a set of parameters and their standard deviations. Table 1 compiles the standard deviations of the Kepler elements for different orbits for a fit span of three days. The standard deviations of radial, along- and cross-track direction and for position are derived by error propagation.

	s_a	s_i	s_Ω	s_ω	s_M	s_r	s_l	s_z	$s_{Position}$
	(m)	(arcsec)				(m)			
STARLETTE	1.55	0.1	0.2	5.2	5.2	4.13	272.40	6.49	273
ERS-1 3drc	1.44	0.2	0.1	5.2	5.2	1.44	255.06	7.74	256
35drc	1.45	0.2	0.1	5.2	5.2	1.45	255.04	7.73	256
176drc	1.44	0.2	0.1	5.2	5.2	1.44	255.13	7.74	256

Table 1 Standard deviations of SAO elements

The SAO element set of the STARLETTE arc was then passed to the AIMTWO program (a modified AIMLASER version; AIMLASER being a standard station prediction software). The long period terms (anyway not reliable from a three days estimation) were set to zero, except $\Delta\eta_0$ got a proper value. For 10 ficticious stations, 4 at equator, 3 at 45deg north and 3 at 45deg south the program delivered a statistically sufficient number of states. The comparision of positions to the original ones yielded a RMS of 249m, in good agreement to the above error propagation. A least squares fit can then be used to correct the SAO element set from these position differences. So with the corrected SAO element set (dedicated to a special type of orbit error model) the position RMS reduces to 25m.

4.3.2 PRARE Elements

Various orbits were recovered from the PRARE element set and compared to the original orbits. Results are compiled in Table 2.

	position errors over 3 days (m)		required	
	max	RMS	for PRARE	for Laser
STARLETTE	810	340	-	70
ERS-1 3drc	780	320	3000	60
35drc	750	330	3000	60
176drc	740	320	3000	60
LAGEOS	280	110	-	430

Table 2 Accuracy of orbit recovery

4.4 Transformations

Transformation of prediction reference frames to the terrestrial reference frame are essential for steering the Laser system. Table 3 summarizes the formulas for rotation of the respective orthonormal base vectors. It also includes some assessments of position errors caused by omitting certain rotations.

1)

$|UT1-UTC| < 0.7$ s
Omission for ERS-1: < 40 m

2) Pseudo body-fixed to terrestrial
$e_{T_0} = R_2(-x_p)\, R_1(-y_p)\, e_P$:

$|x_p| < 0.3$ arcsec, $|y_p| < 0.6$ arcsec
Omission for ERS-1: < 3 m

3) Modified equatorial to terrestrial
$e_{T_0} = R_2(-x_p)\, R_1(-y_p)\, R_3(\hat{\Theta})\, e_O$ with: $\hat{\Theta} = \Theta - \zeta_A - z_A - \Delta\mu$
$|\zeta_A + z_A + \Delta\mu| < 2000$ arcsec until 1994
Omission for ERS-1: < 7.8 km

4) True equatorial to terrestrial
$e_{T_0} = R_2(-x_p)\, R_1(-y_p)\, R_3(\Theta)\, e_t$

Table 3 Rotations and neglects

5. Conclusions

Orbit predictions for the ERS-1 mission will be generated by D-PAF and distributed to the participating SLR stations and to the PRARE system. The prediction message for Lasers will be given in IRVs and SAO elements, and for PRARE a special set of PRARE elements is chosen. The accuracy of IRVs decreases by about 15m/d in position. Accuracy of SAO elements is approximately 260m in along-track direction, 8m cross-track and 2m radial. The corrected SAO element set for use with AIMLASER type programs shows an approximation accuracy of better than 30m in position. By getting the predictions twice a week the Laser stations should be able to track ERS-1. Also the accuracy of the PRARE predictions is safely above what is required by the PRARE system.

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THE TIME AND FREQUENCY SYSTEM
AT THE MATERA SPACE GEODESY CENTER

A. Cenci, L. Garramone
Telespazio S.p.A.
Rome - Italy

G.Bianco, B.Pernice, G.Sylos Labini
ASI, Space Geodesy Center
Matera - Italy

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Workshop on Laser Ranging Instrumentation
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Tab.1

THE TIME AND FREQUENCY SYSTEM AT MATERA

REQUIREMENTS

High **short-term** frequency **stability** ($<1\times10^{-15}$ t=1000 s) is requested for the **frequency syntesis** and phase delay **calibration** for Very Long Baseline Interferometry (**VLBI**).

High **long-term** frequency **stability** ($<1\times10^{-12}$ t>1 day) and accurate **time synchronization** (<0.5 μs to UTC) are requested to generate the time scale for the **datation** of the Satellite Laser Ranging (**SLR**) measurements.

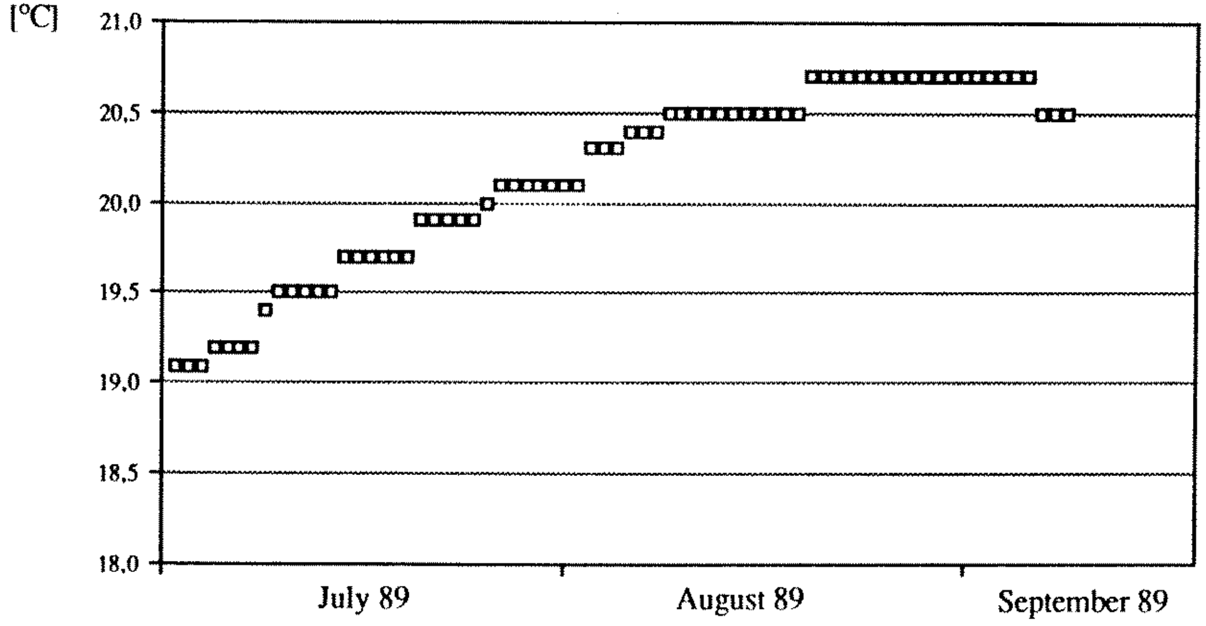
GENERAL CHARACTERISTICS

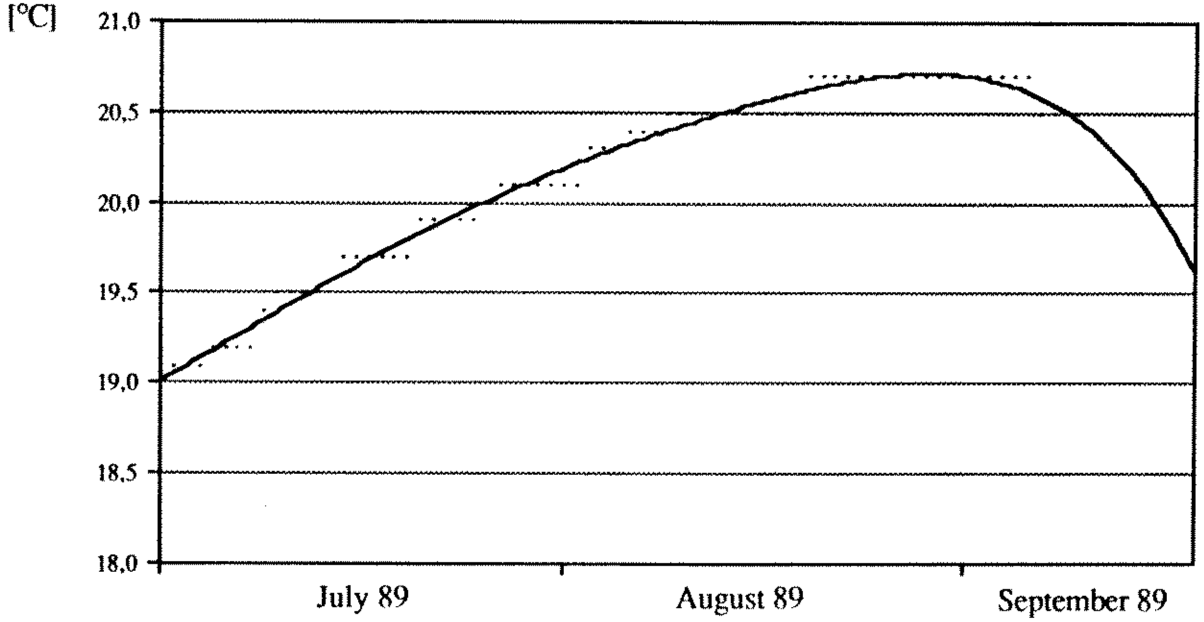
- one **H-MASER** frequency standard;
- two **CESIUM** beam frequency standards;
- one **GPS** time receiver + LORAN-C and TV-SYNC receivers;
- **three independent time-scales** (+GPS);
- **automated** monitor and control system;
- absolute **continuity** of operations;
- **environment-controlled room** to host the frequency standards.

