Latest Trends in Optics and Mount Development

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In early days of the space age most of the artificial satellites were tracked by radio interferometry, optical and radio doppler methods. Since the accuracy of their predictions was usually very poor because of the lack of knowledge of the upper atmosphere density and its temporal variations and of rather large values of the area-to-mass ratios of the artificial satellites, wide-angle cameras of Schmidt type, for an example, had to be used for the optical tracking purpose. Also as any computor-controlled device to drive the telescopes was not available at that time, a third axis, so-called tracking axis, was introduced so that by rotating the telescope around this axis only satellites could be tracked. However, since any satellite does not move along a great circle in the sky it was not possible to track them accurately along a long arc with one tracking axis only. Therefore,some tracking telescopes such as AFU-75 have fourth axes for the precise trackings.

Now only a few laser ranging telescopes have tracking axes. Most of them are on alt-azimuth mounts and the telescopes follow the motions of artificial satellites by rotating them around the two axes simultaneously. This can be done very easily by using small computors which compute predicted directions of the satellites as functions of time and drive the telescopes by comparing their directions in the sky with the predicted ones. Some of the telescopes are on X-Y mounts to avoid the dead angle near the zenith by introducing another horizontal axis instead of the vertical axis for the alt-azimuth mount.

In early days just after satellite laser ranging instruments had become available laser oscillators were usually very compact and short. Therefore, they could be put on the same mount as the telescopes. Now in order to reduce the laser pulse length to the order of a few hundred pico-seconds, to change the original laser frequency for some cases and to amplify the laser power many devices besides the oscillators are necessary. Therefore, the laser oscillator systems are very large and heavy and cannot be, usually, put on the same mount as the telescopes. Instead they are put on fixed platforms. In order to fire the laser beam towards the satellite it should be introduced to the transmitting telescope through its coude focus. Then it is necessary to take alignments among optical axes of the transmitting and receiving telescopes and also laser beam axis very carefully. It is a very time-consuming job. Now some very ingenious devices for the alignments have been developed and introduced in most of the existing systems.

Major modifications of the satellite laser ranging systems were made after Lageos satellite was launched. We can compute predicted positions of the satellite very accurately, namely with two arc second errors. Therefore, it is possible now to range the satellite with very narrow beam divergence if the system can follow the satellite motions with the same accuracy. If so, a moderate size telescope can be used for Lageos satellite ranging and as not so high energy laser is necessary the pulse length can be made very short. For such systems requirements for the optical system and mounts are more severe. The mount should be designed so that the telescopes can be pointed to the predicted positions very precisely with and without guiding and the optical system must be designed so that the alignments can be taken very accurately, easily and quickly.

Now at several institutes mobile(or transportable) laser ranging systems have been developed and in operation. In fact most of recently developed systems are mobile or transportable in some senses. The requirements for such systems are the most severe, however, they have been achieved for most of the systems.

In the session of latest trends in optics and mount developments the report on mount and telescope for the German/ Dutch mobile system is presented by H. Visser and F.W.Zeeman and the satellite ranging mount system of Contraves Coerz Corporation is explained by G. Economou and S. Snyder. Moreover, the 1.5 meter telescope realized by INAG for the CERGA lunar laser ranging system is described by M. Bourdet and C. Dumoulin. The three papers appear in the proceedings. The other two papers which are presented in the session cannot be published here unfortunately because they have not come in written form by the deadline. They are the paper on TLRS II(Tansportable Lunar Ranging System) by T. Johnson and that on MLRS(Mobile Lunar Ranging System) by B. Greene. It is expected that you can have informations on these two systems in the tables of the proceedings and by contacting the authors.

DESCRIPTION OF THE 1.5 M TELESCOPE REALIZED BY INAG FOR THE CERGA LUNAR LASER RANGING SYSTEM

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INTRODUCTION

In 1973, the National Institute of Astronomy and Geophysics (I.N.A.G.) was entrusted with the design of a Lunar Laser Ranging System. The scientific objective is the measurement of the Lunar distance with an accuracy of several cm., by means of the round trip travel time of a Ruby laser pulse. The measure must be obtained within about 10 mn. interval during the firing sequence. The first shots insure the result, the following ones improve the precision.

Our first duty, was to work out the specification for this special experiment. The acquired knowledge from the Mc Donald Observatory and the results of the tests made in France at Pic du Midi Observatory allowed us to choose the important parameters. After approximating the characteristics of the laser, the receptor and the backscattered beam, we were able to define the features of the optical instrument. The most important were the tracking and guiding accuracy, the high collimation between the emission, reception and guiding paths and the telescope size. A preliminary theorical study has shown, that the telescope would have at least 1.4 m in diameter in order to satisfy the scientific objectives.

BACKGROUND INFORMATION

The telescope is located near Grasse on a Plateau, at an altitude of 1 250 m. Its construction began in 1974. The first stars were observed in August of 1978 with a simplified tracking program.

The basic layout of the facility is shown in fig. 1. A 44 m² room where the operators stand, shelters the computers, electronics and laser. The laser stands on a concrete block with an independant foundation and is isolated by a wooden wall. At one end of this room is a circular attachment of which the wall sustains the dome. In the middle of this room is a concrete pier on which rests the telescope. This pier is constructed of six

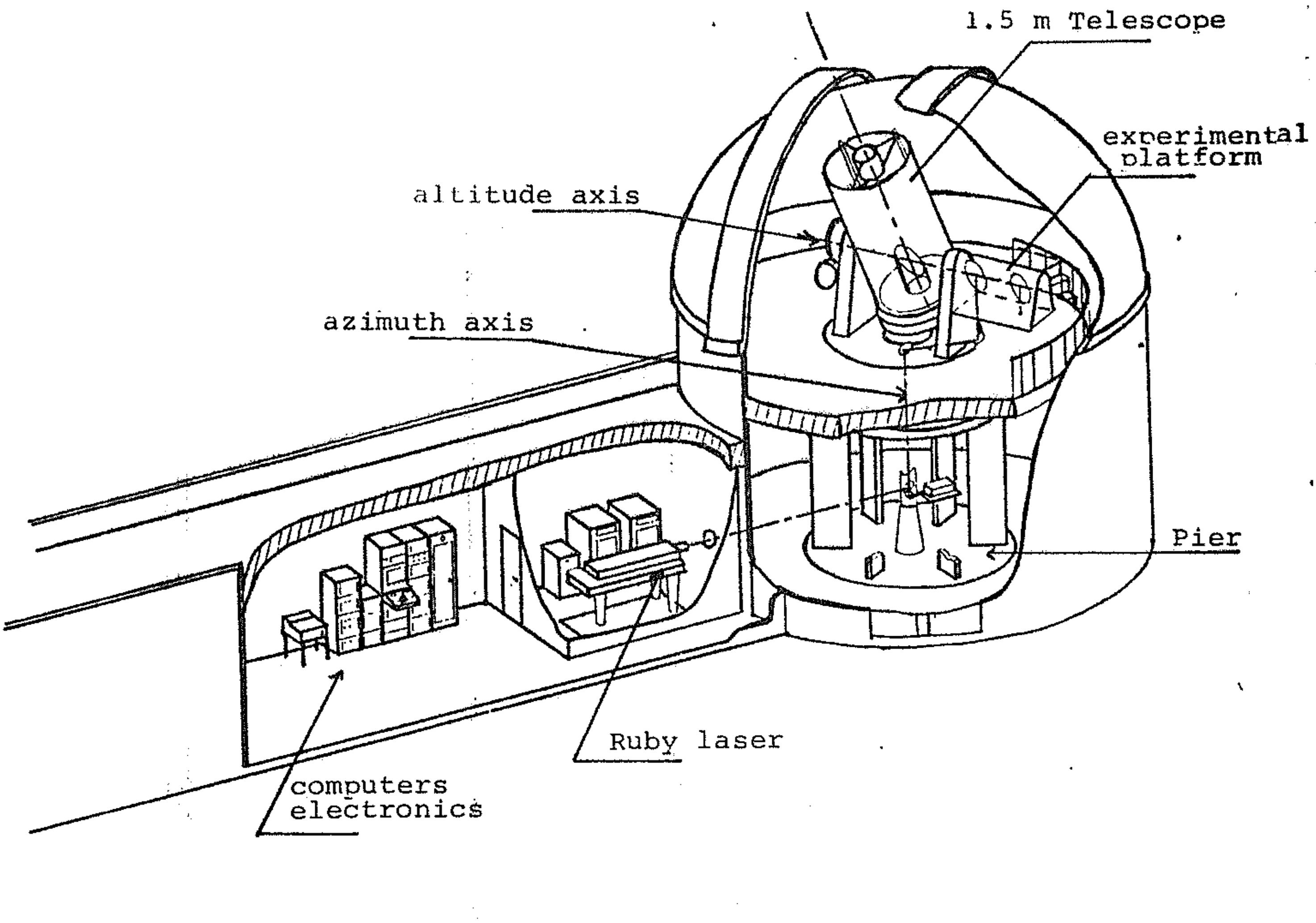

Fig. 1 : THE LOCATION OF THE LASER RANGING EQUIPMENT

radial walls which are tied at the top by a concrete ring and below by an independant bulky foundation. A floor, situated at 4.50 m from the ground, allows the observer to reach the experimental equipment attached to a platform which is fixed to the telescope. The dome of 9.5 m diameter is turned by hydraulic motors. It is slaved whith the rotation of the telescope. A thermal insulation covers the interior of the dome.

MAIN OPTICS OF THE SYSTEM

The optical system consists firstly of the telescope proper with a Nasmyth-Cassegrain focus and secondly of the auxiliary optics which separates the beam into emission, reception and guiding paths. This solution with a telescope used as transmitter, receiver and guider facilitates an alignment of the three paths better than one arc second. The diagram of the major optical components is drawn in fig. 2.

The telescope is composed of a main concave, a convex and a Nasmyth mirror. A diameter of 1.5. m was chosen for the primary mirror. With adequate light efficiency, this receptor surface appeared to offer a sufficient margin of security. Besides when used as a transmitter the divergence of the laser beam might be less than one arc second. The focal ratio of the primary is f/3. The secondary gives an effective single telescope focal ratio of approximately F/20 which corresponds to a 31 m focal length. The Ritchey-Chretien optical system allows the attainment of an utilizable 30 minutes field for the tracking (aberration less than 0.5 arc sec. on the curved focal surface).

There are various guiding methods. At the time of the design, a sure way to point the telescope to the site of a lunar retro-reflector array seemed to be by off-setting from a small reference crater with the electronic reticle of a T.V. camera. Hence, there is a moving guiding camera which is controlled by a computer. To calculate its position, the computer needs the focal length accurately (with a relative precision of 10^{-4}). The chosen solution allows the holding of the focal length during several months by avoiding the variation of the mirrors curvature and of the critical primary-secondary separation. The mirrors are made of zerodur ceramic glass with a low expansion coefficient. The primary and the secondary are linked with three Invar rods. The secondary is connected to the three bars by only a three brace spider. This solution equally allows the maintenance of the focusing which eliminates a constant adjustment on the secondary, thus rendering its position very stable.

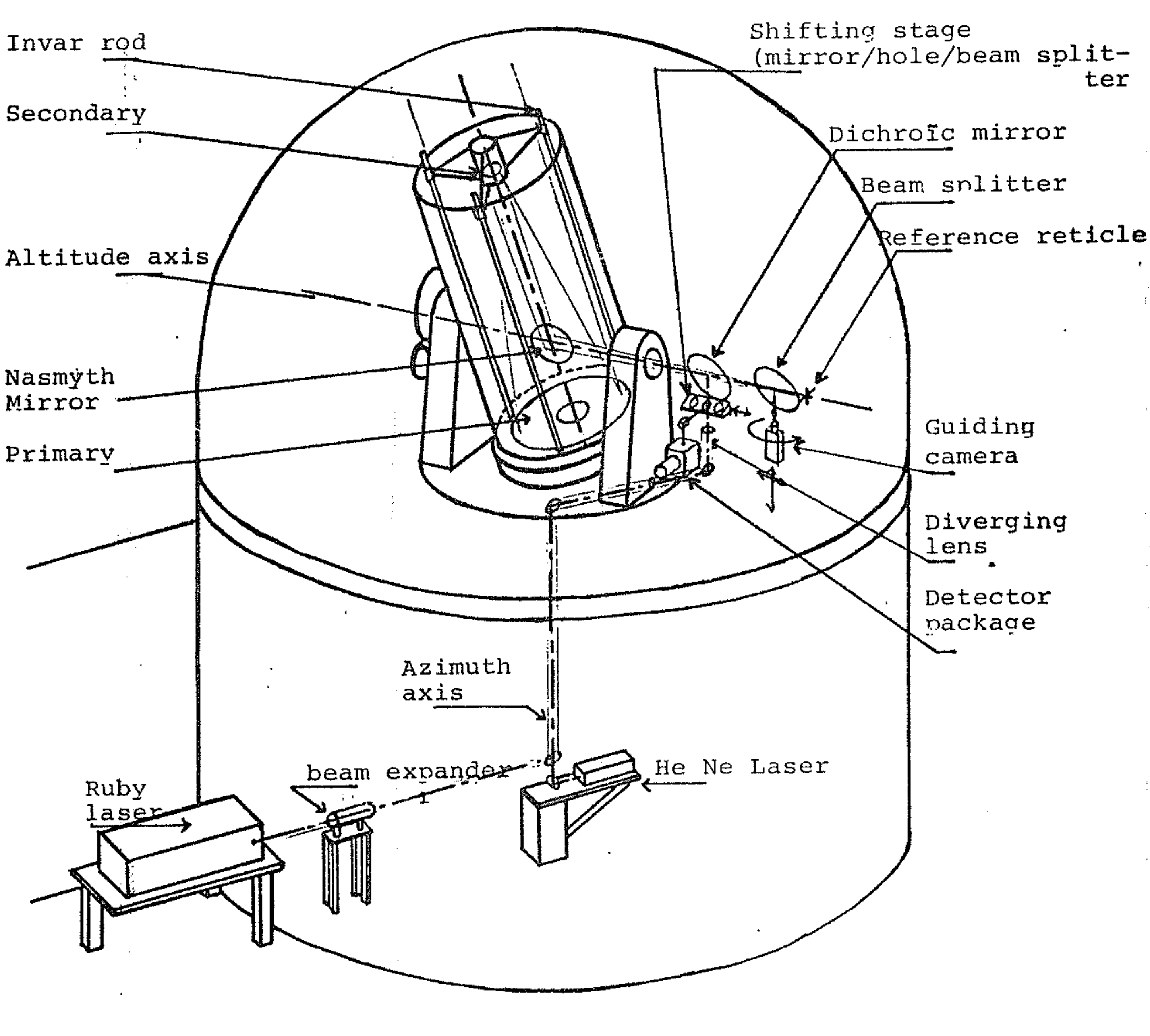

Fig. 2 : DIAGRAM OF THE MAJOR COMPONENTS

To improve the light efficiency, the secondary and flat mirrors are overcoated with silver (R≃98 %). For the same reason, the Cassegrain's location was determined by minimizing the central obstruction (taking into account the protecting light-baffles, a loss of only 11 % is obtained) . Furthermore, by frequently recoating and cleaning the mirrors the light efficiency obtained is greater than 0.8.