TECHNICAL CHARACTERISTICS

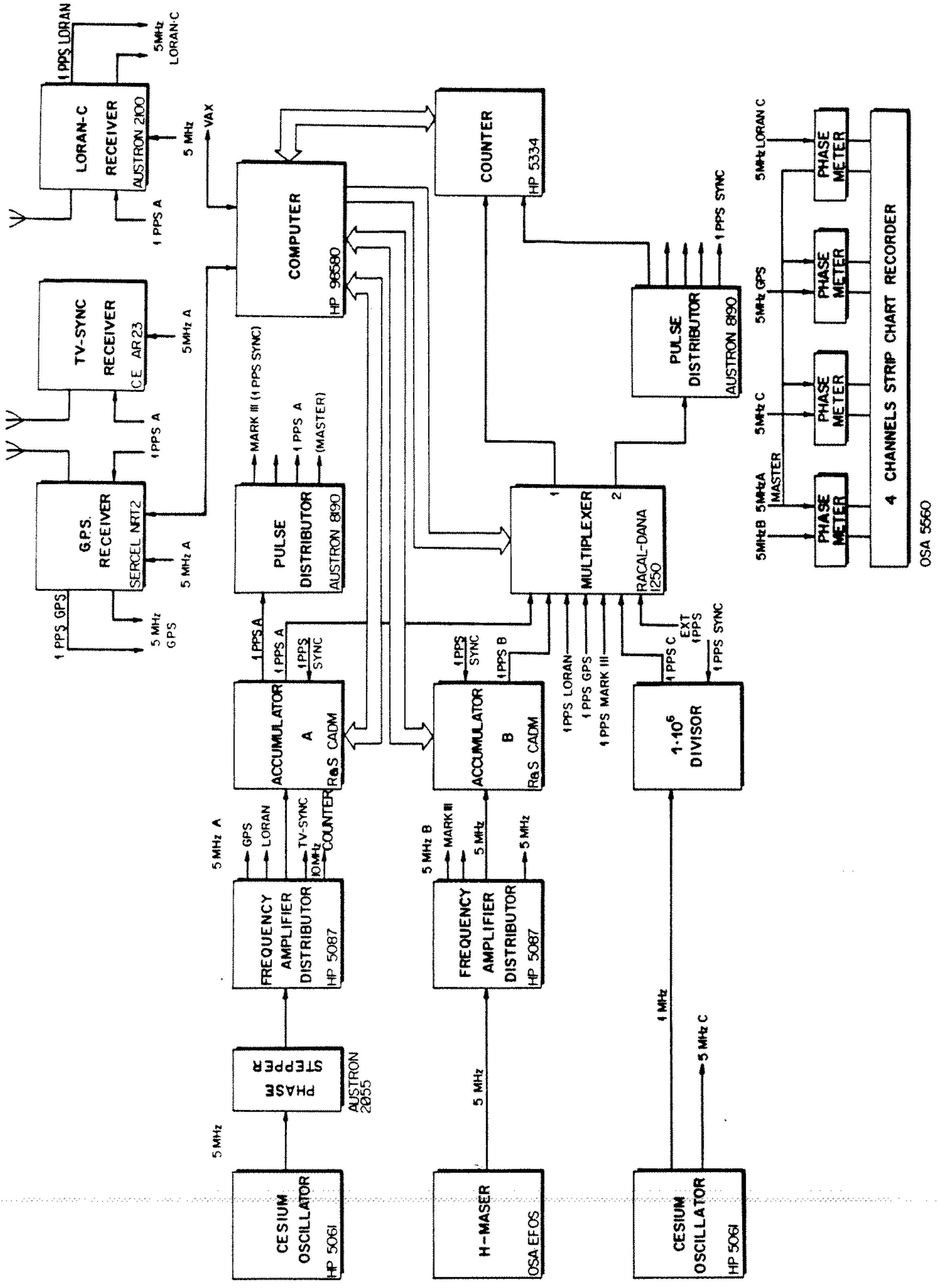
- **frequency stability** ($\Delta f/f$, t=1000s)	< **2x10^{-15}**	(H-MASER)
- **spectral purity**	> **110 dB**	(1 Hz)
- **time stability** ($\Delta t/t$, t>1 day)	< **5x10^{-13}**	(CESIUM)
- **synchronization** (UTC)	< **100 ns**	(GPS)

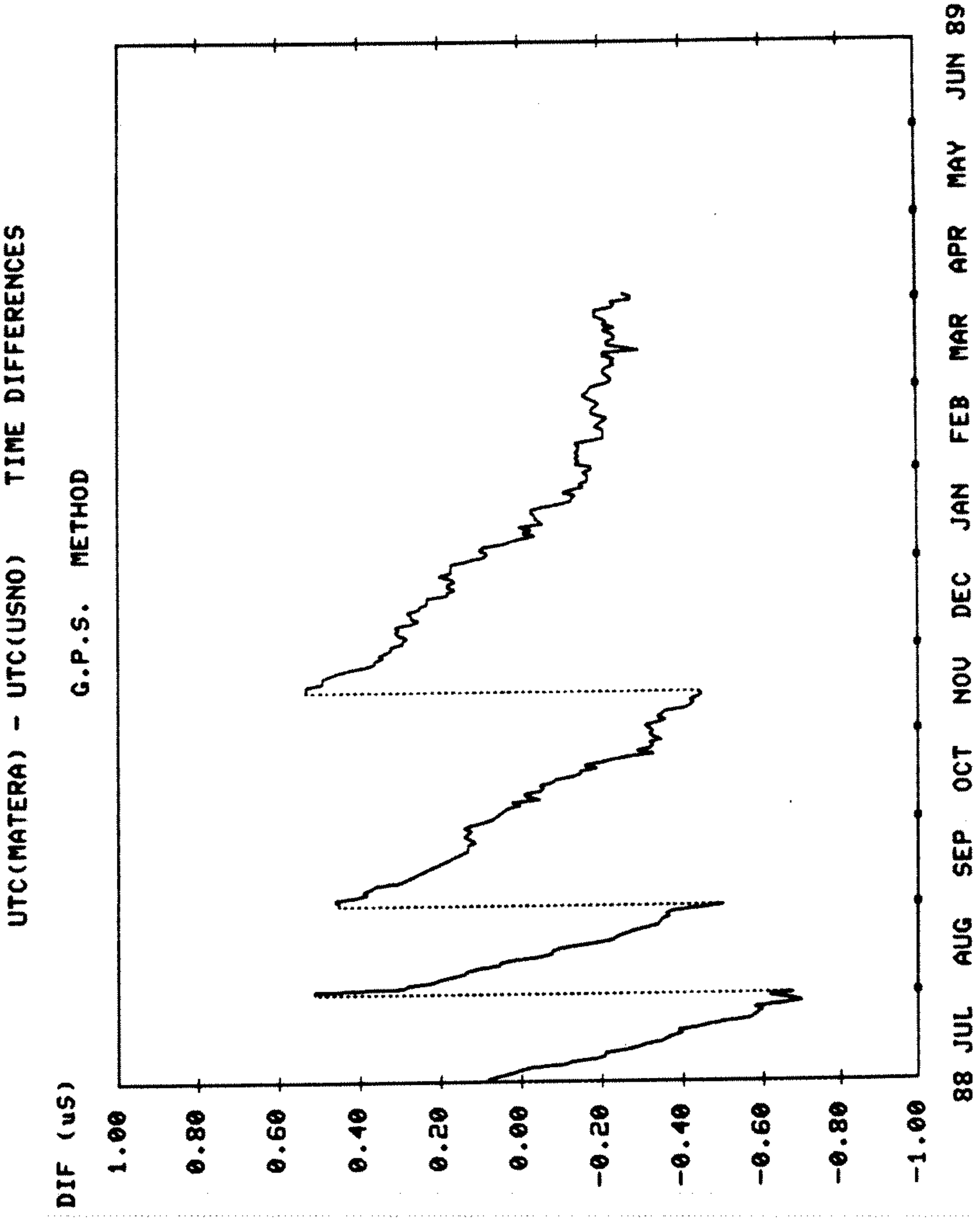
TEMPERATURE VARIATIONS
IN THE FREQUENCY STANDARDS ROOM





TEMPERATURE VARIATIONS
IN THE FREQUENCY STANDARDS ROOM


LORAN-C RECEIVER AUSTRON 2100
1 PPS LORAN
5MHz LORAN-C
5 MHz
VAX
1 PPS A
TV-SYNC RECEIVER C.E. AR23
5MHz A
G.P.S. RECEIVER SERCEL NRT2
5 MHz A
1 PPS GPS
5 MHz GPS
COMPUTER HP 98580
COUNTER HP 5334
PULSE DISTRIBUTOR AUSTRON 8190
1 PPS SYNC
MARK III (1 PPS SYNC)
1 PPS A (MASTER)
MULTIPLEXER RACAL-DANA 1250
1
2
EXT 1PPS
1 PPS SYNC
1 PPS C
1 PPS LORAN
1 PPS GPS
1 PPS MARK III
1 PPS B
1 PPS SYNC
ACCUMULATOR A R&S CADM
ACCUMULATOR B R&S CADM
1·10⁶ DIVISOR
1 MHz
5 MHz C
FREQUENCY AMPLIFIER DISTRIBUTOR HP 5087
5 MHz A
GPS
LORAN
TV-SYNC
10MHz
COUNTER
5 MHz B
MARK III
5 MHz
5 MHz
PHASE STEPPER AUSTRON 2055
5 MHz
CESIUM OSCILLATOR HP 5061
H-MASER OSA EFOS
CESIUM OSCILLATOR HP 5061
5MHz LORAN C
5MHz GPS
5MHz C
5MHz B
5MHz A MASTER
PHASE METER
PHASE METER
PHASE METER
PHASE METER
4 CHANNELS STRIP CHART RECORDER
OSA 5560


UTC(MATERA) - UTC(USNO)   TIME DIFFERENCES
G.P.S. METHOD
DIF (uS)
1.00
0.80
0.60
0.40
0.20
0.00
-0.20
-0.40
-0.60
-0.80
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88 JUL
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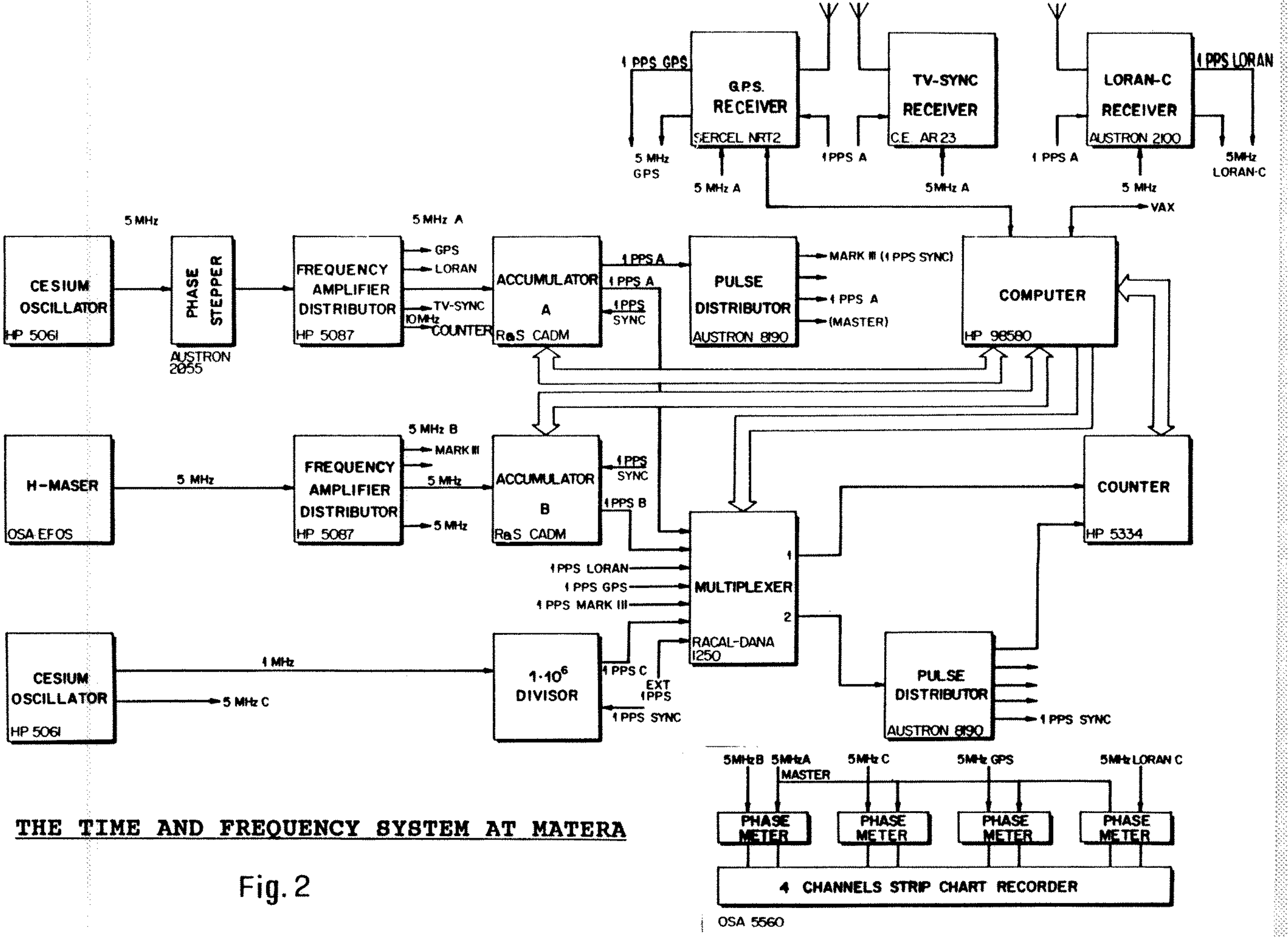
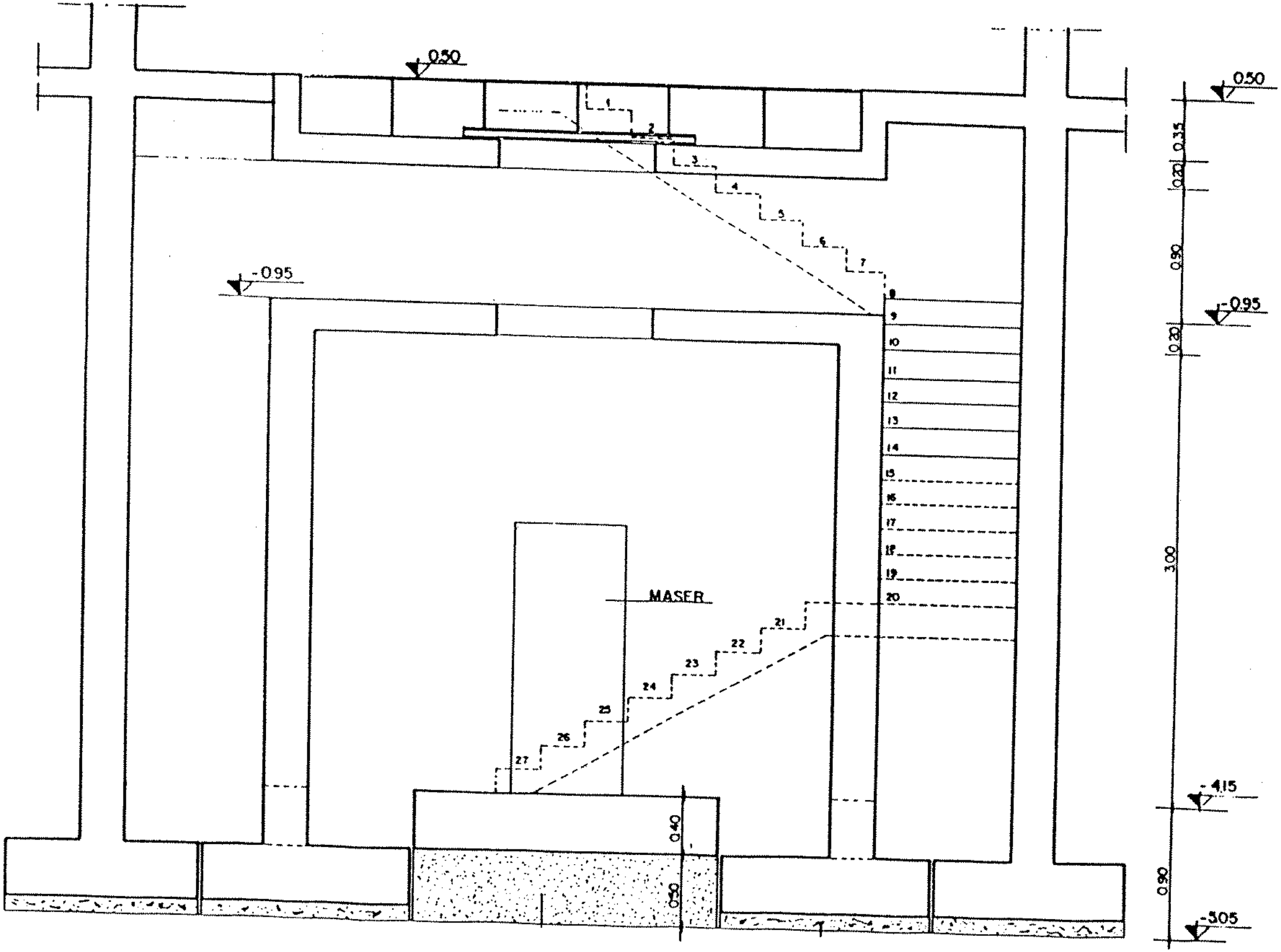
MAY
JUN 89