AUXILIARY OPTICS

The separation of the emission, reception and guiding paths is facilitated by the accessibility of the focus, due to the alta-zimuth mount Fig. 2 and 3 shows the principle.

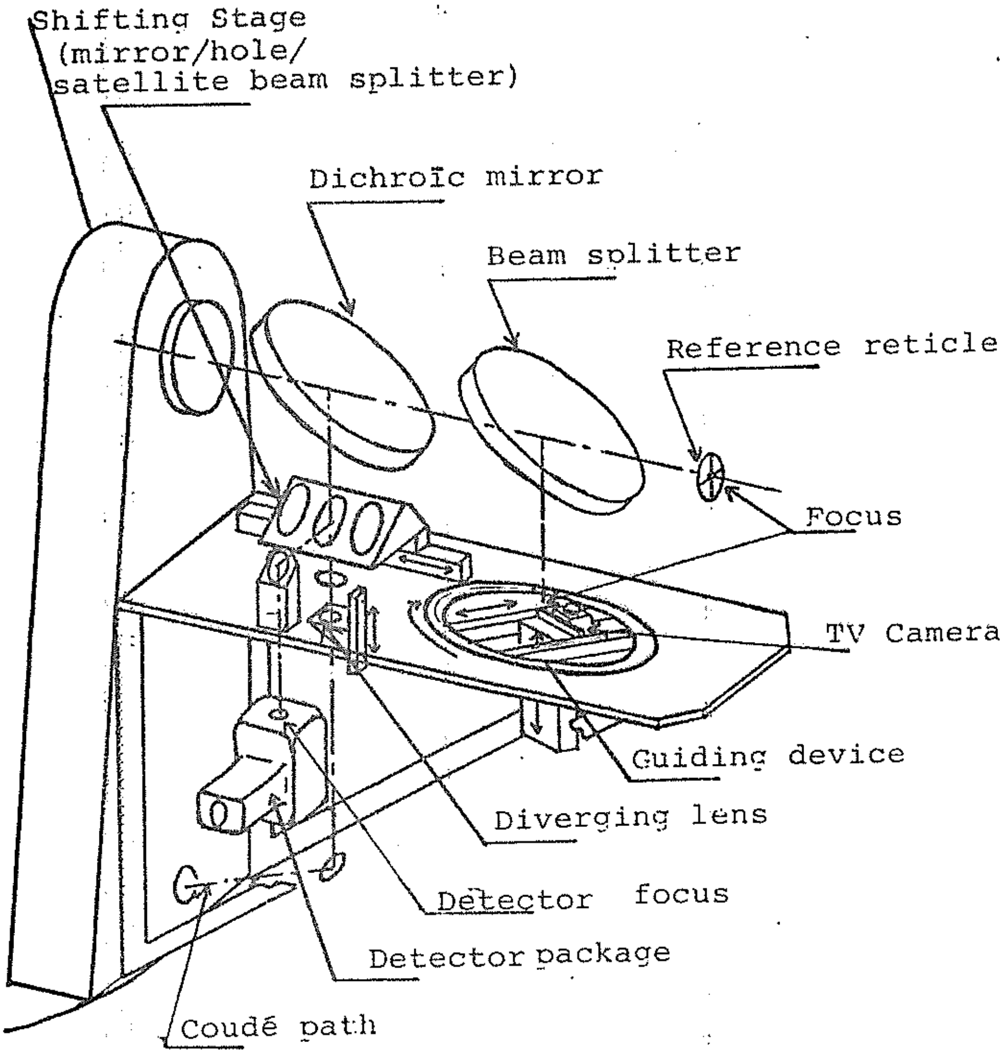

Fig. 3 : SEPARATION OF THE EMISSION, RECEPTION AND GUIDING PATHS

After emission, the laser beam is expanded to 30.5 m diameter and begins to follow the coudé trajectory. After the dichroïc mirror, the beam appears to issue from the focus of the telescope. On the return trip after the dichroïc, a shifting mirror reflects the light onto the detector package which contains a photomultiplier, spatial and spectral filters. In the case of shots at satellites or earth targets, a beam splitter is substituted which permits simultaneous emission and reception. All of these optical components have a multilayer dielectric coating. Due to special precautions against dust, the light efficiency is excellent.

The dichroïc, which reflects 99 % of the ruby wave-length, is transparent to the bulk of the visible spectrum used for guiding. A beam splitter reflects 75 % of this light while giving a horizontal guiding field. The searching of the focal surface is accomplished with the aid of a moving T.V. camera. Used without auxiliary optics, it receives a field of about 5 arc minutes in which the definition is sufficient. The camera is carried by a motorized micropositioning device controlled by a computer. This device consists of a rotary stage, which easily compensates for the rotation of the field, and two translatory stages, one for off-set field observation and the other for focusing. Due to the horizontal focal surface, the system operates in favorable mechanical conditions. Nevertheless, the original adjustment is important to hold the precision. Both the electronic reticle of the camera and the focus of the telescope must fall accurately on the rotation axis, when the camera stays in the center of the field. To make these adjustments, the focus is materialized by a projected reticle (this process is explained in the following paragraph). By rotating the device, the camera image of this focus describes a circle with a center on the axis of rotation. It now suffices to merge the projected and electronic reticles on this center.

The light transmitted by the beam splitter gives an available auxiliary focus. This one, in particular, is used as the reference focus of the telescope for aligning the three parths. A reticle define its position on the horizontal rotation axis (or more exactly its image through the two beam-splitters). To put the reticle in place, a spherical mirror is attached to the horizontal bearing and turns with the tube. Its center of curvature was chosen to be in telescope's focal plane ; hence, the reticle and its image can be merged by tilting the mirror. The adjustment is achieved when the image superimposes with the reticle ands stays fixed with the turning of the tube. Both the reticle and the center of curvature are on the horizontal rotation axis. With the lighting of the reticle, the spherical mirror projects its image on the detector package and the guiding camera, thusly defining the focus of the telescope.

For the alignment of the ruby laser beam, a He-Ne laser situated under the telescope is used. Firstly, its beam is sent out parallel to the rotation axis by auto-collimation on a flat mirror attached to the telescope. This mirror is made perpendicular to the axis by rendering fixed the reflect beam with an azimuth rotation. Afterwards by translation, the beam is centered on the axis. Then the passage of the beams rests fixed with respect to the telescope when it turns. To adjust the emission direction, the diverging lens must be regulated so that the laser beam seems to issue from the telescope's focus. The spherical mirror, used once again, gives an image of the laser beam at the auxiliary focus. By shifting the diverging lens, this image is centered on the reference reticle. Furthermore, a beam comes back to the ruby laser and is later used to adjust it. Thus, a translation of this lens parallel to the optical axis gives the wanted divergence of the emission beam which may be chosen between 1 and 15 arc seconds. It remains to merge the ruby laser beam with the He-Ne one.

This method gives an alignment of the paths better than 1 arc second and permits an easy checking of the adjustment without looking at the sky. With this mount, gravity always works in the same way, so the reliability is high.

THE MECHANICAL STRUCTURE

To obtain a good pointing and tracking quality, the alt-azimuth mount was recognized for its many advantages. Its compact and symmetricalstructure which operates in favorable conditions is better adapted to the computation of distorsion. This permits mastery of design and results in excellent unit rigidity. The axles always operate in the same conditions. Their positions, with regard to the optics, simplify the use of oil bearings. This insures a greater stability and allows a sensitive driving due to negligible frictions even at quasinull speeds. The telescope erection is easy. The control of rotation optical axis adjustment is facilitated, resulting in improved accuracy for setting and tracking. In addition, residual adjustment, defects, bending, gear faults, etc..., give an analytical expression which is easily inserted in the control program.

The mounting and the mechanical structure have been designed and drawn at the INAG Technical Division and manufactured in France. The principle elements are shown in Fig. 4. At the lower part of the telescope is a bulky platform of 2.75 m diameter. Below, a bright ring is attached and rests on 6 flats oil pads while 3 spherical ones hinder horizontal translatory movements of the axle. Above the platform, two tines support the altitude bearings.

The pads glide on spherical surfaces and their centers, which are unaffected by errors of adjustment and elastic deformations, define a steady position of the rotation axis. One of the bearings is fixed, while the other is free to move parallel to the axis with thermic dilation. The tube, formed of a 6 mm coiled sheet iron, is strengthened at the axle and holds up the primary mirror cell with its lever-weights at one hand and the secondary support at the other. The observing platform and the drive are attached to different fork-tines. The driving gear, identical on the two axes, is a worm and wheel system, with a 360 gear ratio. The torque motor, tachogenerator encoder and safety inertia wheel are directly mounted on the screw to benefit from the rigidity of the driving system. To improve the gear efficiency, contact is made with only one flank of the gear-tooth. To prevent blacklash, the worm-wheel is preloaded with a torque produced by an inert weight.

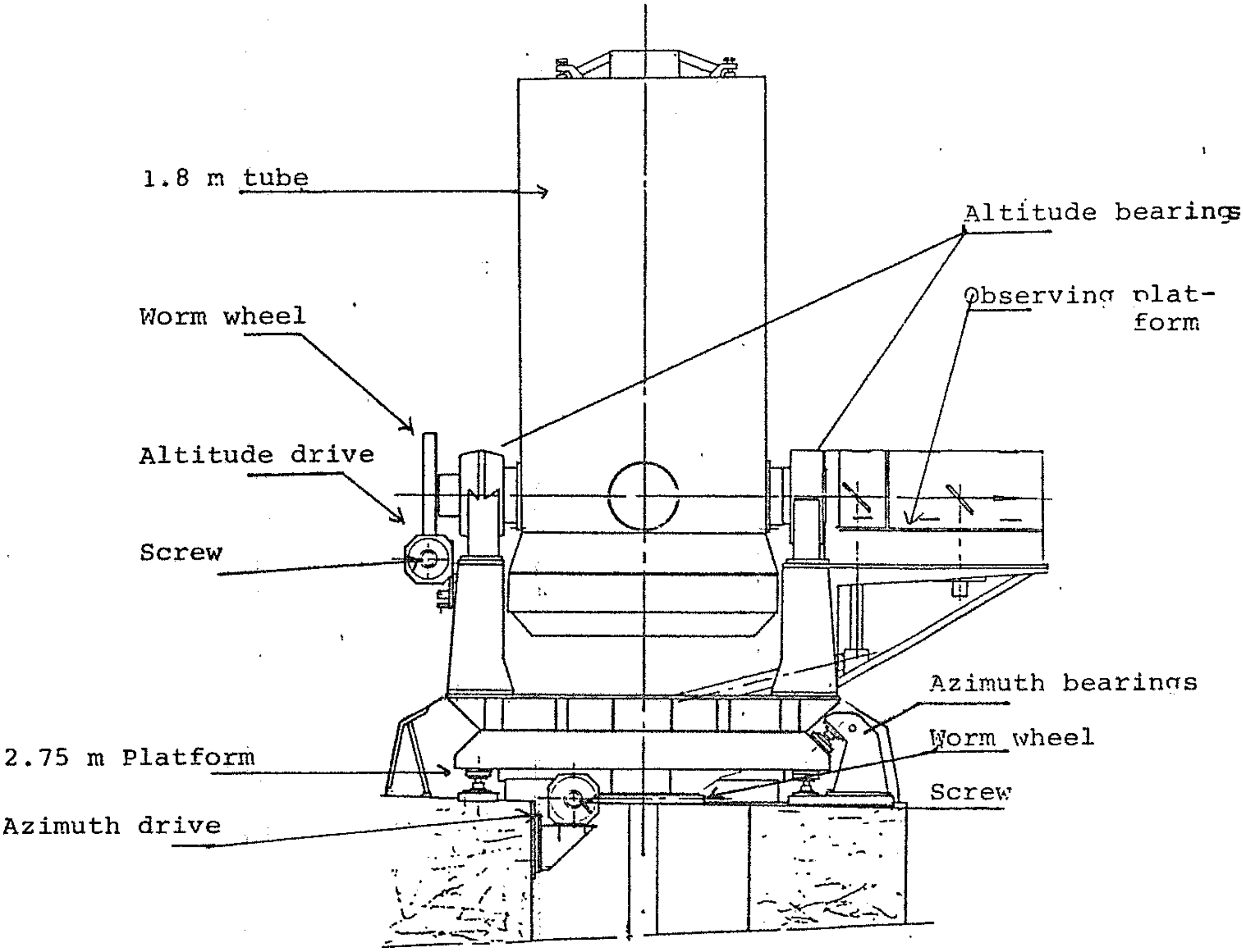

Fig. 4 : SCHEMATIC DRAWING OF THE STRUCTURE

CONTROL DRIVE SYSTEM

The control drive system is affected by the altazimuth mounting which causes the tracking speed to vary on the two axles. This produces the need of a servodrive with an important range of speeds controlled by a computer. At the conception of the telescope, the servodrive system was not evident. The technological progress permitted the finding of this satisfactory solution. Afterwards, it was noted that the recent large telescopes utilize nearly the same type of system.

The control drive system, which consists of a servomechanism directed by a computer runs succintly as described below. The computer calculates the trajectory of the telescope from the given data. To follow a star, a transformation of co-ordinates is sufficient. For the moon or a satellite, an interpolating formula is added. Moreover, the program takes into consideration the atmospheric refraction and corrects the systematic errors linked to the telescope. Over a steady interval, it gives the servosystem the necessary angle variation that the telescope must cover at constant speed. The tracking speed varies so slowly that it is nearly the same from one second to another, making a period of one second adequate.

To control the pointing, the computer needs the position of the telescope which is supplied from the encoder device. The incremental encoders, mounted on the worm screw, have a zero track which allows the position of the telescope to be known. This is achieved by relating the sum of the number of pulses to the angle turned through from a given starting point. This device produces an unambigous read-out encoder with a resolution of 0.1 arc-second on the sky, and gives the position of the sighting direction of the telescope with an average precision subordinated to the knowledge of the mechanical faults. For the tracking, the computer is outside the servoloop and does note use the encoder position.

The servosystem is identical on the two axes. It works out the speed command from the computer instructions, encoder position and possibly from manual corrections introduced by the guiding observer. Each axis is composed of an analog speed servoloop including the tachometer generator and a numeric position servoloop including the encoder. With respect to the restrictions of speed and acceleration, the numeric component generates the law of movement in terms of time, the average speed and the position error signal to control and adjust the speed of the analog component.

The obtaining of high performance with an important speed range characterizes the system. The maximum speed of the telescope is 1 revolution per 10 minutes on the two axes. On the elevating axis, the maximum tracking speed only attains 11"/s ; but, it becomes 0"/s at the meridian. In this region the working is equivalent to that of a stepper system. On the azimuth axis, as the star goes through the zenith, the tracking speed approaches infinity. However, at one degree, it becomes only a quarter of the available speed and on the moon trajectory, it never exceeds 45"/s. For a speed slightly larger than this, the sighting error during tracking is less than 0.3 arc second on the encoder. On the azimuth axis, this error is greater than the sky sighting one, because the encoder read out is the projection of the sky error. Furthermore, the encoder error stays less than 2 arc seconds for a tracking speed of 600"/s which corresponds to the maximum satellite speed that this telescope can track.