Fig. 1



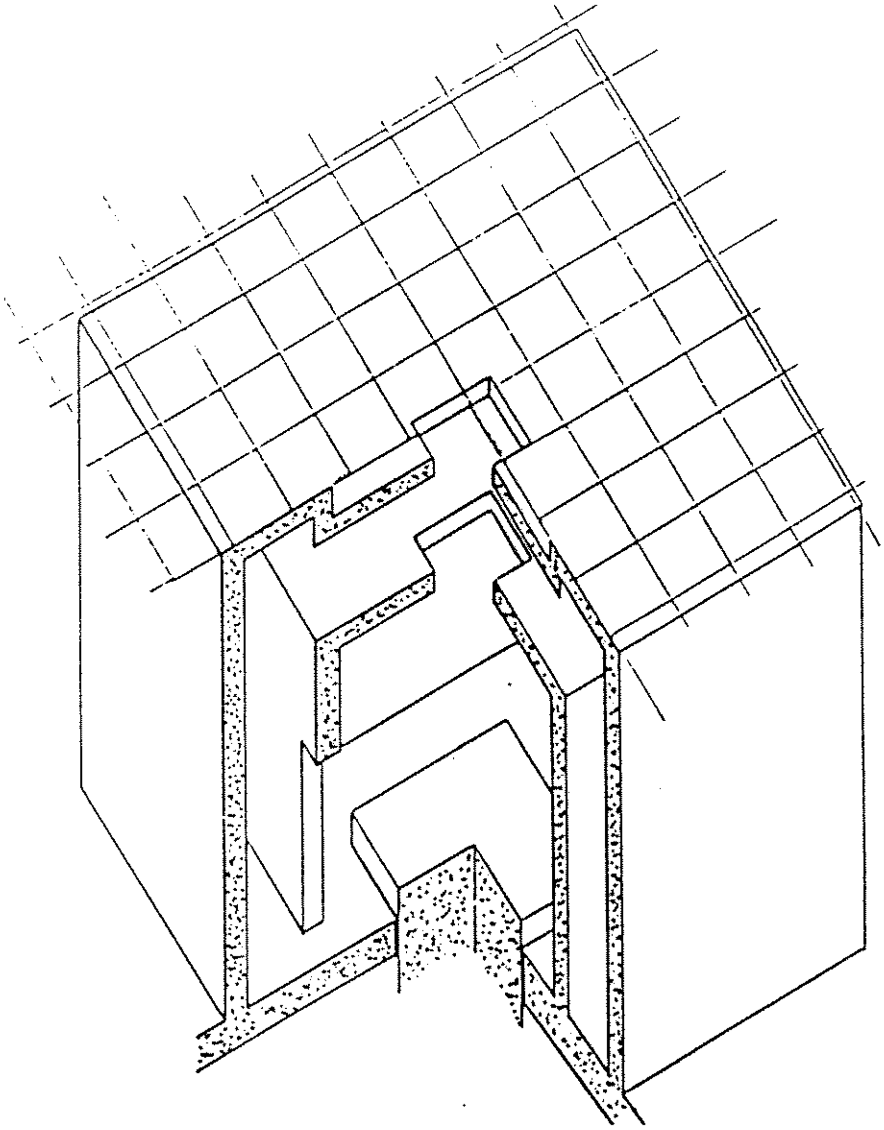
THE TIME AND FREQUENCY SYSTEM AT MATERA

Fig. 2



Frequency standards room: cross-section

Fig. 4



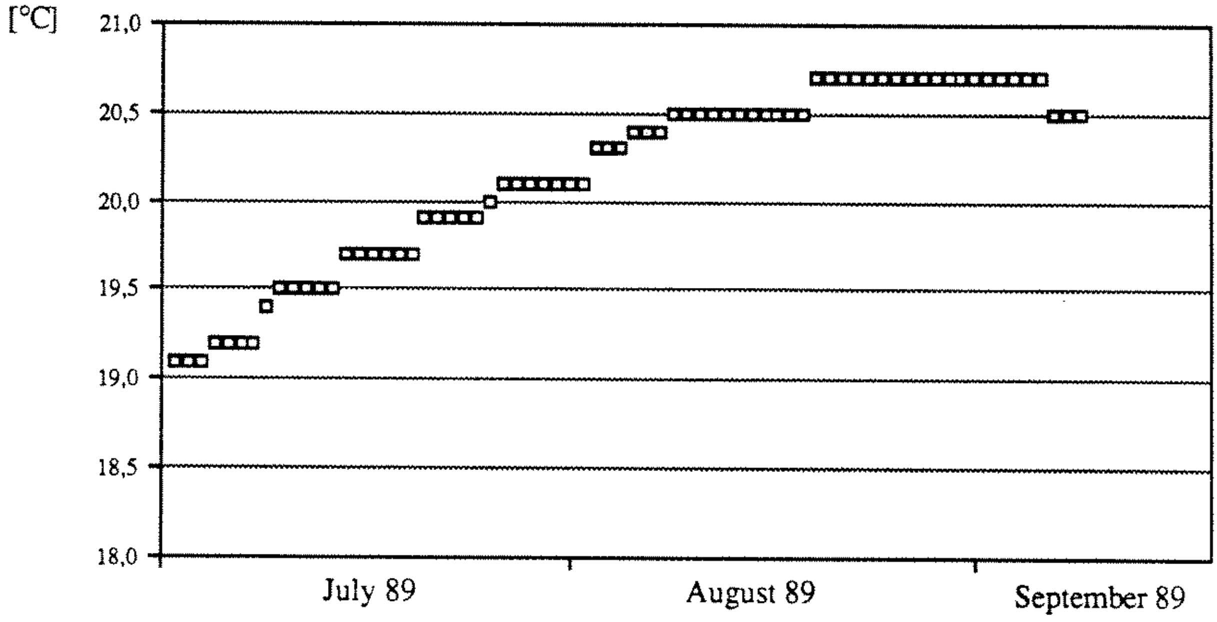
Frequency standards room: axonometry

CHARACTERISTICS OF THE FREQUENCY STANDARDS ROOM

- Underground room 4m x 4m x 3.4m (L x W x H) located 4m (floor) below the equipment room
- 1m air space around the room and above the ceiling
- double access door
- 1.3m x 1.3m double porthole in the ceiling to accomodate the H-MASER installation
- 2m x 2m x 0.4m concrete pedestal on the floor (for H-MASER and Cesium Beam Standards) insulated with respect to the rest of the building to reduce vibrations
- Temperature variations less than 1 °C/month (see fig. 5)
- No active air conditioning is expected in the room