CONCLUSION

Since August 1978, this telescope has been functioning regularly. The first shots at satellites took place in June 1980 and from June 1981 the measurement of Lunar ranging began. These successes confirm the tracking quality and the alignment accuracy of the emission, reception and guiding paths. As for the pointing quality, the root mean square actually obtained is about 4 arc second, with a rough correction of mechanical faults. Using a large number of star observations, the correcting factors can be hoped to be significantly improved. If this is the case, this could open new prospects of range measurement during the new moon period where the optical guiding seems quite impossible.

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SATELLITE RANGING MOUNT SYSTEM
(HALF METER APERTURE)

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CONTRAVES COERZ CORPORATION

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1.0 INTRODUCTION

The latest satellite tracker designed, fabricated, tested, and delivered by Contraves Goerz Corporation is the system being installed at the Royal Greenwich Observatory. A second system has been delivered and installed at the Technical University, Graz, Austria (Figures 1, 2, and 3).

Like most alt-azimuth or elevation over azimuth trackers, this system utilizes a laser transmit path with Coudé mirrors and a beam expander. The satellite redirected energy is collected with a receiving optic. The system provides a customer specified detector interface. (The customer is designing and fabricating their own detector assembly.)

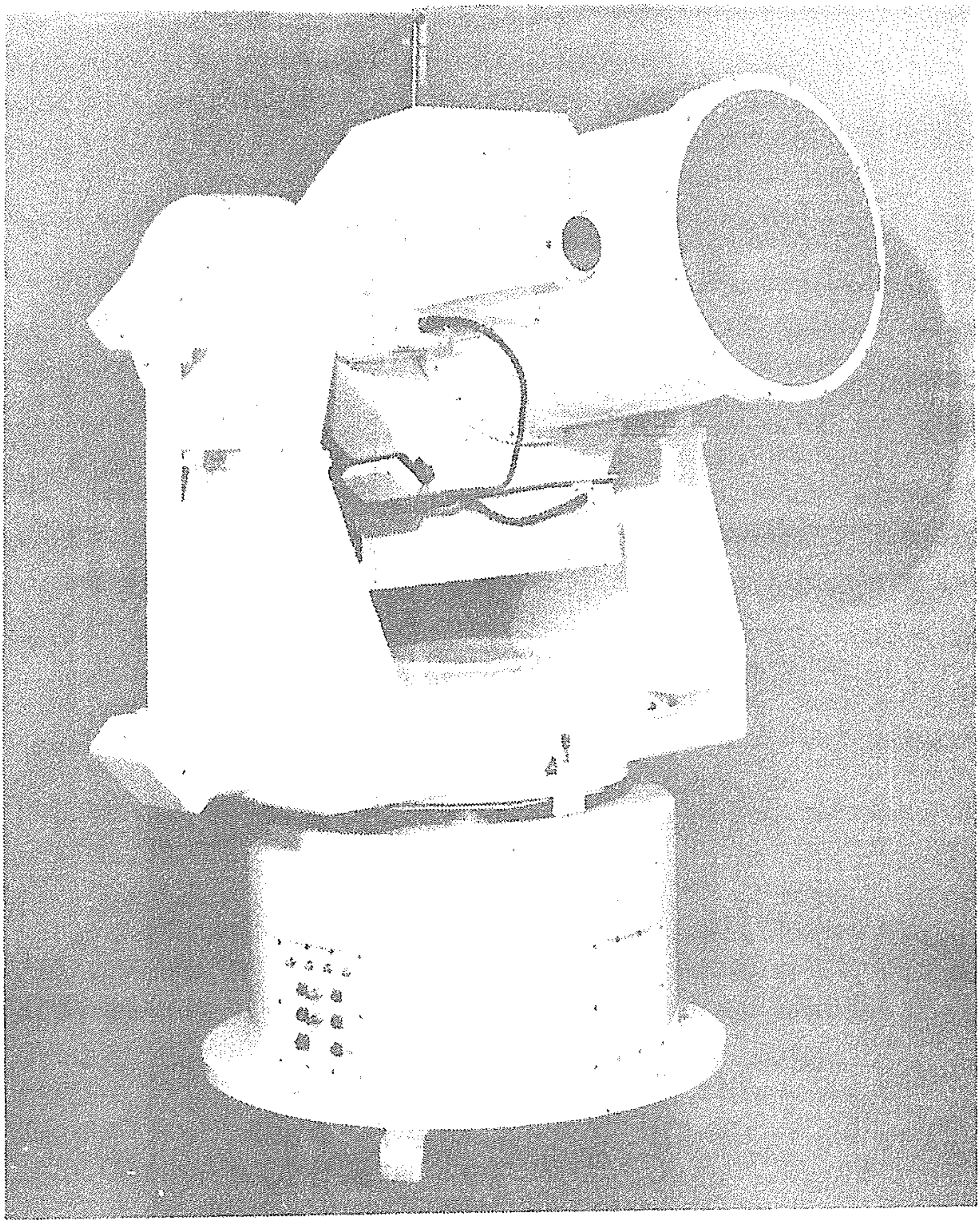

Figure 1. Graz Mount

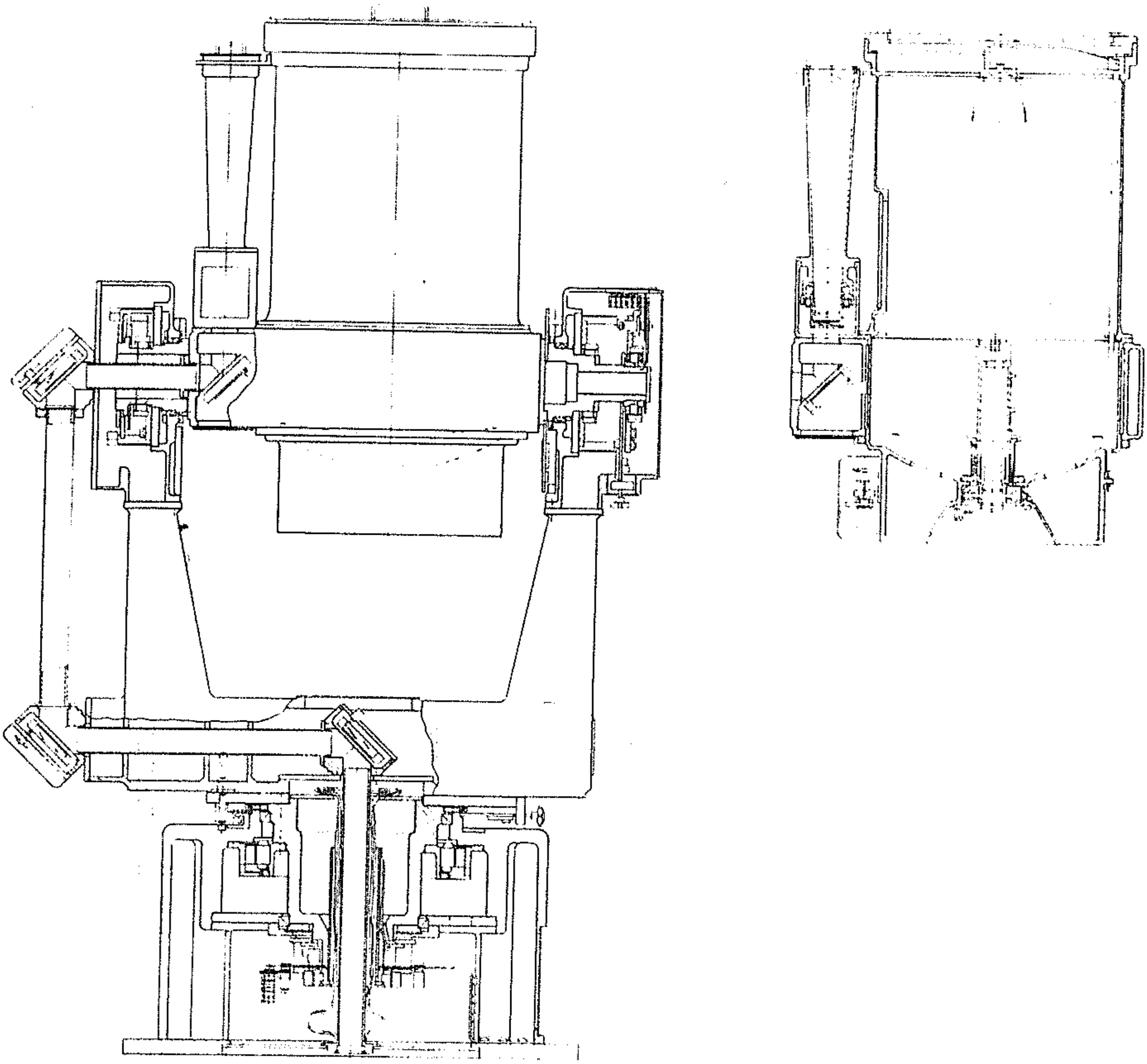

Figure 2. Graz Mount

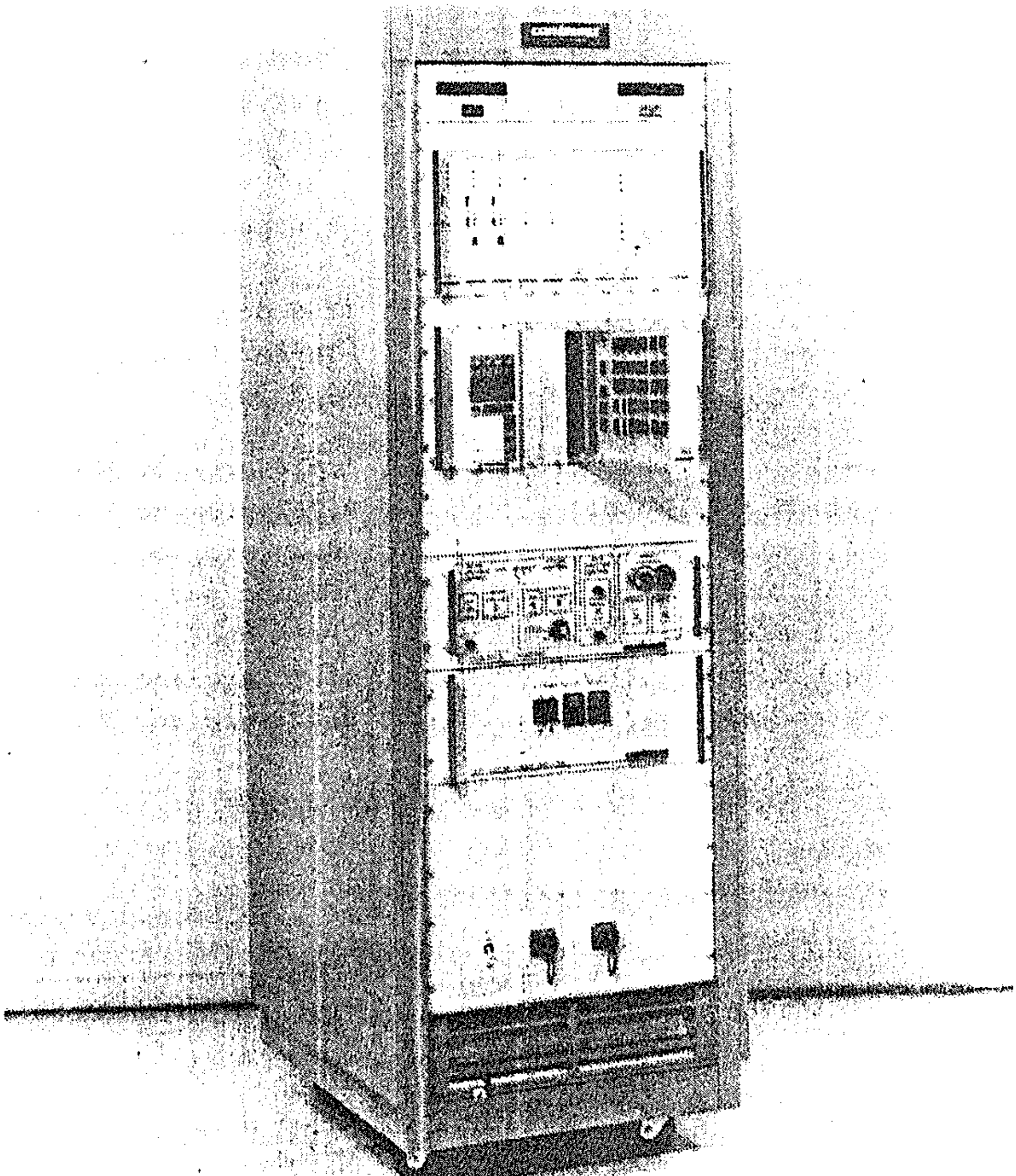

Figure 3. Mount control Console

1.1 SPECIFICATIONS

1.1.1 PHYSICAL CHARACTERISTICS

Weight	2000 pounds
Height, Floor to Elevation Axis	67"
Elevation Swing Radius	36"
Azimuth Swing Radius	36"
Payload Capability	110 pounds
Rotational Freedom	
Azimuth	±350 deg
Elevation	-10 to 190 deg
Static Precision	
Azimuth Axis Wobble	0.316 arc sec RMS
Elevation Axis Wobble	0.762 arc sec RMS
Orthogonality	±0.15 arc sec
Optical Tube Sag (calculated)	0.3 arc sec
Optical Axes Parallelism	2 arc sec
Azimuth Encoder	0.533 arc sec RMS
Elevation Encoder	0.421 arc sec RMS

1.1.2 OPTICS

Receive Optics	
Clear Aperture	20 inches f/11 telescope system f/2 primary mirror
Transmission Losses (without window)	<15% (to detector)
Obscuration Losses	<7%
Mirror Materials	Fused Silica
Performance	80% energy from a point source is imaged in a 3-arc second blur circle.
Video	
Camera	RCA TC1040/H Camera ISIT Tube
Field of View	10 arc minutes
Tube Protection	Sun Shutter

Transmit Optics	Four independently adjustable Coudé mirrors allowing a 2-inch clear aperture laser beam transmission through the mount to the beam expander
Mirror Parameters	
Flatness	λ/10 at 653 nm
Energy Handling Capability	10^{12} watts per square meter in a pulse of 3 ns duration at a repetition rate of 20 Hz
Reflective Coating	95% reflectivity at laser wavelength 70% at visual wavelengths
Beam Expander	2-inch clear aperture input 4-inch clear aperture output Variable beam divergence of 5 to 200 arc seconds

1.1.3 SERVO WITH PAYLOAD

Acceleration	
Azimuth	47 deg/sec^2
Elevation	18 deg/sec^2
Velocity	
Azimuth	0.008 to 23 deg/sec
Elevation	0.008 to 21 deg/sec

<u>Encoding System and Control</u>

Range	0.00 to 359.9999 deg
Velocity Error	1 arc sec/rad/sec
Acceleration Error	2 arc sec/rad/sec

Transducer	720-pole, 1 arc sec Inductosyn
Resolution	0.0001 deg, 0.36 arc sec
Accuracy	±1 arc sec
Repeatability	0.1 arc sec

Precision Range Command (Tracking Mode)

Rate Range	0.0001 to 199.9999 deg/sec
Resolution	0.0001 deg/sec
Accuracy (long term)	0.001% + 0.001% per year
Position Step Size .... (Rate modes of operation)	0.0001 deg

2.0 SYSTEM HARDWARE

The mount and telescope assemblies are aluminum castings and weldments, ground to a smooth exterior finish and painted for high solar reflectivity with a titanium base white point. Light paths are painted with a flat black and other elements are alodined or anodized for corrosion resistance.

The measured resonant frequency of the system is 73 Hz.

2.1 AZIMUTH AXIS

The stationary base consists of a cylindrical casting with a bolted plate flange. The angular contact bearing pair supports the azimuth shaft with the torque motor directly coupled to the shaft between the bearings. The bearing spread provides a very stable axis.

Below the lower bearings is the Inductosyn plates (encoding transducer), tachometer, and the gear driven synchros and electrical limit switches. Passing inside the azimuth shaft is the stationary laser transmist tube, with the rotary seal being at the tube-yoke mirror housing interface.

An azimuth torquer between 75 and 300 foot pounds can be accomodated without alteration of the manufacturing drawings. Further, the present design accomodates a vertical incoming laser beam, but a Coudé housing can be added inside the base allowing a horizontal beam. This is accomplished by simply adding to the cylindrical portion of the base.

Cables and wiring to the elevation axis and payload are distributed and wrap about the beam transmit base. The azimuth rotation, as stated in Section 1.1.1, is approximately ±350 degrees.

The yoke, a part of the azimuth assembly, supports the elevation pillow blocks and thus the elevation axis, telescopes, and payload. It also supports the outboard Coudé mirrors and provides a conduit for wiring. The yoke is a weldment. Wiring to the payload is via a table drape across the elevation axis, the connector panel being on the yoke tine inner wall.

2.2 ELEVATION AXIS

The pillow blocks are standard. The casting pattern was generated in 1973 and used through these instruments. We have had 1000 pounds on the gimbal ring without deteriorating the wobbles or orthogonality.

Our standard configuration is an identical torquer in each pillow block. Then, the Inductosyn plates are mounted on the one side, usually with the Coudé path interface. The opposite pillow block houses the limit switches, synchros, and tachometer.

Like the azimuth axis, there are mechanical snubbers for end stops, a stow lock pin, and manual slow motion/lock assembly.

An integral part of the elevation axis is the gimbal ring. The ring is designed to accomodate a 24-inch clear aperture receiver assembly. This mount has the previously mentioned 20-inch receiver telescope.

2.3 OPTICS

The optics are normally part of the payload. However, the payload cited in Section 1.1.1 is the detector assembly that mounts aft of the receiver telescope.

2.3.1 TRANSMIT

The terminus of the Coudé path is the 2X transmit beam expander. The remote driven beam expander consists of a fixed front lens element and rear air spaced doublet. The second element of the doublet is driven to cause the divergence to range from 5 arc seconds to 200 arc seconds, a milliradian.

This movement is also sufficient to provide collimation for laser wavelengths between 0.5 μ and 1.1 μ. The Coudé mirrors are coated for 0.532 μ wavelength energy and different coatings are necessary to optimize the other wavelengths.

Four individual Coudé mirrors, manually adjusted, direct the beam through the azimuth and elevation axes and into the beam expander. The allowable transmit beam is two inches.

2.3.2 RECEIVER

The receiver telescope is a Cassegrain with a fused silica primary and secondary. Invar spacer rods are used between the primary and secondary, with the tube structure being cast aluminum.

The receiver has a field lens and a collimating doublet that is motorized and used for focus. The outgoing beam, approximately 1.25 inches in diameter, passes through a beam splitter, the 0.532 μ wavelength passing through to the detector and all other energy reflected to the TV cameras. As stated previously, the detector responsibility was retained by the customer. However, subsequently, the customer requested an iris to be integrated with the field lens. This was accomplished using an iris that cut the field of view (FOV) in half to approximately 5 arc minutes.

2.3.3 RETROREFLECTOR

As part of the optical package, a retroreflector (simulated corner cube) was built to place the transmit beam in the receiver. The retro assembly makes the beam to the receiver parallel to the transmit output. This device allows the mount to be exercised full range across both axes and to observe beam movement with the TV.

The specification was axis parallelism of 2 arc seconds and differential fixture of 3 arc seconds. With this technique, separating the two error sources is nearly impossible and observations of movement of less than 5 arc seconds on the TV screen becomes very subjective. Nonetheless, all observers felt the movement was less than 5 arc seconds.

2.4 CONTROL SYSTEM

The control system consists of the MPACS (Modular Precision Angular Control System) control chassis, dual power amplifier, display module, and joystick box, which can be housed in a 19-inch console. The control chassis contains the controls for focus, beam diverger, reticle intensity, and mount limit functions. MPACS is the heart of the control system and contains the digital and analog servo circuitry that implements all the different modes of operation and provides position readout. The dual power amplifier drives the azimuth and elevation DC torque motors in response to outputs from MPACS. The joystick box provides MPACS with a rate command proportional to the stick deflection.

2.4.1 MPACS

The MPACS chassis is a modular precision absolute control system. It is an integrated control module, the CGC MPACS form of control system which features minimum distraction placed on the customer's control computer during operation. This is significant in two ways.

1. The position control servo loop is controlled within the MPACS system, with only the position command being generated by the customer's computer.

2. The MPACS system accepts a digital rate command input from the customer's computer which commands the system to rotate at a very precise rate, such that the predictability of position versus time velocity is better

than 1 part per million. As a result, during a normal satellite pass, the customer's computer has to output rate only when a rate change is necessary in order to keep the mount pointed on a correct line of sight to the satellite. For the extreme case of a 200 km orbit which approaches 4° from zenith, rate update of once per second will ensure that the deviation, as the mount pointing angle from the desired line of sight, will be less than 2 arc seconds.

2.4.1.1 CONTROL MODES

Keyboard Control Mode (Manual)

Control via hand-held (25-meter extender cable) or front panel mounted Keyboard Control module.

Access to all Position/Rate Readout/Self-Test modes.

Computer Control (Remote)

Multiplexed, bidirectional, general purpose computer interface (16-bit parallel or GPIB module) providing Position, Rate, Readout, and Self-Test mode control from remote computer.

Manual Rate Mode

The servo system provides closed-loop rate control. The loop is closed via the Servo module using the tachometer input provided from the joystick in the remote pendant control box. This provides the operator with the option of moving the azimuth or elevation axis while in Computer mode.

2.4.2 CONTROL CHASSIS

The control chassis contains the control circuitry for the FOCUS, BEAM DIVERGER, SHELTER PROTECT, and MOUNT STATUS indicators. The beam expander control consists of two switches. The SPEED switch allows the selection of either HIGH or LOW speed when the DIAMETER switch is activated. The DIAMETER switch increases or decreases the size of the beam that exits the beam diverger.

The focus is controlled by the SPEED and DIRECTION switches. The above switches are active when the LOCAL/REMOTE switch is in the LOCAL position. The REMOTE switch position allows the above functions to be controlled by the customer.

A SUN SHUTTER control switch allows the selection of AUTOMATIC operation or REMOTE operation of the sun shutter. An indicator lamp tells when the shutter is closed.

A SHELTER PROTECT switch is provided which will indicate, via a closure, if the elevation axis has reached 20 degrees above horizontal.

The MOUNT DUMP switch, when on, allows the elevation axis to travel through its normal 95-degree limit until it reaches 180 degrees. If at any time a limit condition occurs, an alarm will sound until that condition is clear. The alarm can be disabled.

EXPANDER LENS COVER and MAIN LENS COVER indicators tell when the covers are in place.

2.4.3 DUAL POWER AMPLIFIER

The dual power amplifier contains two 60-CG-500 linear amplifiers. The chassis also contains the 60 VDC power supply for the power amplifier as well as the on/off control logic for the output contactor.

MOUNT AND TELESCOPE FOR THE GERMAN/DUTCH MOBILE SYSTEM

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1. Introduction

In close co-operation with the Working Group for Satellite Geodesy in Kootwijk (a part of the Delft University of Technology) the Institute of Applied Physics is manufacturing two mobile laser ranging stations. One system will be delivered to the "Institut für Angewandte Geodäsie" (IFAG) in Frankfurt, Germany and the other system will be used by the group in Kootwijk.
The co-operation can roughly be characterized by stating that the mechanical and optical aspects of the system are handled at the Institute of Applied Physics while the electronical hardware and software is developed by the Working Group in Kootwijk.

2. Station configuration

In figure 1a the mobile ranging station is shown in its road transportable configuration. The telescope mount, detection package and pulse laser are built into a small cart of about 2,1 x 1,8 x 1,9 m^3 (l x d x h) inside the off-loadable truck cabin. In the operational configuration (figure 1b) the cart is rolled out of the truck cabin over rails of more than 10 m length to the selected location of the telescope mount. When the cart is positioned at its location the wheels of the cart are lifted and the cart will stand with four feet on the ground. The mount itself is supported independently of the cart with three feet directly on the ground.

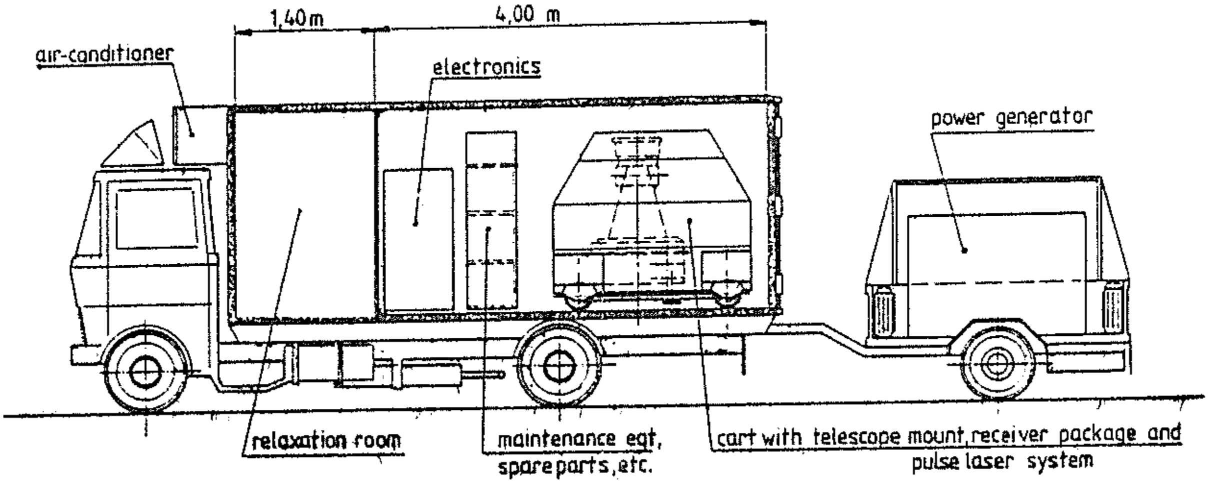

Figure 1a Road transportable configuration

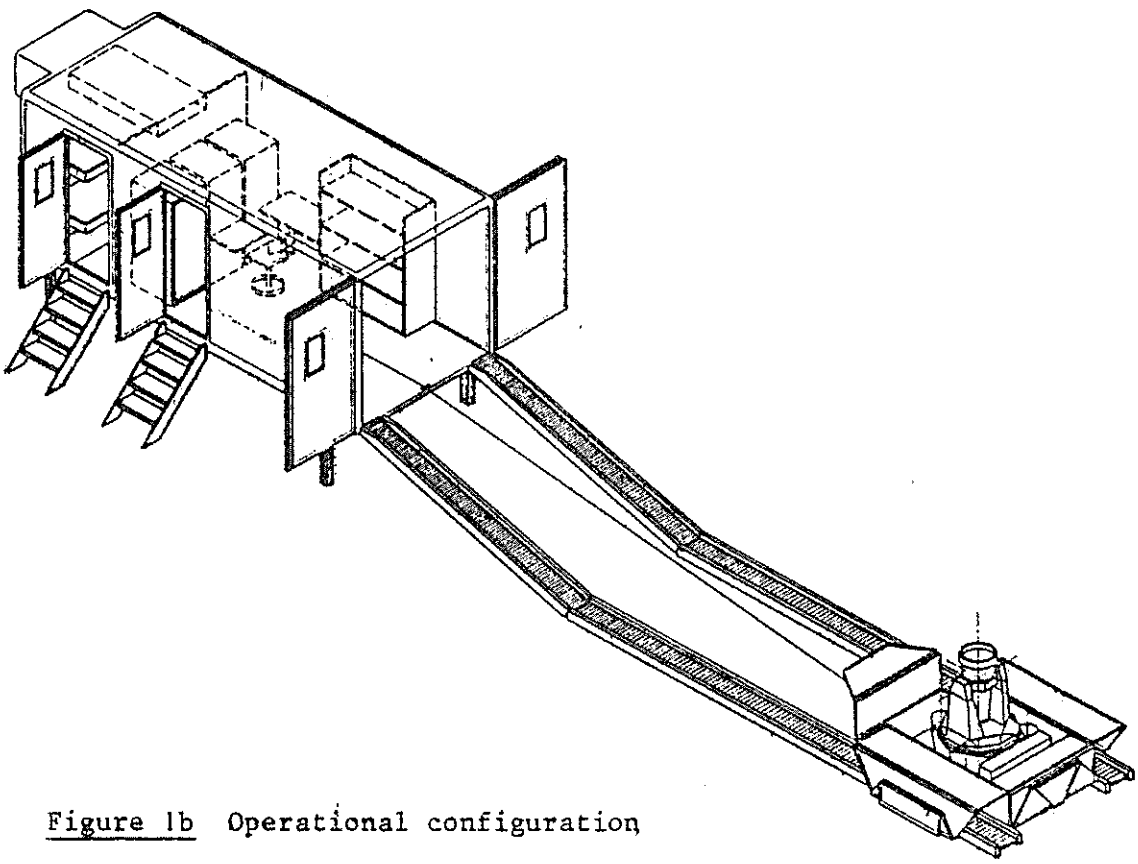

Figure 1b Operational configuration

The truck can be driven from underneath its ground supported cabin to maintain the contact between the ranging station and the outside world.
The thermally insulated, air-conditioned cabin has a relatively large observation room of about 4,0 x 2,1 x 2,1 m^3 interior and a small relaxation room.

Transformation from the road transportable configuration to a fully operational status inclusive precise orientation and a functional calibration can be achieved within a single 24 hours time period, given good weather conditions.

The actual ranging system can also be transported by regular air transportation. The cart with the telescope mount, pulse laser and detection package, together with the entire electronics-racks, can just be stowed on one standard air freight pallet of 3,1 x 2,1 m^2 maximum loading area.

3. Telescope mount

3.1 Mechanical aspects

In figure 2 a schematic outline of the altazimuth telescope mount is presented. Except for the aluminum telescope tube all the major mount structures will be made of welded steel. The total weight of the telescope mount will be no more than about 500 kg.
The axial and radial bearing of the azimuth axis are separated. Three conical wheels carry the weight of the rotating part of the mount and provide for the axial bearing of the azimuth axis.
A preloaded set of ball bearings near the main gear-wheel defines the position of this gear-wheel with the respect to the rest of the drive system. D.C. servo motors drive both axes through a combination of high grade spur and spiroïd gears. All backlash in the gearboxes will be removed.
Angular read-out is by incremental encoders coupled to axes in the gearing system that are 36 times faster than azimuth and elevation axis. The incremental encoders give 50.000 pulses per revolution of the encoder axis which corresponds to 0,0002 degree (0,72 arcsec) of the azimuth or elevation axis.
The encoders are provided with zero indexers that give one pulse per revolution of the encoder axis (10,000 degrees of the azimuth or elevation axis). The zero pulses reset the counters that give the angular position of the telescope to the nearest exact tens of degrees. In this way lost or incorrectly added counts are corrected every ten degrees of rotation of the azimuth or elevation axis.
In table I the most important design specifications of the mount are presented.