Fig. 3

TEMPERATURE VARIATIONS IN THE FREQUENCY STANDARDS ROOM



TEMPERATURE VARIATIONS IN THE FREQUENCY STANDARDS ROOM

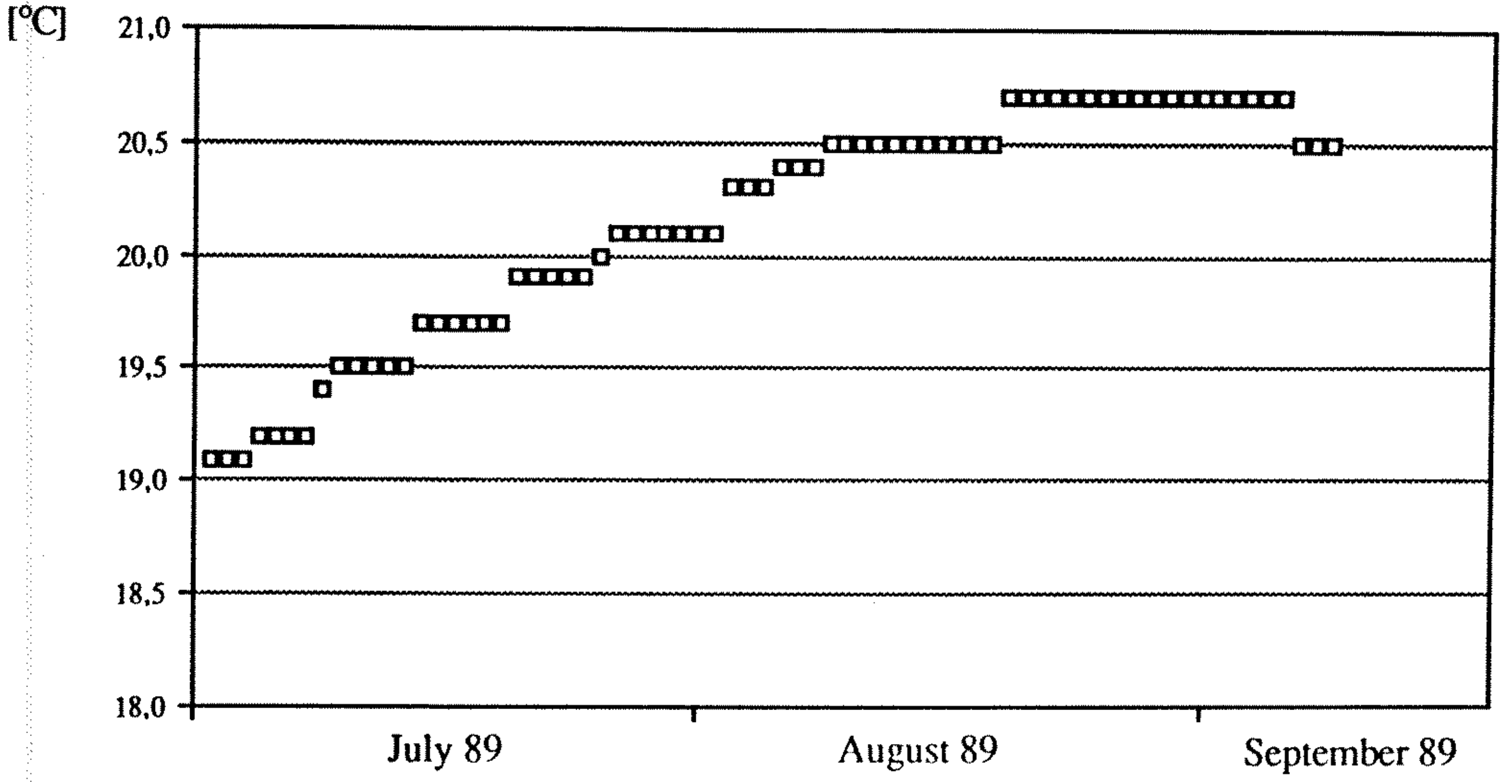
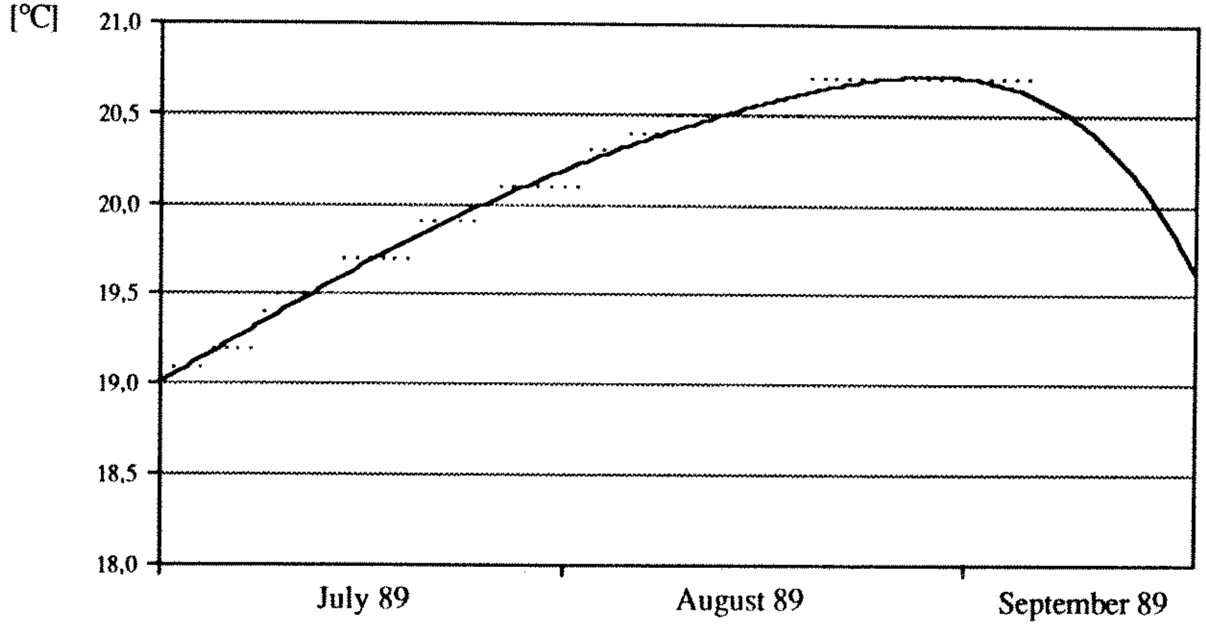


Fig. 5

TEMPERATURE VARIATIONS
IN THE FREQUENCY STANDARDS ROOM



MODE LOCKED SEMITRAIN LASER RANGING DATA PROCESSING SOFTWARE

I.PROCHAZKA

Faculty of Nuc Sci and Physical Engineering
Czech Technical University
115 19 Prague,Brehova 7
Czechoslovakia
Telex 121254 fjfi c
Phone +42 2 848840

General

The advantages of transmittion of several picosecond mode locked pulses of fixed spacing for laser ranging has been described by [1], [2], [3] and others. To exploit fully these advantages the special ranging data analysis procedure has to be applied. The final goal of such a procedure is, along with the noise points rejection, precision estimate evaluation and satellite ephemeris improvement, the conversion of the results into the form of ranging results obtained using single transmitted pulse. In contrast to the use of a full train of mode locked pulses, the echoes corresponding to the first pulse, which is ever triggering the flying time interval unit, is clearly remarkable within all the echoes in this set up. This fact drastically simplifies the ranging data analysis procedure and removes the ambiguity from the ranging frequently critised when using the full train of pulses.

Analysis flowchart

The mode locked semitrain laser ranging data analysis procedure is carried out in four main steps. All the ranging results (the No. of shot, epoch and propagation time) are stored together with the data analysis results (O-C residuals #0, #1, #2, the weight, etc.) in one file. Thus, each the analysis step may be independently checked and, if requested, redone again anytime.

An interactive graphic data editor may be used to delete or reconsider the data points before/after each analysis step.

Step #0 During the satellite ranging, the epoch and the propagation time are stored together with the No. of the shot and an Observed-Predicted propagation time values. Completing each satellite pass, these O-C "on-line" residuals are used for obvious noise rejection.

Step #1 The initial satellite orbit prediction is matched to the measured ranges applying the range and time biases together with the Earth rotation correction parameter. To avoid the numerical instability problem, an special modification of a least square procedure has been developed. To speed up the procedure, only 30-50 points of the pass are used for this orbital fitting procedure.

The O-C residuals #1 are plotted, the echoes corresponding to the first peak within a semitrain are "marked". The next data analysis steps are carried out only for the echoes corresponding to the first peak.

Step #2 The low order polynomial fitting of the O-C residuals #1 are computed, the deletion criteria (2.5 sigma) is applied. The standard iteration process is repeated until no more points are deleted and the sigma is not decreasing more.

The plot of the O-C residuals of the Lageos pass, Oct.15,1989, at UT 2:15 is in [1] along with the histogram of the residuals.

Step #3 The ranging data are "folded". Integer number of the laser semitrain pulses spacing is substracted from the measured propagation times corresponding to the second and the next peaks. On the end of this procedure the user gets the SLR data converted to the form identical to the form of data obtained using a single pulse.

The steps #1 and #2 are repeated, the possible noise points are rejected, the resulting total number of echoes and the precision estimate is evaluated.

Computer requirements

All the programs were written in Fortran 77 with except of the interactive graphic data editor, which was written in C and Basic languages. The computing time to proceed one satellite pass, using an IBM PC AT with coprocessor, is 10-30 minutes, depending on the number of echoes and the data quality. Most of the process is running automatically, only the initial noise rejection (step #0) and the first pulse marking (step #1) may need operators interaction.

Data analysis performance

The data analysis procedure described above has been used at the Helwan SLR in 1987 and 1988 campaigns. In fact, the leakage of the pulse selector of the laser caused the semitrain character of the transmitted/ received signal. In 1987 and 1988 the Univ. of Texas analysis edited only 2.1% and 2.5% of our data, while the second pulse contributed about 10% of energy and the same percentage of single photon echoes. The world average of percentage edited was 9.7% and 6.9%, respectively. Since July 1989 the semitrain of 2-3 pulses has been used. Despite the multipulse character of the transmitted signal, only some 3% of our data were edited by GLTN q-1 data analysis, ranging

Lageos on the single photon level, the precision estimate of the system is typ. 32mm RMS, the contribution of the semitrain is 2.6 increase of the number of echoes per pass in comparison to a single pulse. No one of more than 200 passes, acquired using the semitrain laser, has been edited.