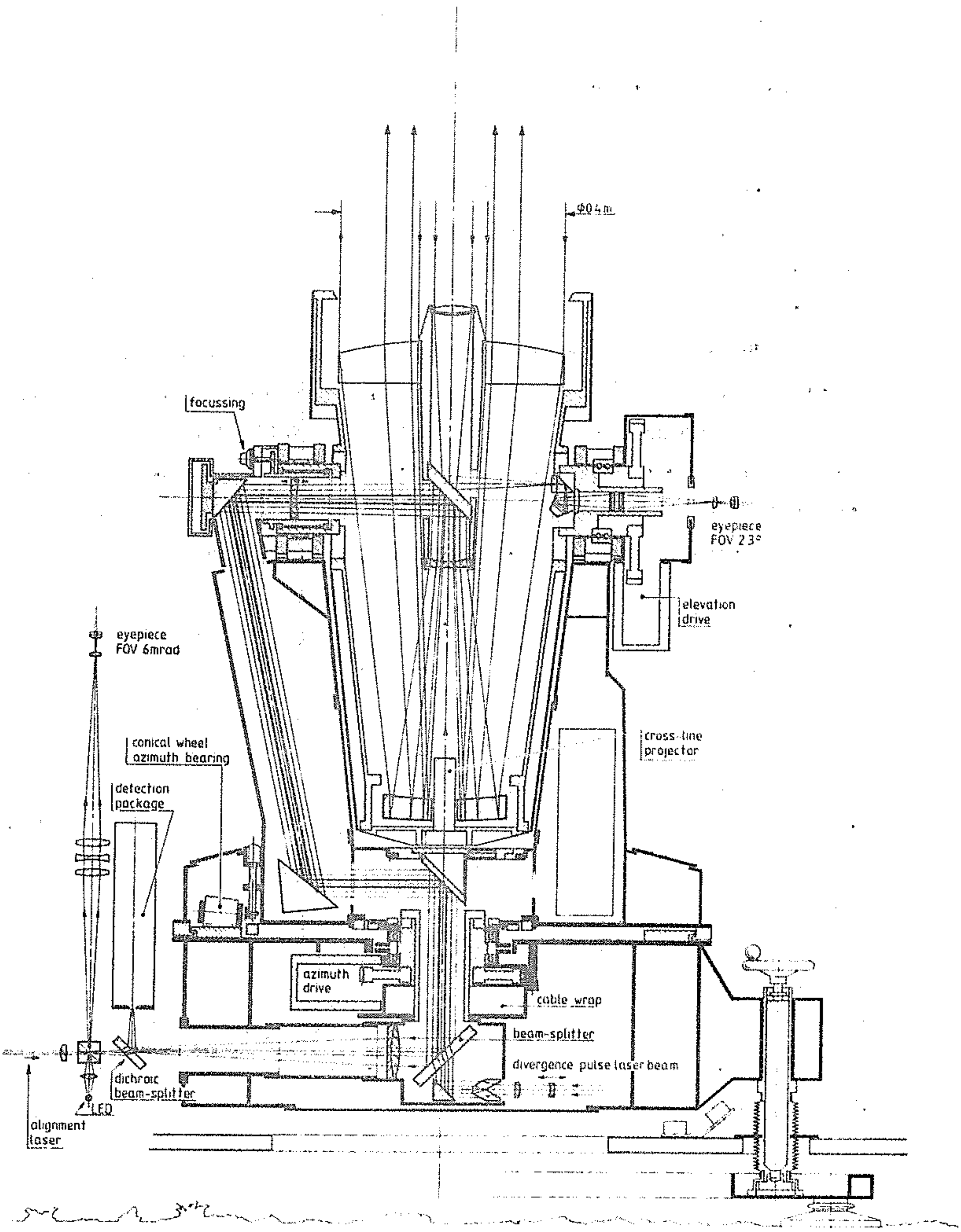

Figure 2 Schematic outline of the telescope mount

Table I Design specifications of the mount.

- max. angular velocity: in azimuth > 10 °/sec
  in elevation > 4 °/sec
- max. angular acceleration: in azimuth > 5 $^{\circ}/sec^2$
  in elevation > 2 $^{\circ}/sec^2$
- total angular travel: in azimuth 720°
  in elevation 200°
- tracking of all present co-operative satellites
- static pointing possibility
- maximum pointing error due to flexure, wobble, non-orthogonality of the axes, gear and encoder errors: less than 10 arcsec without computer correction
- maximum angular jitter: less than 2 arcsec r.m.s.
- operational environment: temperature -20 °C to +50 °C
  humidity 0 % to 95 %
  altitude 0 km to 4 km.

3.2 Mount guidance

A hard wired digital servo system will handle the signals from the optical encoders and will supply a control voltage to the (speed-) servo amplifiers.

The digital servo unit will display:

- the actual position of both axes;
- the difference between desired and actual position of both axes;
- the speed of both axes during tracking.

The digital servo unit accepts desired positions and/or rate commands from a micro-processor based fixed program controller (Motorola 6809). This controller translates the desired positions at given times (with e.g. 1 second intervals) into commands for the digital servo unit, using adequate interpolation techniques.

3.3 Optical aspects

As shown in figure 2 there is one common catadioptric coudé telescope system with an aperture of 0,4 m diameter for both transmitting and receiving.
The frequency doubled Neodymium pulse laser system is not shown in figure 2 but this laser is mechanically connected to the base of the telescope mount in such a way that the direction of the pulse laser beam is defined by the telescope mount without loading the mount with the full weight of the laser system.
The laser beam is directed into the base of the telescope mount where first the divergence of the beam is adjusted to the desired value. By the indicated movement of the negative lens the divergence of the beam that leaves the telescope mount can continuously be adjusted from less than 0,05 mrad (10 arcsec) to over 1,0 mrad (200 arcsec).
After the divergence adjustment lens system the laser beam is split into two halves by two plane plates of glass at the brewster angle so that the central obscuration of the main telescope will not introduce a "hole" in the beam in the "far field".
The pulse laser beam is coupled into the coudé optical train by means of a beamsplitter. This beamsplitter is used as a mirror for the received beam while two semi-circular holes in the mirror coating transmit the laser beam. The reduction of the effective receiver aperture that is introduced by the two holes in the mirror coating will be less than 20%. The rest of the transmitting optics consists of the coudé mirrors and the main telescope.
The overall optical efficiency of the entire transmit optical train of figure 2 will be over 80%.

The received light is collected by the common main telescope and is also directed through the coudé optical train. At the beamsplitter most of the received light is reflected and is then focussed by an achromatic doublet.

The unvignetted field of view of the telescope system as receiver is limited by the aperture of the coudé optical train to about 2,0 mrad.
At the dichroic beamsplitter a wavelength band around the laser wavelength (green) is reflected into the entrance diaphragm of the detection package. This detection package will be described in another paper to be presented during the Workshop. The rest of the visual spectrum is transmitted through the dichroic beamsplitter. This light is focussed on a beamsplitter cube that reflects the entire useful field of view of the telescope system (about 6 mrad diameter) to an eyepiece, except for a small pinhole in the reflective coating of the cube.
The position of this pinhole corresponds to the middle of the entrance aperture of the detection package. Through the pinhole a He-Ne alignment laser beam can be transmitted into the coudé optical train. A LED indicates the middle of the entrance aperture of the detection package in the eyepiece.
Visual viewing through the telescope system will be possible and eye-safe also when the pulse laser is firing. The eyepiece has a fixed and convenient position for an observer. With an eyepiece magnification of 8 times the magnification of the entire telescope system as seen through the eyepiece will be about 120 times.

In the central hole in the main telescope mirror a cross-line reticle projecting system is indicated in figure 2.
This cross-line can be seen in the eyepiece and is used as an alignment aid and for the determination of the station position from a geodetic star program.

In the central hole of the 0,4 m diameter front lens of the main telescope the objective of an auxiliary sighting telescope with a 78 mm clear aperture is located. The light of this small telescope is directed through the motor side of the elevation axis to an eyepiece.

With an eyepiece magnification of 8 times the auxiliary sighting telescope has a magnification of about 20 times and a field of view of over 2 degrees.

4. Brief description of the rest of the ranging system

The third generation ranging system will be capable of day and night time ranging to all present co-operative satellites (Lageos, Starlette, etc.).

The pulse laser will be an actively mode-locked, frequency doubled Nd-YAP or Nd-YAG system (539 nm or 532 nm respectively), that has been ordered at Kristalloptik in Germany (near Munich). Besides the oscillator the laser will have one double pass amplifier. The laser system has the following general specifications:

- pulse width: 0,2 ns
- pulse energy: 10 mJ of green light
- repetition rate: 10 pps
- operational environment: as for the telescope mount.

The detection system will be described in another paper to be presented during the Workshop.

The ranging station will be equipped with several micro-computers. A large micro-computer system (HP 1000 Model 5) will perform all activities that are not directly related to hardware. This "central computer" is, for instance, used for predictions, data recording, data screening, diagnostics, etc. A smaller micro-processor (Motorola 6809) with a fixed program will take care of detector control, laser firing control and data formatting. Another small micro-processor (Motorola 6809) with a fixed program controls the mount servo system and the range gate generator. Operation of the ranging system during a satellite pass will be through an "operator control panel" with switches and displays. This control panel is connected to the central computer. The central computer controls the two micro-processors.

SESSION 4 : LASERS

Chairmen: K. Hamal, Czech Technical University, Prague, Czechoslovakia
D.R. Hall, Applied Physics Dept., Hull University, Hull, England

INTRODUCTION

While it is clearly self evident that high precision long range optical distance measurements are only made possible with the aid of wide bandwidth laser transmitters, it is also apparently true that lasers, at the heart of satellite and lunar ranging systems have been, historically, a likely source of ulcers and high blood pressure for those charged with the responsibility for producing high quality ranging data on a regular basis from operational stations. Over the years there have been problems, not only with laser reliability, resulting in station 'down' time but also with data interpretation because of range uncertainties due to temporal fluctuations in the laser output pulse as well as variations in the spatial distribution of transmitted energy.

Following this Session of the Workshop there was a distinctly more optimistic air both from the standpoint of the understanding and control of fluctuations in laser output and also in view of improvements in demonstrated performance reliability.

The Session was organised in two parts, the first - a collection of five papers from the U.S., England, Czechoslovakia and Germany, followed, after a short break, by a panel discussion addressing the topic of "Lasers for Ranging - Present Problems and Future Prospects".

In the first paper in the Session, John Degnan described some important work in which a range of laser types, Q-switched, cavity dumped, passively mode-locked and actively mode-locked were assessed in a ranging system operating over a fixed terrestrial range for the contribution to rang uncertainty due specifically to laser fluctuations. The results clearly indicate that mode-locked lasers offer superior performance not only because they offer shorter pulses, but also because of the absence of spatial effects due to variation in the transverse mode structure of the laser output.

S.R. Bowman presented the next paper on the design and early development stages of a laser intended for lunar ranging. It is designed to produce an output of 1 Joule in 100 psec pulses at up to 10 Hz in the green, and utilise a face-pumped slab of YAG as the final amplifier. D.R. Hall described the design and performance characteristics of a passively mode-locked, oscillator-amplifier, doubled YAG system developed for use in the U.K. SLR system to be sited at

Herstmonceux. This was followed by a presentation from the Czech Technical University on Laser Activity in the Interkosmos Network. In particular, Helena Jelinkova discussed the technique of constant gain Q-switching and presented results on its application in both Nd:YAG and ruby lasers. Finally, H. Puell described the outline design of the planned actively mode-locked laser for use in the German/Dutch Mobile SLR systems (described elsewhere).

After a short break at the end of the formal presentations, the Session recommenced with a Panel Discussion. A somewhat hastily assembled Panel of J. Degnan, T. Johnson (NASA), D. Burns (Sylvania) J. Wohn (Smithsonian), H. Puell (Kristalloptik) chaired by D. Hall (Hull University) discussed a number of issues relating to lasers in and for ranging systems, with considerable "audience" participation. Topics discussed included difference in laser requirements for satellite and lunar ranging systems, laser reliability, servicing frequency, ultra-small lasers for mobile systems and the commercial realities relating to the small size of the extra terrestrial ranging systems market and the impact this has on the developments in which companies are prepared to invest resources to produce well-engineered lasers for field us. Finally, some time was spent airing the inevitable dichotomy between system/laser users who want regular data now and hardware specialists who are inclined towards continual hardware improvement and refinement.

Fourth International Workshop
on Laser Ranging Instrumentation
Austin, Texas October, 1981

THE NEW UNIVERSITY OF MARYLAND RANGING LASER †

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ABSTRACT

For the last year and a half, a new laser for laser ranging and time transfer has been taking shape at the University of Maryland. This paper describes our objectives and design considerations, as well as the progress made on the construction of the laser.

† Work supported by U.S. Naval Observatory and Office of Naval Research.

OBJECTIVES

The new ranging laser is being built in two stages. When completed near the end of this year, the major portion of the new laser will replace the existing laser in the University of Maryland ranging station at the Optical Site of the Goddard Space Flight Center[1]. The resulting system will be used as a ground-based relay station in the LASSO (Laser Synchronization from Stationary Orbit) experiment[2]. This experiment is designed to demonstrate the feasibility of achieving time synchronization between remote atomic clocks with an accuracy of one nanosecond or better. The Maryland station will serve as the connection between the atomic clocks at the Naval Observatory in Washington, D.C. and the clock on a SIRIO-2 geostationary satellite. Similar laser ground-based stations in Europe will complete the link.

To complete the round-trip link with the SIRIO-2 satellite, the new laser must provide at least 200 millijoules at 530 nanometers. This must be delivered in a single pulse with a duration of less than a nanosecond. The designed performance is several times these minimum requirements.

The second stage in the construction of the new laser is the addition of a final amplifier. This will allow the Maryland ranging system to do lunar ranging. Our objective is to prove the feasibility of high accuracy lunar ranging using modest size telescopes. To accomplish this, we need a sub-nanosecond, high average power laser with good beam quality. Our goal is to obtain one joule of green light in a 100 picosecond pulse at ten shots per second while maintaining less than ten times the diffraction limit at the laser.

LASSO LASER DESIGN

Meeting the above requirements for laser energy, pulse duration, and beam quality do not present a serious technological problem. The problem lies with the requirement on the repetition rate. To avoid damage from high power densities, the laser rod cross-section must be large. This, in turn, increases the thermal decay time. Thermally induced lensing and birefringence then limit the repetition rate, if the beam quality is to be preserved.

In order to minimize thermal problems, the laser rod diameters are kept as small as possible. Damage from high peak power densities is avoided by keeping the laser environment clean, the spatial profile of the beam smooth, and minimizing the number of optical components exposed to high intensities.

Three different laser materials were seriously considered for use in the new laser. Their most important characteristics are compared in Table 1. Athermal Neodymium doped glasses are available with the required physical dimensions and have relatively low nonlinear indices. However, their combination of low absorbtion cross-section and low thermal conductivity make high repetition rates difficult.