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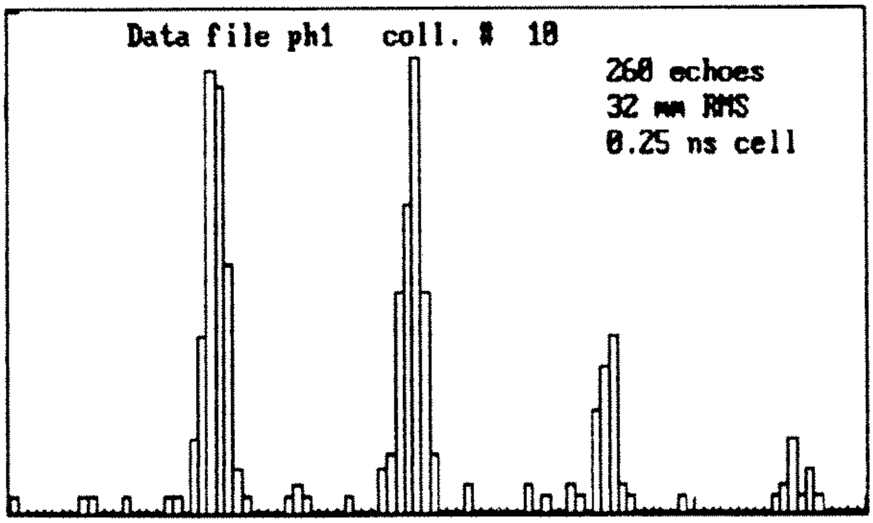

The histogram of the range residuals #2, LAGEOS,Oct.15,2:15UT
In fact, it represents a sampling of the laser output pulse shape.

Streak Camera Full Frame Image Processing

Pavel Valach

Czech Technical University, Prague
Faculty of Nuclear Science and Physical Engineering
115 19 Prague 1, Břehová 7
Tel.: +42 2 848840, telex 121 254 FJFI C

Abstract

This paper deals with computer measurement and image analyze system for linear and circular streak camera. The system is based on PC/AT computer with video frame grabber and SIT or CCD TV readout. Full frame image processing software allows to analyze both linear and circular sweep records even with distortion of symmetry and nonlinearity.

1 Introduction

There is a continuous effort to exploit streak camera as a laser ranging detector, expecting millimeter precision. Modular streak camera for laser ranging both with linear and circular sweep has been treated [1] [2].

The advantage of the linear streak is relative simple data analyze, however the necessity of trigger delay within the range of 20-30 nsec may cause several problems. Using the circular streak, the main limitation is the complexity of data analyze especially with nonsymmetry of deflection.

To solve the problem of streak camera readout, computer measurement system and full frame image processing software has been developed.

2 Hardware Configuration

Hardware configuration of streak measurement system is on Fig. 1. Modular streak camera with linear and circular sweep is used [1]. For the linear deflection the sweep speed is between 40 psec/mm and 400 psec/mm. For circular deflection 320 MHz RF signal is applied. Diameter of the circle is 6mm resulting in 165 psec/mm.

To readout streak camera the Haimann SIT or Proxicam Intensified CCD camera is used. The output TV signal in connected to the video frame grabber VFG 512/8BC in PC/AT computer. No interlaced 256 x 256 pixels 8 bits resolution is used. This results in 2 psec/pixel to 18 psec/pixel resolution for linear deflection and 423 psec/circle or 7.3 psec/pixel resolution for circular deflection.

To Synchronize readout with incoming laser signal parallel port LPT1 is used. CCD or SIT camera integrates signal over one TV frame, e.g. 20 msec.

3 Full Frame Image Processing Software

Modular software package for image processing includes:

- synchronization of readout and laser
- image grab, save and retrieve
- image display
  - pseudocolor map
  - contour map
  - 3-d projection
  - rows/columns
- basic image analyze and operations
- linear and median filtering
- averaging of images
- gain nonuniformity correction
- calibration of circular streak track
- fixed center analyze of circular streak track
- shifted center analyze of circular streak track

For analyze of distorted circular streak records new full frame algorithm has been used. Calibration of the track have to be done at the first, Fig. 3. The sweep rate is considered to be constant. For each value of time expansion t

a integration line penperdicular to track and boundary points p_1^t and p_2^t are determined at calibration time, Fig. 2. To obtain time expansion $T(t)$ of streak record following equations are used:

$$\mathrm{T(t)} = \int_{\mathrm{p}_1^t}^{\mathrm{p}_2^t} \mathrm{J(p)\,dp} \tag{1}$$

$$\mathrm{J(p)} = \sum_{\mathrm{i=0}}^{255} \sum_{\mathrm{j=0}}^{255} \mathrm{W}\left(\sqrt{(\mathrm{y_p} - \mathrm{j})^2 + (\mathrm{x_p} - \mathrm{i})^2}\ \right) \mathrm{I_{ij}} \tag{2}$$

$$\mathrm{W(r)} = \begin{cases} \epsilon^{-\frac{\epsilon^2}{\epsilon^2 - r^2}} & \text{if } r < \epsilon \\ 0 & \text{otherwise} \end{cases} \tag{3}$$

$$\mathrm{y_p} = \mathrm{c_y} + \mathrm{p} \sin\,(\mathrm{t}) \tag{4}$$

$$\mathrm{x_p} = \mathrm{c_x} + \mathrm{p} \cos\,(\mathrm{t}) \tag{5}$$

where:

T	intensity in time expansion
t	time
p	parameter of integration line
p_1^t, p_2^t	limits determined at calibration time
I_{ij}	intensity in streak record image at pixel ij
W	weight function for interpixel calculation
x_p, y_p	coordinates along integration line
c_x, c_y	coordinates of center

To improve speed of analyze, for each t a list of pixels and their weight are calculated at calibration time, then analyze use only additions and multiplications od pixel intensity.

4 Experimental Results

The example of the circular streak record of the train of mode locked pulses and it's time expansion is on Fig.4. The circular streak camera range difference jitter limit has been tested using two pulses separated by the fixed interval 100 psec. Completing statistical measurement the sweep speed and the range difference jitter may be estimated [1]. Nonlinearity in sweep speed is caused by the higher order harmonics in driving RF deflection wave. Compensating this effect, the range difference jitter of 6 psec corresponding 0.8 pixel has been achieved.

References

[1] K. Hamal, I. Procházka, M. Schelev, V. Lozovoi, V. Postovalov: *Modular Streak Camera for Laser Ranging*. In: this proceeding.

[2] I. Procházka, K. Hamal: *Streak Camera as a Laser Radar receiver, its performance and limitations*. In: Proceedings of the 6th International Workshop on Laser Ranging Instrumentation, Antibes, Sept.1986.