Neodymium doped yttrium aluminum garnet (Nd:YAG) has been a standard laser material for many years. It has a higher thermal conductivity and absorption cross-section than glass, but limited crystal diameters have excluded YAG as a candidate for high energy, short pulsed systems until very recently[3].

Neodymium doped yttrium lithium fluoride (Nd:YLF_4) is a very promising laser material which has recently become commercially available. It is similar to YAG but with the advantage of low nonlinear index and large diameter crystals. Also, YLF_4 is naturally birefringent, so beam depolarization from thermal birefringence should not be a problem.

The initial stage of the laser is being built with YAG rods. Replacement YLF_4 rods have been obtained for research purposes. Present plans are to build the final amplifier out of YAG because of the delay and expense of obtaining larger YLF_4 rods.

To operate an amplifier chain efficiently without damage, a stable input pulse is needed. This is achieved by using both an acousto-optic modulator and a saturable dye to modelock the oscillator (Figure 1.). Proper adjustment of the dye concentration and cavity length have produced 30 picosecond, TEMoo mode pulse-trains with less than ten percent fluctuations in the shot-to-shot energy. Improved stability is expected after current modifications to the dye circulation system. Pulse durations can be lengthened using intracavity etalons.

The growth of the laser pulse in the oscillator is monitored by a bulk semiconductor detector with a risetime of 30 picoseconds[4]. (Figure 2). This detector triggers a voltage level discriminator whose output in synchronized with the 50 MHz signal from the acousto-optic modulator. A single three volts pulse with one nanosecond rise is produced. This signal triggers a planar-triode amplifier to launch a travelling, high voltage pulse to the Pockels cells. Risetime of the high voltage is 1.8 nanosecond and the internal jitter of the amplifier is only 30 picoseconds. (In addition, the amplifier's lifetime is effectively not a function of the repetition rate.) When the half-wave voltage reaches the Pockels cell in the oscillator, the laser energy is reflected out by a thin-film polarizer. Single pulse energies of 1.5 millijoules have been obtained.

After the oscillator lies a double-pass, 1/4-inch diameter amplifier. This is followed by a single-pass, 3/8-inch amplifier. Two Pockels cells and several thin-film polarizers isolate the amplifiers and oscillator until the cavity dump occurs. This reduces amplified spontaneous emission and amplified leakage from the oscillator.

Each amplifier is followed by a vacuum spatial filter. Spatial filters serve several functions:

1.) Reduce optical damage by smoothing out the spatial profile of the beam.

2.) Restrict the growth of nonfocusable energy.

3.) Correct for thermal lensing and diffraction ripples by imaging amplifier output to amplifier input.

4.) Expand beam to fill amplifier.

Following the second spatial filter is a KD*P, type II, doubling crystal. Conversion efficiencies of 60 to 70 percent are expected. Table 2 summarizes the expected output parameters of the LASSO laser.

FINAL AMPLIFIER

To accomplish our lunar ranging objectives, more energy per shot must be obtained than the above laser can deliver. Unfortunately, adding a larger laser rod amplifier would reduce the repetition rate below an acceptable level. For this reason, we intend to build the final amplifier in a face-pumped. slab geometry (Figure 3). In this geometry, the thermal gradients are linear so thermal birefringence problems are avoided. The slab will consist of a rectangular YAG crystal with dimensions of 1.0 x 5.0 x 9.0 centimeters and will be mounted similar to the glass slabs developed by Professor R. Byers and his group at Stanford. Unlike the glass slabs, it will not use multiple internal reflections. When finished, it will replace the second amplifier in the LASSO laser (Figure 4). A cylindrical optics beam expander will fill most of the slab's end face with an eliptical beam. The same optics will then convert the beam back to a circular cross-section after a double-pass through the slab. The expected output parameters of the modified laser are listed in Table 3.

CONCLUSION

The initial stage of the new laser should be ready for interfacing to the telescope by the first of 1982. Construction of the final amplifier will probably take six months longer. When completed, we hope this laser will be successful enough to serve as a prototype for future systems.

Table 1: LASER MATERIALS PROPERTIES

PROPERTY		Nd:YAG	$Nd:YLF_4$	Q-98
Index of Refraction	n_0	1.82	$(1.45)_o(1.47)_e$	1.55
Laser Wavelength	λ	1.064μ	$(1.047\mu)_\pi(1.053\mu)_\sigma$	1.053
Emission Cross Section	σ	$4.6 \times 10^{-19} cm^2$	$(6.2 \times 10^{-19} cm^2)_\pi (1.8 \times 10^{-19} cm^2)_\sigma$	$4.5 \times 10^{-20} cm$
Density	ρ	$4.55\ gr/cm^3$	$3.99\ gr/cm^3$	$2.5\ gr/cm^3$
Thermal Conductivity	K	$0.13\ ^W/cm\text{-}°K$	$0.06\ ^W/cm\text{-}°K$	$0.01\ ^W/cm\text{-}°K$
Specific Heat	c	$0.59\ ^J/gr\text{-}°K$	$0.79\ ^J/gr\text{-}°K$	$1.2\ ^J/gr\text{-}°K$
Diffusity	k	$0.048\ ^{cm^2}/s$	$0.019\ ^{cm^2}/s$	$0.003\ ^{cm^2}/s$
Thermal Expansion	α	$6.9 \times 10^{-6} °K^{-1}$	$(13 \times 10^{-6} °K^{-1})_A (8 \times 10^{-6} °K^{-1})_c$	$8.2 \times 10^{-6} °K^{-1}$
$\frac{dn}{dT}$ (1.06μ)	$\frac{dn}{dT}$	$7.3 \times 10^{-6} °K^{-1}$	$(-2.0 \times 10^{-6} °K^{-1})_A (-4.3 \times 10^{-6} °K^{-1})_c$	
Nonlinear Index	n_2	$4.09 \times 10^{-13} esu$	$0.59 \times 10^{-13} esu$	$1.2 \times 10^{-13} esu$
Fluorescence Lifetime	τ	$(1\%)\ 2 \times 10^{-4} s$	$(1.5\%)\ 4.8 \times 10^{-4} s$	$(6\%)\ 2.7 \times 10^{-4} s$
Fluorescence Linewidth	$\Delta\nu$	$6\ cm^{-1}$	$12.5 cm^{-1}$	$216 cm^{-1}$
Damage Theshold	D	$10.1\ ^{GW}/cm^2$	$18.9\ ^{GW}/cm^2$	$8\ ^{GW}/cm^2$
Livermore Figure of Merit $(\frac{\sigma n_0}{n_2})$	F	2.05×10^{-6}	15.2×10^{-6}	0.58×10^{-6}

Table 2: EXPECTED OUTPUT PARAMETERS OF MARYLAND LASER STAGE ONE

Pulse Duration (picoseconds)	Energy @ 530nm (millijoules)
100	180
250	285
500	400
1000	570

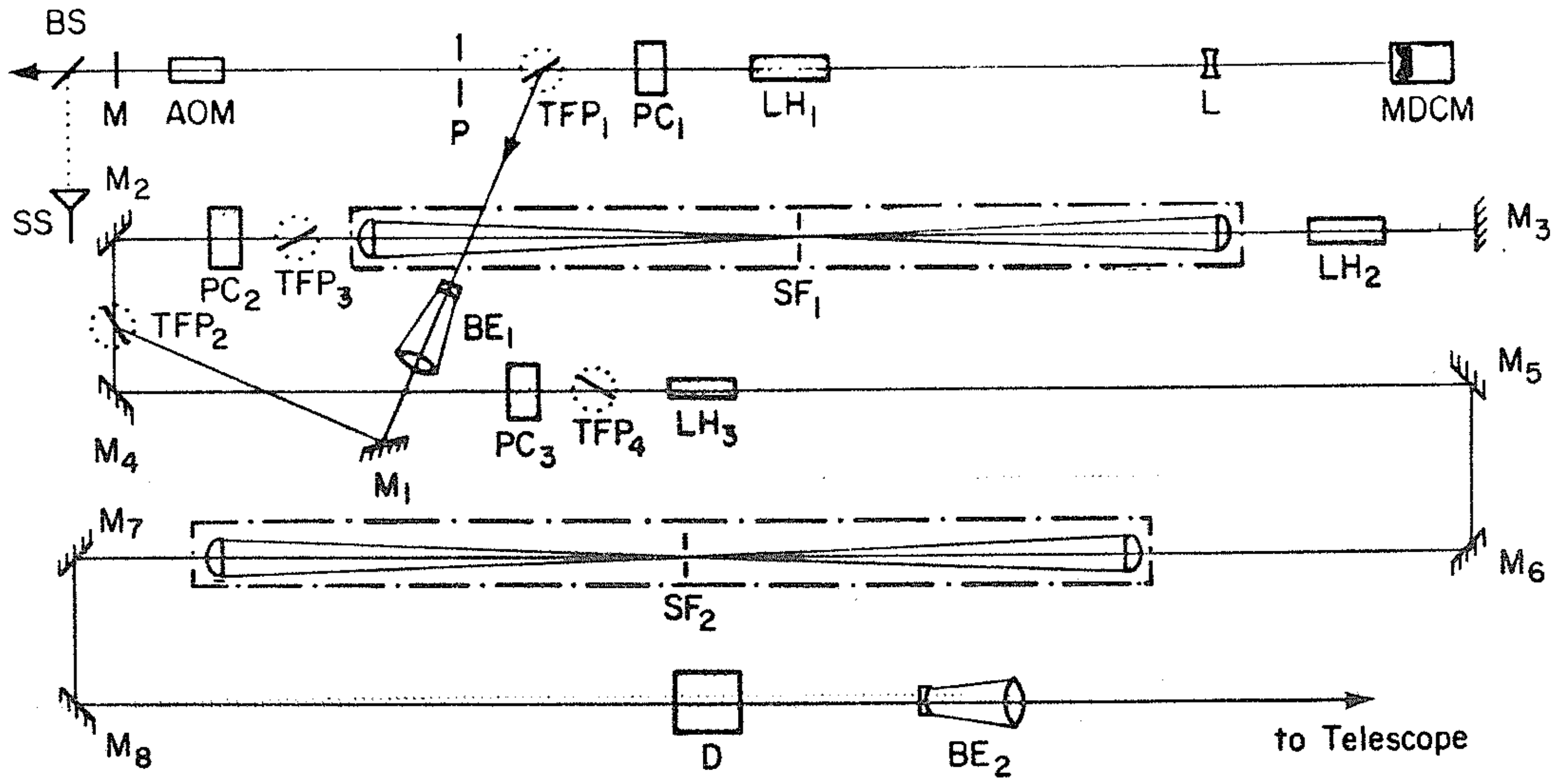
Repetition Rate	3 - 6 Hz
Beam Divergence	≤ 0.5 milliradians
Doubling Efficiency	60%

Table 3: EXPECTED OUPUT PARAMETERS OF MARYLAND LASER
STAGE TWO

Pulse Duration (picoseconds)	Energy @ 530nm (millijoules)
100	760
250	1200
400	1520

Repetition Rate	3 - 6 Hz
Beam Divergence	$\leq$ 0.5 milliradians
Doubling Efficiency	60%

FIGURE 1 : Optical Layout for New Nd:YLF Ranging Laser



MDCM — Modelocking Dye Cell and Mirror (r=3/4 m, R=100 %)

L	Lens (f=−33 cm)	P	Pinhole (ϕ=2 mm)
LH_1	Laser $Head_1$ (3.0 × 65 mm)	AOM	Acousto-Optic Modulator
LH_2	Laser $Head_2$ (7.0 × 100 mm)	M	Flat Mirror (R=65 %)
LH_3	Laser $Head_3$ (9.5 × 100 mm)	BS	Beam Splitter (R=8 %)
PC	$\lambda/2$ Pockel Cell (KD^*P)	SS	Semiconductor Switch (GaAs)
TFP	Thin Film Polarizer	M_i	Mirror (R=100 %)
SF	Spatial Filter	D	Doubling Crystal (KD^*P)
BE	Beam Expander		

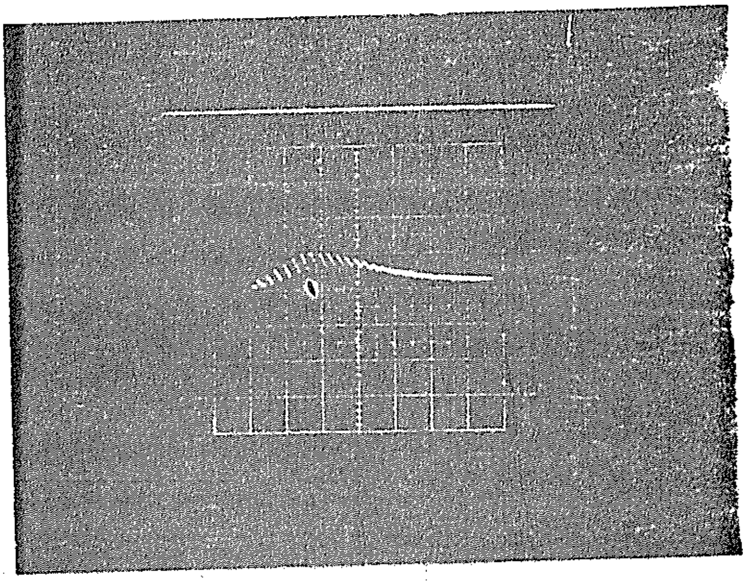


Fig. 2a. Bulk Semiconductor Detection Output
(100 ns/cm, 1 volt/cm)

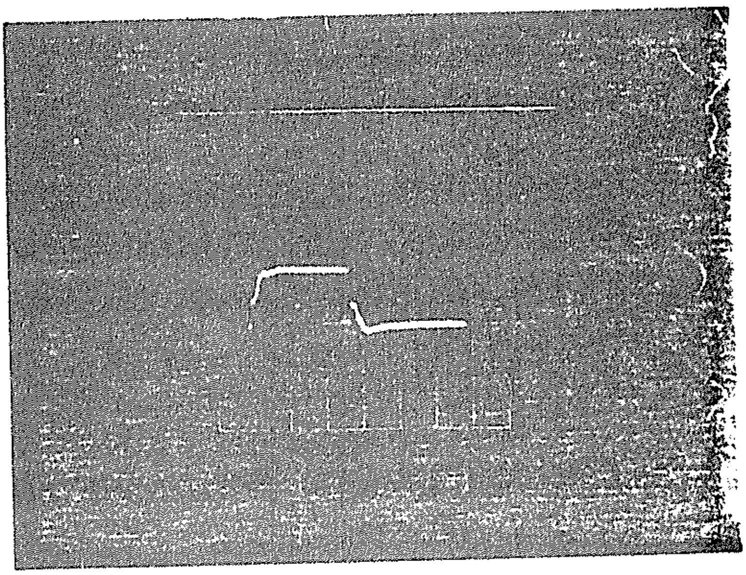


Fig. 2b. Voltage Level Discriminator Output
(100 ns/cm, 1 volt/cm)

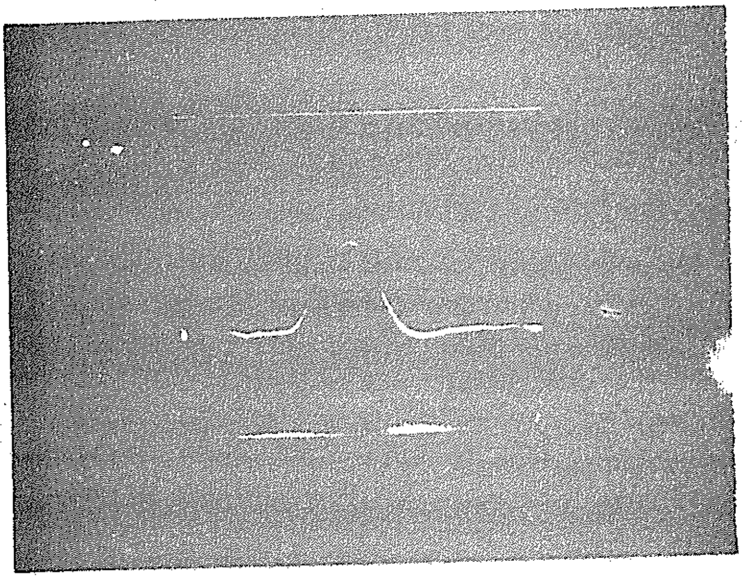


Fig. 2c Planar-Triode Amplifier Output
(0.4 volts/cm, 50 db, 2 ns/cm)

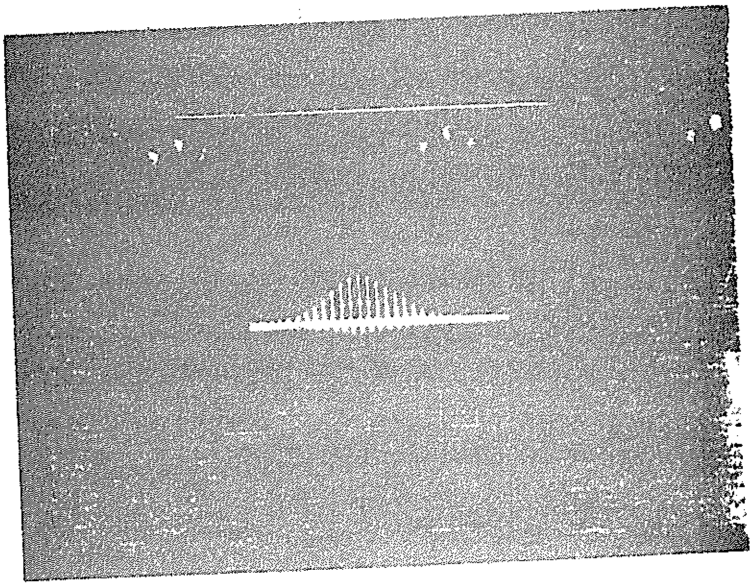


Fig. 2d Laser Pulse Train, No Cavity Dump
(40 ns/cm)

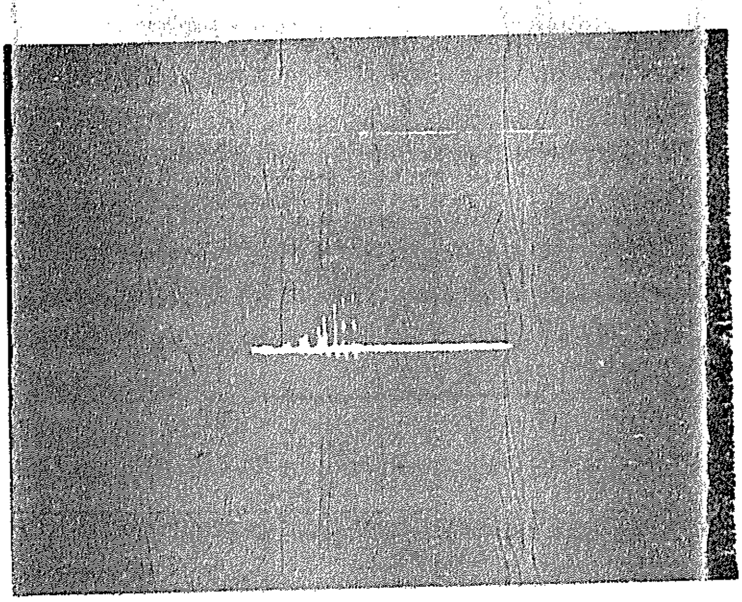


Fig. 2e. Laser Pulse Train with Cavity Dump
(40 ns/cm)

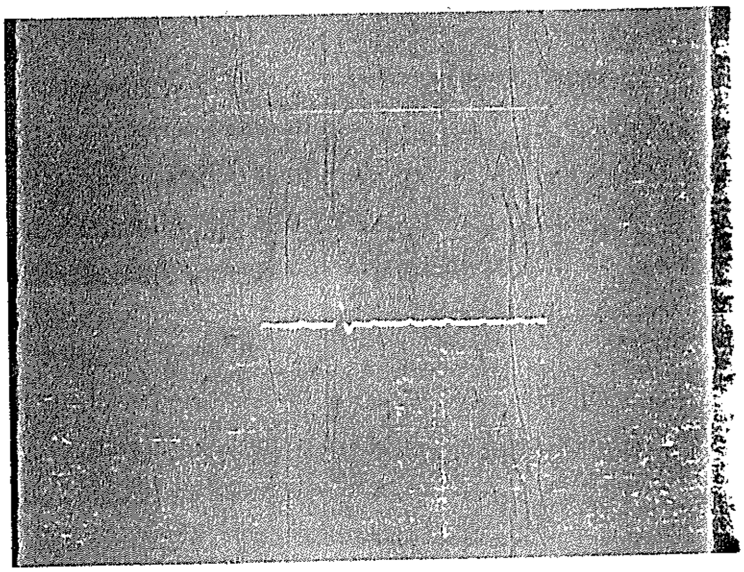


Fig. 2f. Single Laser Pulse from Cavity Dump

YAG SLAB CONCEPT

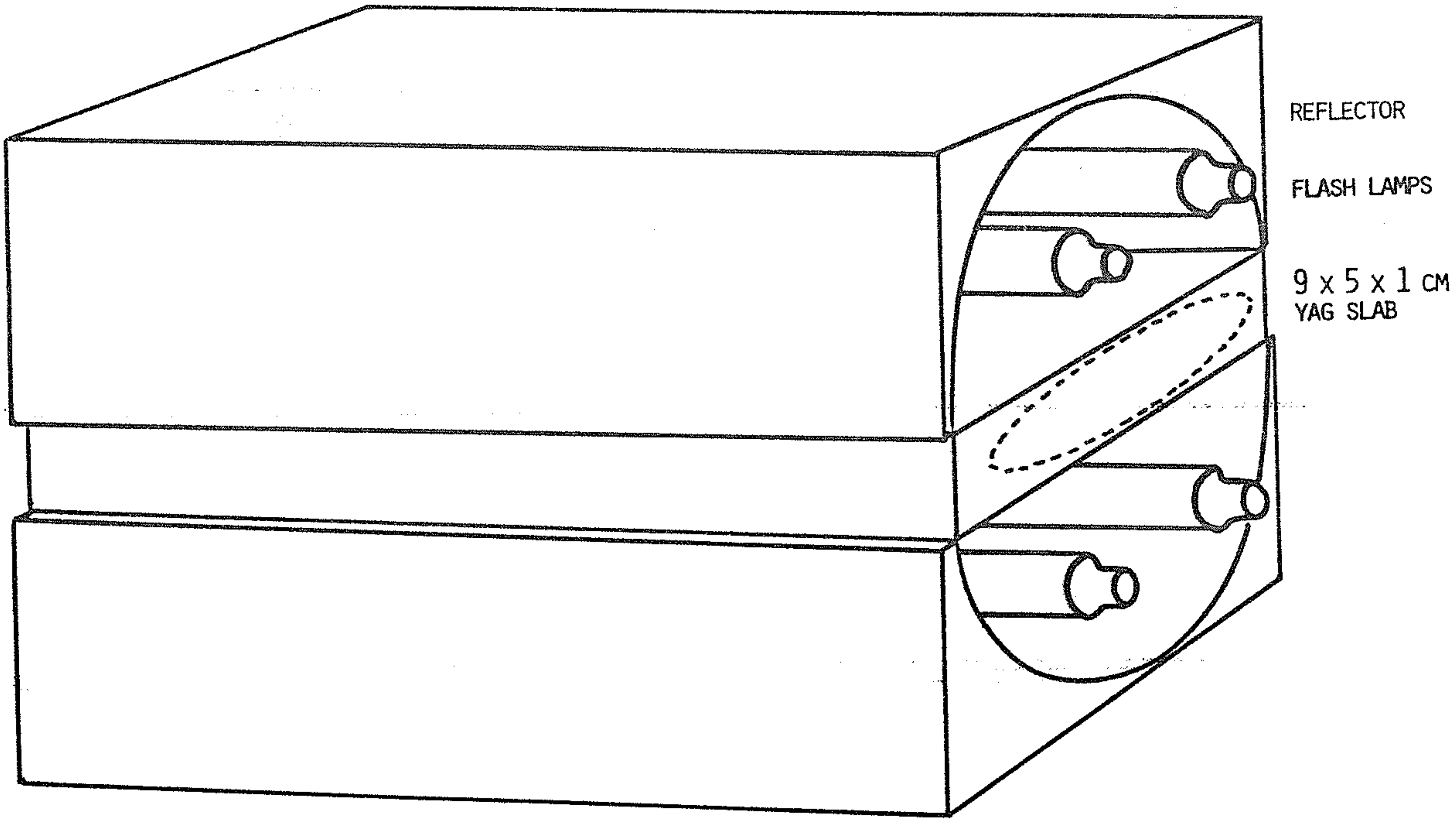
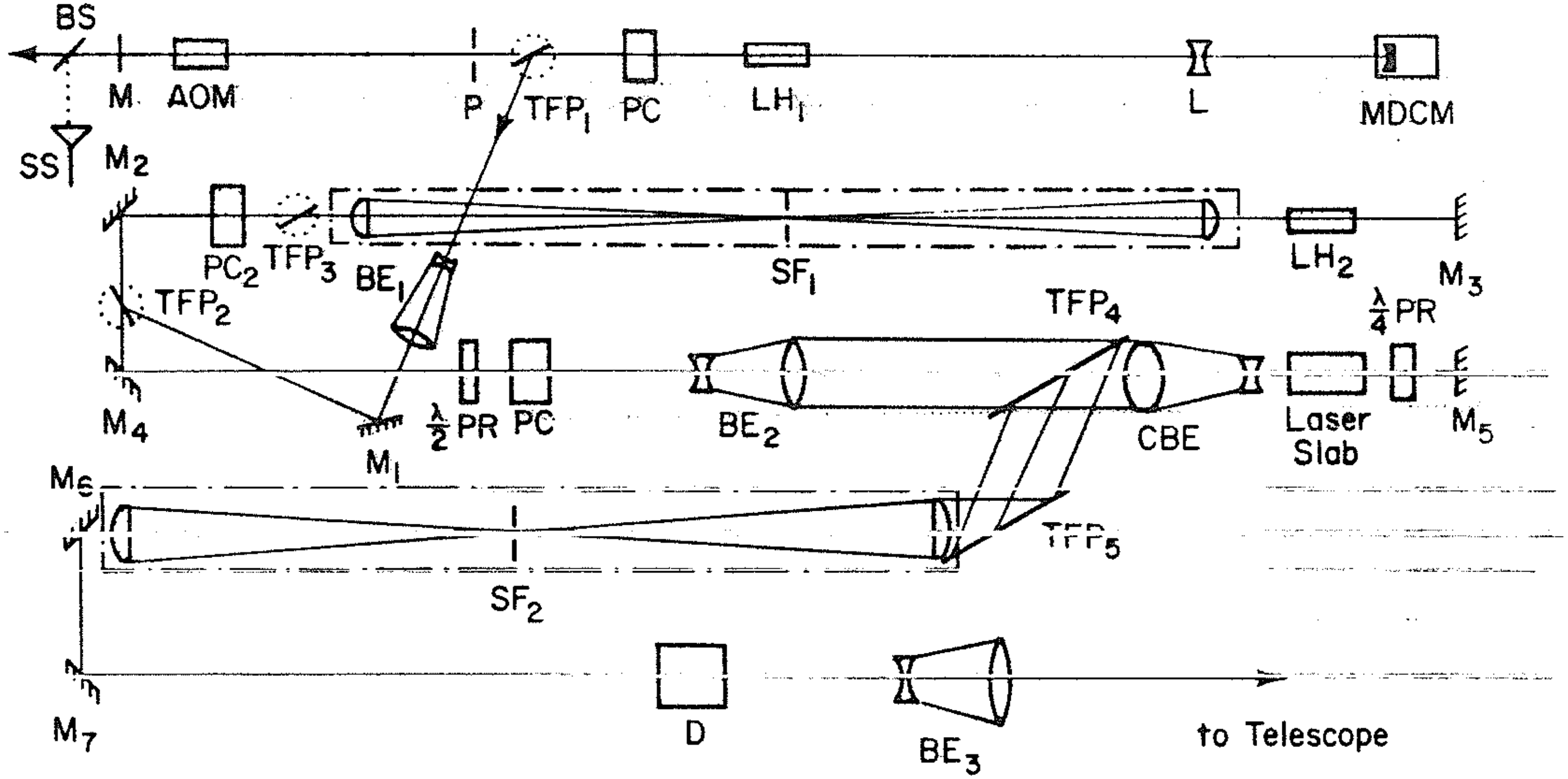


FIGURE 3

FIGURE 4 : Optical Layout for New Nd:YAG Ranging Laser



MDCM	—	Modelocking Dye Cell and Mirror (r = 3/4 m, R=100 %)			
LH	—	Laser Head (3.0 × 100 mm, 9.5 × 100 mm)	P	—	Pinhole (ϕ=2 mm)
PC	—	λ/2 Pockel Cell (KD^*P)	AOM	—	Acousto-Optic Modulator
L	—	Lens (f = -33 cm)	M	—	Flat Mirror (R=65 %)
TFP	—	Thin Film Polarizer	BS	—	Beam Spliter (R=8 %)
SF	—	Spatial Filter	SS	—	Semiconductor Switch (GaAs)
BE	—	Beam Expander	M_i	—	Mirror (R=100 %)
CBE	—	Cylindrical Beam Expander	PR	—	Polarization Rotator
D	—	Doubling Crystal (KD^*P)			

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A COMPARATIVE STUDY OF SEVERAL TRANSMITTER TYPES FOR PRECISE LASER RANGING

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1.0 Introduction

During the past three years, a total of ten laser transmitters have been submitted to a fairly standardized laboratory test program in order to determine their expected contribution to the range biases and RMS noise in a satellite laser ranging system. Among the transmitter types tested were four Q-switched configurations varying in pulsewidth from four to eight nanoseconds (FWHM), three PTM Q-switched (cavity dumped) configurations varying in pulsewidth from 1.5 to 4.0 nanoseconds (FWHM), and three mode-locked transmitters with FWHM pulsewidths in the range 60 to 225 picoseconds. The lasers tested are summarized in Table 1.

In order to isolate the errors contributed by the transmitter, it was necessary to construct, test, and calibrate a range receiver whose time walk and time jitter contributions were at the subcentimeter level for the laser pulsewidths being tested. Furthermore, during the ranging experiments, special care was taken to keep the average signal level well within the low time-walk regime of the constant fraction discriminator. Details of the receiver hardware and the calibration techniques employed are described elsewhere[1].