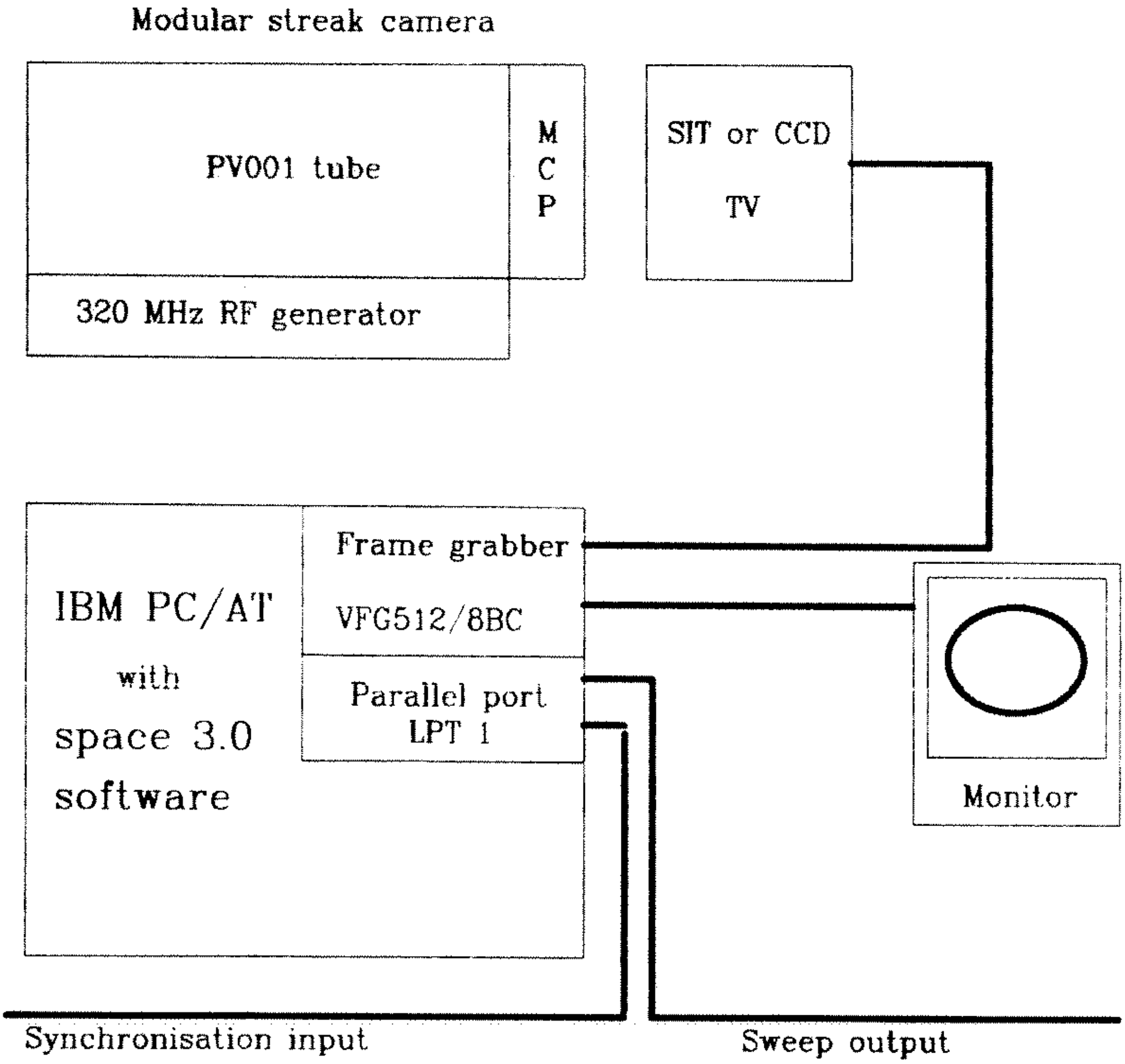

Fig. 1. Hardware configuration

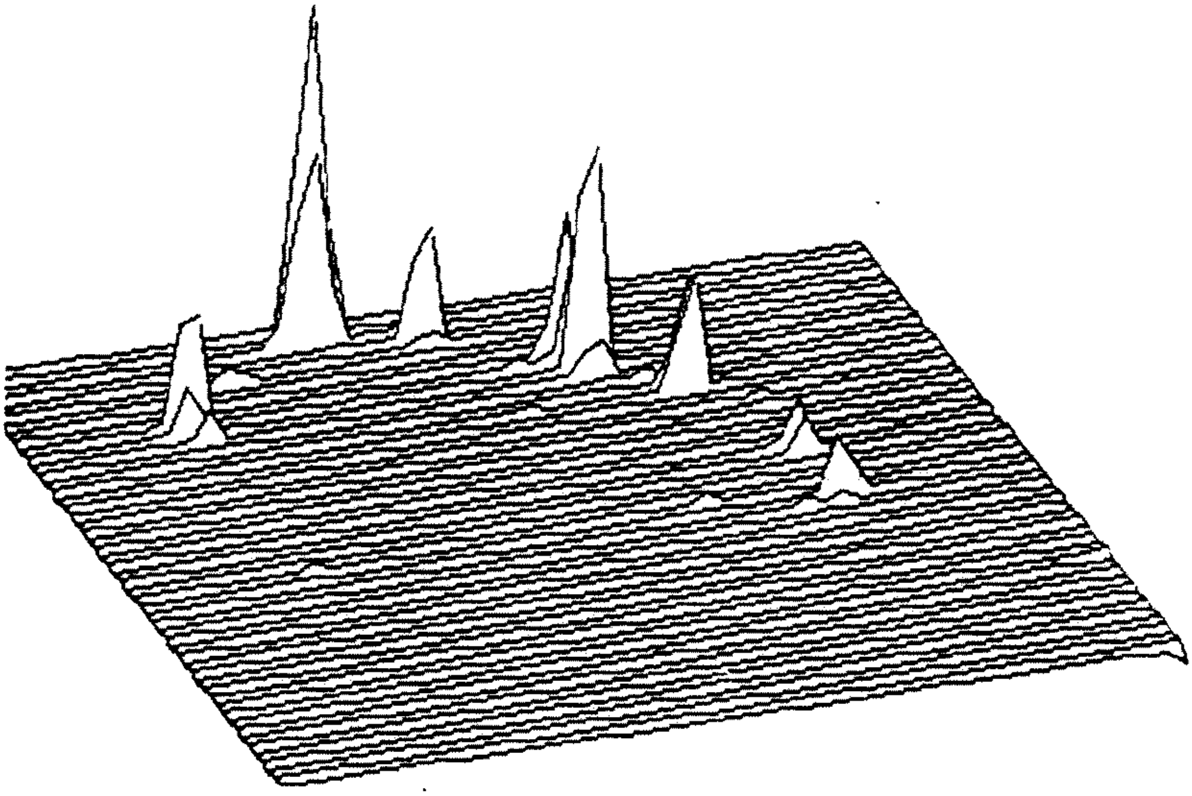

Fig. 4. Circular streak record of a mode locked train

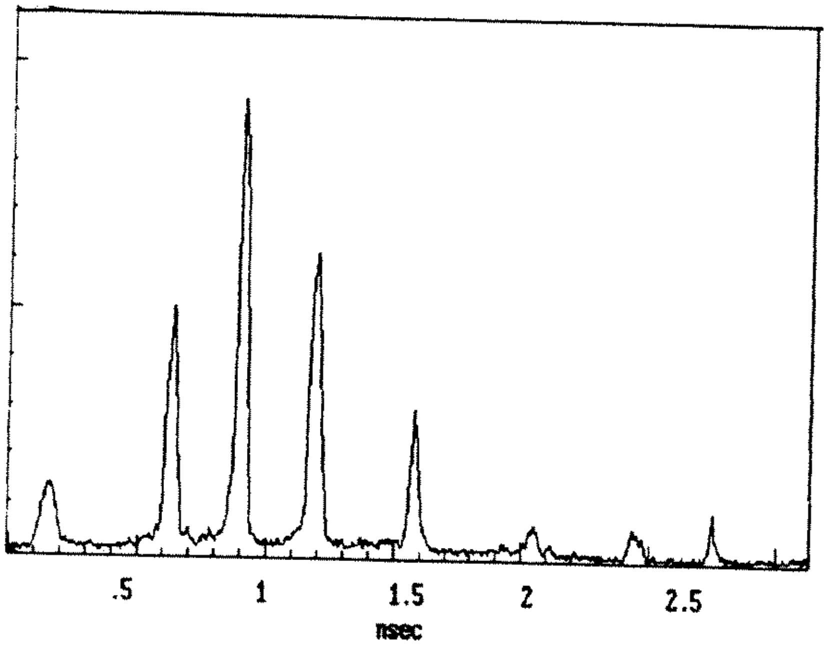

Fig. 5. Time expansion of streak record

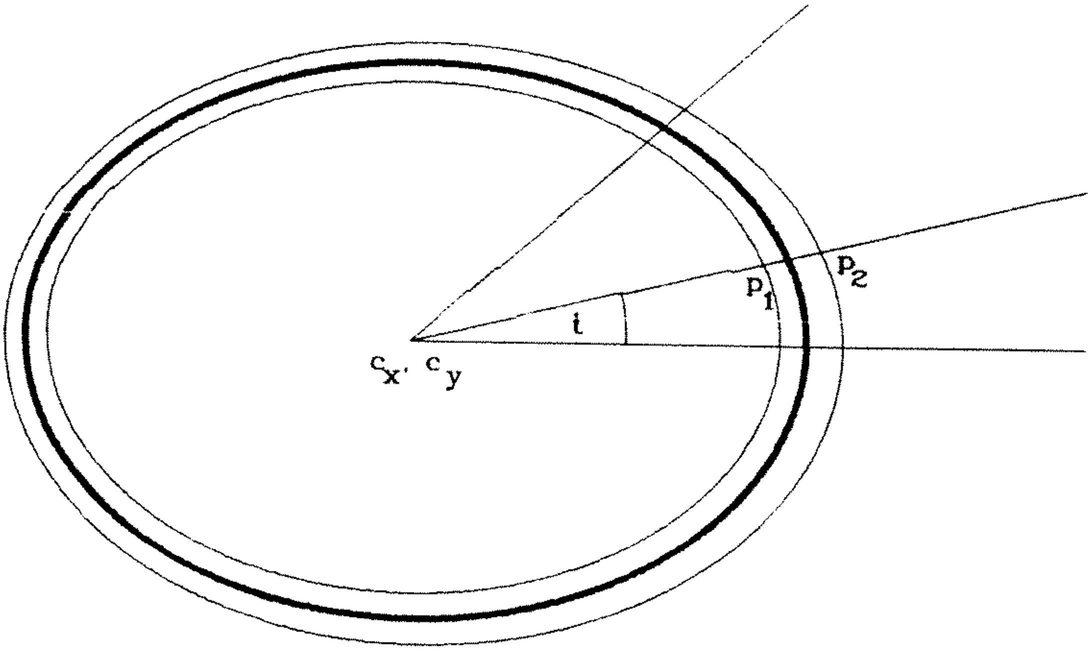

Fig. 2 Calibration track

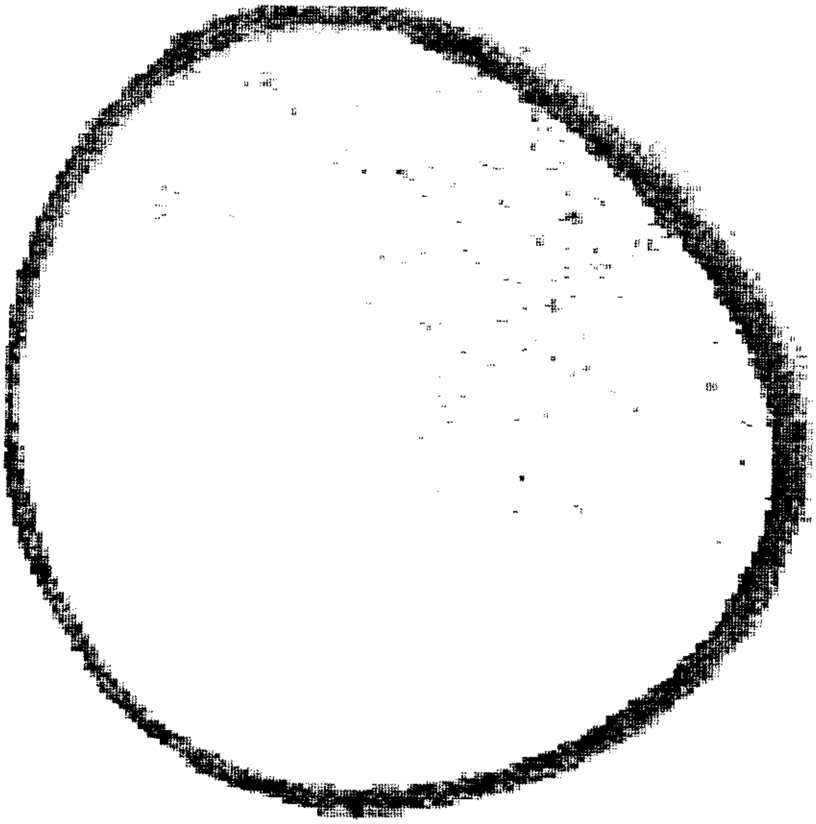

Fig. 3. Calibration track

Conclusions

FUTURE CONCEPTS

A summary of the discussions held in the last technical session of the 7th International Workshop on Laser Ranging Instrumentation held in Matera

PETER WILSON
INSTITUT FÜR ANGEWANDTE GEODÄSIE
RICHARD STRAUSS ALLEE 11
D-6000 FRANKFURT

The final technical session of the Workshop addressed Future Concepts. It was conducted as a dialogue between a panel of experts and the audience, with no formal presentation of papers. To initiate discussion during this session, a letter had been circulated to some twenty participants before the Workshop, inviting the preparation of opinions on a number of issues considered by the session chairman to be central to the conceptual design of future systems. A copy of this letter is given in the appendices. The discussions were led by the session chairman and the panel, which comprised Peter Wilson (Session Chairman), John Degnan, Jean Gaignebet, Ben Greene, Karel Hamal and Bob Schutz. The ensuing discussions centred on the following topics:

- operational effectivity,
- technological criteria,
- network deficiencies,
- constraints on instrumental availability.

Due to time constraints, a final topic:

- analytical limitations,

received only scant attention during the discussions, despite the fact that the session was extended for an additional hour, to accomodate the response that had been generated.

In a summarising a session of this nature it is virtually impossible to do justice to all the contributions that were made, so that the following reflects only the main trends of the discussions.

Each of the foregoing topics was treated in turn. After a brief statement by the chairman, each of the panel members was asked to give an opinion before the discussion was opened to the floor. Thanks to the engagement of the entire audience a lively dialogue followed and each topic was analysed critically.

On the subject of operational efficiency it became clear that significat cost reductions will result from the availability of additional satellites (a point of considerable importance to those groups operating mobile systems). Furthermore, it was observed that the overall laser ranging network efficiency is in need of considerable improvement in order to meet the requirements of the next decade. In this period satellite laser ranging has been selected as the primary tracking facility for a large number of new satellites. To meet these demands it will be essential that the data turn-around time is reduced from months to days, and that better coordination be introduced between tracking stations with the objective of spreading the tracking load and avoiding duplication of coverage, e. g. over Central Europe. The rapidly increasing tracking load will place heavy burdens

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on those stations capable of producing high quality date. With only very limited prospects for increasing staff, this implies the introduction of added features to automate tracking and reduce the burden on the operators. Many contributions were made on these earliest possible implementation of software to derive field generated normal points. A resolution to this effect was passed at the close of the Workshop.

There was recognition of the potential offered for technological improvement in response to the scientific need. This became apparent in foregoing sessions, where the presentations on the availability of new lasers and avalanche photo-diodes open up the possiblilities of significantly higher ranging accuracies and improved operational reliability. Attention was given to the non-uniform ranging performance characteristics of the global network. Although there is a general improvement towards a more even distribution of high quality systems ranging at the 1 to 5 cm single shot r.m.s. level, each major technological break-through leading to significant ranging performance improvement opens up a new gap in the table of performance characteristics. It is doubtful whether the best system performance can be exploited so long as the majority of the network is not operating at a correspondingly high level of accuracy. On the contrary, there appears to be a general sensitivity in the network (curently somewhere between 2 and 4 cm), which reflects the performance characteristics of the majority of the regularly contributing stations in it. Furthermore, it was recognised that the majority of systems currently being operated are more than 10 years old, and, despite ongoing up-grades, suffer from some characteristic design deficiency which limits their ultimate performance. For example, the upgrading of the Moblas-type systems has reached will ultimately be limited by the absence of a Coude path through the mount. This opened up a discussion on the desirability of introducing common design standards, and, if possible joint manufacturing of components for future systems.