In this paper, we will provide some detailed data for one laser in each of the three categories, i.e. (1) simple Q-switched; (2) PTM Q-switched (cavity dumped); and (3) modelocked. A detailed discussion of some of the Q-switched and cavity-dumped tests is given in an earlier report[1]. The modelocked results have not been published previously.

2.0 Experiment Description

Two basic tests were performed on each laser. The first is a ranging repeatability or "stability" test which attempts to identify time dependent biases in the range data to a fixed retroreflector. The second is a "range map" which is designed to identify biases associated with the location of the target in the transmitter far field pattern resulting from the presence of higher order transverse modes in the laser output.

In the ranging repeatability test, the mean of 100 successive range data points is calculated, plotted against time of day, and repeated over a time frame comparable to or longer than a typical LAGEOS pass (> 45 minutes). The target retroreflector, located on a water tower located approximately 0.455 Km from the ranging laboratory, is placed in the approximate center of the transmitter beam and signal levels are adjusted via attenuators so that the start and stop input voltages to the discriminator lie in the low time walk regime. The following procedure was used to generate the angular range map:

1. Center the target in the transmitter beam and average the on-axis results of 100 pre-calibration range measurements.
2. Change the transmitter beam direction by a 25 to 30 arcsecond step in one axis using a calibrated pointing mirror.
3. Adjust the amplitude of the received signal, via a neutral density attenuator wheel, so that the average signal level is in the center of the low time walk regime of the receiver.
4. Take two sets of range measurements of 100 data points. Compute the local mean range and standard deviation for each set.
5. Subtract the on-axis pre-calibration mean range from the two local means and print the results adjacent to the corresponding azimuth/elevation coordinates on the map along with the corresponding standard deviation. The deviation of the local mean and the standard deviation (one sigma) are expressed in centimeters.

6. Repeat sets 2 through 5 until the map is completed.
7. Center the target on the transmitter beam and average the on-axis results of 100 post-calibration range measurements. Compare with the pre-calibration results.

3.0 Representative Test Results

Figures 1 through 3 show representative results of the ranging repeatability test and the range map for three different transmitter types. Figure 1 presents the results for a modified Q-switched General Photonics laser. The laser is identical to that originally installed in the Mobile Laser Ranging Stations[2] except for a somewhat shorter oscillator. This reduced the pulsewidth to about 4 nsec (FWHM) compared to 7 nsec in the original design. When operated at a 1 pps rate, system bias would drift at rates up to 0.6 cm per minute of operation. At 5 pps, the on-axis drift rate was often considerable with the system bias changing by about 25 cm during a 40 minute period as in Figure 1. The range map in the same figure shows a peak-to-peak variation in the mean range of 18.2 cm. At 5 pps, the peak-to-peak variation was as much as 75 cm. Interestingly enough, the RMS standard deviations for a given 100 point data set were always in the 2 to 6 cm (one sigma) range as in the map of Figure 1.

Figure 2 summarizes the results for a PTM Q-switched (Q-switched and cavity dumped) laser built by General Photonics and modified by NASA. The original cavity-dumped electro-optic switch was too slow and was replaced by an inhouse NASA design[3] which provided subnanosecond switching and a steep leading edge on the output pulse. The mean range was typically stable to better than $\pm$1.5 cm during two hours of continuous operation as in Figure 2. The peak-to-peak variation in the mean range over the angular map was always less than 4 cm ($\pm$2 cm). The RMS standard deviation of all 100 point data sets was stable at the 2 to 3 cm level (one sigma).

Figure 3 gives the corresponding results for a prototype compact subnanosecond laser built for NASA by International Laser Systems. The system consists of an electro-optically modelocked, PTM Q-switched Nd:YAG laser oscillator, followed by a double-pass amplifier and a KD*P Type II doubling crystal. The oscillator is folded four times yielding a fairly compact system which is described in more detail elsewhere[4,5]. The laser is currently serving as the test transmitter in the TLRS-2 system[2]. As one can see from the figure, the peak-to-peak variation in the mean range for the repeatability test is only ±0.5 cm while the peak-to-peak variation in the angular map was always less than ±1 cm. The one sigma RMS standard deviation for all 100 point sets was in the range of 1 to 3 cms.

4.0 Summary

Table 1 summarizes the overall ranging performance of ten different laser configurations. Each laser has been assigned two ratings (poor, fair, good, very good, or excellent) summarizing its performance in each of the two tests, ranging repeatability and angular range map. The ratings are based on the peak-to-peak variations in the mean range as computed from 100 point data sets in the two tests according to the criteria outlined in Table 1.

Q-switched lasers, in general, were rated "poor" to "fair" in both categories. This is most likely due to several factors. The pulses are temporally longer and have slower risetime. Multiple transverse modes build up randomly and at different rates within the laser oscillator and are allowed to leak out of the cavity at arbitrary times by the partially reflecting output mirror. Because of their different antenna patterns, the individual temporal profiles of the modes do not sum uniformly in the far field. As a result, the stop waveform returning from the retroreflector may vary significantly from the start waveform leading to angularly dependent range biases and this has been observed. Finally, unstable temporal profiles were observed periodically in all of the Q-switched lasers except the Westinghouse military laser. The pulses would vary between smooth Q-switched waveforms through partially modulated waveforms to full self-modelocked profiles. The Quanta-ray laser, which utilized an "unstable" resonator, was rated "very good" in stability but "poor" in the range map. This laser also exhibited self mode-locking effects at times.

In the cavity dump system, no radiation is permitted to leave the resonator until the dump electro-optic switch is fired. Thus, even though many transverse modes are present, they leave the resonator at the same time. Furthermore, the speed of the switch determines the risetime of the pulse as seen by the target, and a fast switch appears to reduce the bias errors in the far field map. The NASA-modified General Photonics laser had the best overall performance in this category.

Not surprisingly, subnanosecond modelocked lasers gave the best results with peak-to-peak variation in the mean of less than 2 cms in both tests. This was true not only of the prototype actively modelocked ILS laser discussed previously but also of two commercial passively mode-locked units built by Quantel. The YG40 is a low repetition rate (0.5 pps), low energy (3 mJ green) laser while the YG402 is a medium repetition rate (10 pps), medium energy (<100 mJ green) transmitter. The latter system is currently installed in a MOBLAS trailer for tests as part of NASA Laser Tracking System Upgrade program[2].

REFERENCES

1. J.J. Degnan and T.W. Zagwodzki, "Characterization of the Q-switched MOBLAS Laser Transmitter and its Ranging Performance Rèlative to a PTM Q-switched Systems," NASA Technical Memorandum 80336, October 1979.

2. J.J. Degnan and A. Adelman, "Upgrade and Integration of the NASA Laser Tracking Network," Proceedings of the Fourth International Workshop on Laser Ranging Instrumentation, this issue.

3. T.S. Johnson and J.G. Lessner, NASA Goddard Space Flight Center, Greenbelt, MD, USA, unpublished.

4. R.H. Williams, L.L. Harper, and J.J. Degnan, "Ultrashort Pulsed Solid State Transmitter Development," presented at Lasers' 78, Orlando, Florida, December 1978.

5. T.S. Johnson, J.J. Degnan, and T.E. McGunigal, "200 Picosecond Laser Development - A Status Report," Proceedings Third International Laser Ranging Workshop, Lagorrissi, Greece, May 1978.

TABLE I: LASERS TESTED BY GSFC

TYPE	MANUFACTURER	PULSEWIDTH (FWHM)	REPEATABILITY	RANGEMAP
Q-SWITCHED (S)	GENERAL PHOTONICS (MOBLAS)	7 NSEC	POOR	POOR
Q-SWITCHED (S)	MODIFIED GENERAL PHOTONICS	4 NSEC	FAIR (1PPS) POOR (5PPS)	FAIR (1PPS) POOR (5PPS)
Q-SWITCHED (S)	WESTINGHOUSE (MILITARY)	8 NSEC	POOR	POOR
Q-SWITCHED (U)	QUANTA-RAY	5 NSEC	VERY GOOD	POOR
PTM Q-SWITCHED	INTERNATIONAL LASER SYSTEMS (LL102)	4 NSEC	EXCELLENT	FAIR
PTM Q-SWITCHED	GENERAL PHOTONICS	3.6 NSEC	EXCELLENT	FAIR
PTM Q-SWITCHED	NASA-MODIFIED GP	1.5 NSEC	VERY GOOD	VERY GOOD
ACTIVE MODE-LOCK	INTERNATIONAL LASER SYSTEMS	225 PSEC	EXCELLENT	EXCELLENT
PASSIVE MODE-LOCK	QUANTEL INTERNATIONAL YG40 AND YG402	60 PSEC, 150 PSEC	EXCELLENT	EXCELLENT

CRITERIA FOR RANGING PERFORMANCE RATINGS

RATING	PEAK-TO-PEAK VARIATION IN 100 POINT MEAN
POOR	EXCEEDS 20 CM PEAK-TO-PEAK
FAIR	BETWEEN 10 AND 20 CM PEAK-TO-PEAK
GOOD	BETWEEN 6 AND 10 CM PEAK-TO-PEAK
VERY GOOD	BETWEEN 2 AND 6 CM PEAK-TO-PEAK
EXCELLENT	LESS THAN 2 CM PEAK-TO-PEAK

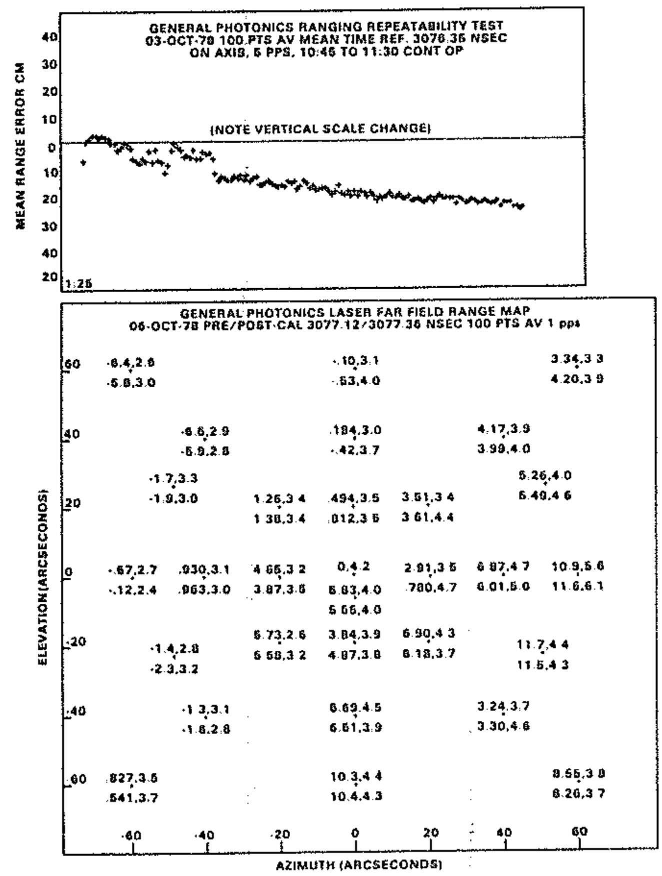

FIGURE 1: RANGING REPEATABILITY AND RANGE MAP TESTS OF FOUR NANOSECOND GENERAL PHOTONICS Q-SWITCHED TRANSMITTER

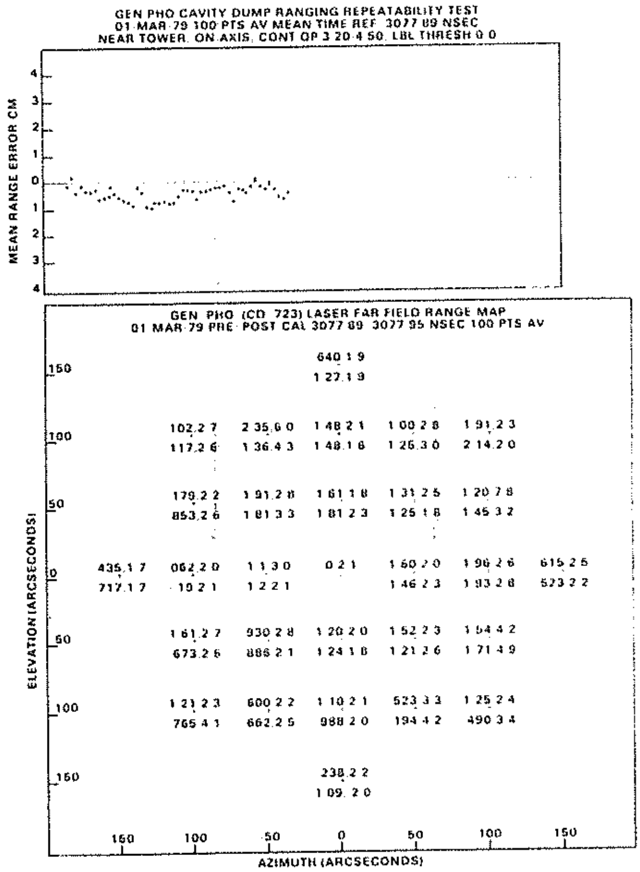

FIGURE 2: RANGING REPEATABILITY AND RANGE MAP TESTS OF NASA-MODIFIED GENERAL PHOTONICS CAVITY DUMP LASER

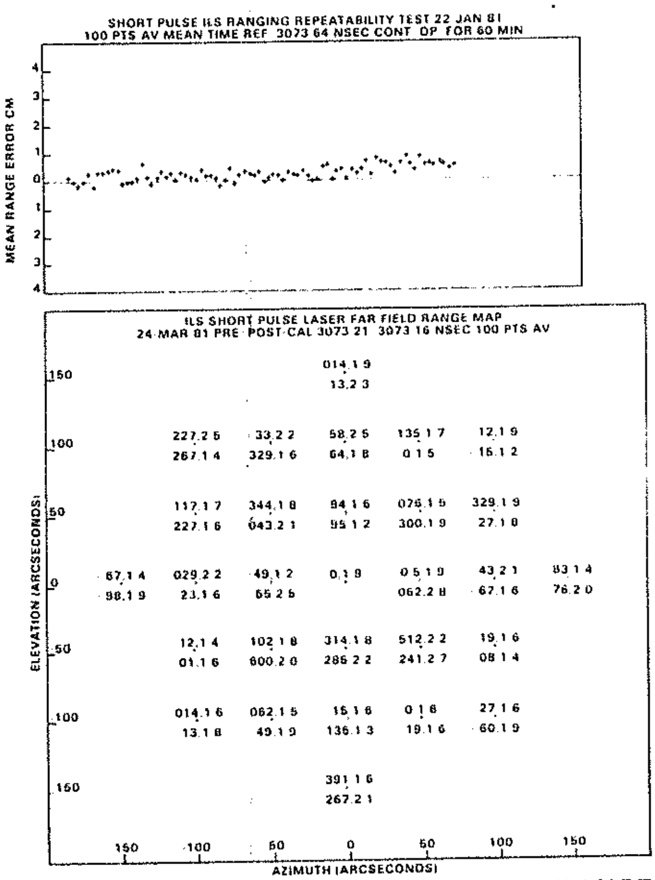

FIGURE 3: RANGING REPEATABILITY AND RANGE MAP TESTS OF ILS ACTIVELY-MODE LOCKED, PTM Q-SWITCHED LASER TRANSMITTER