Network deficiencies were discussed in terms of the inadequate distribution of stations in the present global net, particularly the abundance of stations in Europe and the dirth of stations in the southern himisphere. Though no solution could be found to this problem within the terms of reference of the Workshop, it was agreed that a solution may ultimately be found by coordinating the efforts of several of the larger agencies to establish a joint initiative for the southern hemisphere. Such an activity would also serve to spread the burden of responsibilities for establishing tracking stations in regions outside the industrially developed nations of the world. Similarly, it was recommended that efforts should be made to improve the exchange of technical know- how between the existing groups.

The most pressing of the analytical problems affecting ranging activities at this time is undoubtedly the limited accuracy to current predictions for the lower satellites and the inability to provide orbital elements or IRVs for these satellites for extended periods of time. This deficiency limits the ability of the individual tracking systems to acquire the satellite without manual intervention. Here again there was considerable discussion and Dr. Andrew Sinclair was assigned the task of proposing numerical techniques and the software solutions to overcome these problems. Prof. Bob Schutz agreed to work with Dr. Sinclair on this task and it was recommended that a member of the analytical team working at Goddard Space Flight Center should also be invited to participate. It was requested that a first report of the working group should be presented at the meeting of Principal Investigators to the Crustal Dynamics Project, due to be held at Goddard Space Flight Center during the last week of October 1989, with more detailed reports to be prepared for the following meeting of this group to be held in April 1990 at JPL. This discussion was also linked to the problem of providing software for the on-site generation of normal points, where it was assumed that special algorithms will required to perform this task for the low-flying satellites. This aspect will also be addressed at the meeting at Goddard Space Flight Center at the end of October.

Some attention was given to the necessity for check, and eventually improve the modelling of the tropospheric refraction and to provide better modelling of the centre of mass correction to keep these factors in line with (or preferably even ahead of) the highest achievable ranging accuracies. The need to designate an acceptable format for reporting dual (multiple) frequency range measurements was also a topic of discussion. Here a solution was envisaged in which the current MERIT-2 format would be applied separately for each of the reported frequencies. A need for dual (multiple) frequency ranging from all stations in order to meet the increased accuracy demands is currently recognised, but it is considered that the ability to model tropospheric refraction will ultimately be the limiting factor defining the accuracy of satellite laser ranging.

The session was finally closed by the Chairman with thanks to the Panel and to all present for their lively and vigorous participation in the discussions.

Appendix

Notice to participants

Friday session on future concepts

The session will have no formal presentations and will be presented in the form of a panel discussion and dialogue with the participants from the floor.

Having heard the "requirements and goals" during the first technical discussions on Monday, it will be desirable to use the opportunity to exploit the intervening exchange of information (Tuesday to Thursday) to define the means by which we anticipate that the "goals and requirements" can be met in the coming years and in improved system design.

to stimulate the discussion I offer some of the "weak points" on the basis of which SLR is often criticised as a technique:

Operational effectivity

- the cost of operations is too high;
- observations take too long;
- the data turn-around time is too long;
- the computation of final results is too slow;
- ...

Technological criteria

- the technique has a low reliability record;
- there is a need for higher ranging accuracy;
- network performance characteristics are not uniform;
- most systems operating today are over 10 years old;
- ...

Network deficiencies

- the global distribution of stations is inadequate;
- there is an uneven burden of responsibilities;
- there is still need for improved cooperation at the technical level;
- ...

Analytical limitations

- the gravity field is inadequately described;
- the modelling of the disturbing forces requires improvement;
- improved ranging accuracies will bring a demand for overall model improvement;
- the modelling of the troposphere represents a limiting factor;
- ...

Constraints on instrumental availability

- a number of new satellites require tracking support now and further satellites will soon be launched;
- a number of missions require calibration support;
- how can the overall tracking load be satisfied?
- ...

The list is not exhaustive, but I feel sure that technical innovation will make it possible to overcome all of these difficulties. Please participate freely in the discussions.

High accuracy and lower cost per data point will ensure that we stay in business!

Peter Wilson, Session Chairman

CONTENTS

Scientific results. requirements and goals

International cooperation

Station status and developments

Laser technology

Detection

Multiple wavelength ranging

Epoch and event timing

Calibration

Mobile systems technology

Recent software developments

Conclusion