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THE PROCUREMENT AND EVALUATION OF A
PROTOTYPE LASER SATELLITE-TRACKING SYSTEM

Final Report

Contract NSR 09-015-039

For the Period 1 January 1967 through 30 September 1968

September 1968

Prepared for

National Aeronautics and Space Administration
Washington, D. C.

Smithsonian Institution
Astrophysical Observatory
Cambridge, Massachusetts 02138

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THE PROCUREMENT AND EVALUATION OF A
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Contract NSR 09-015-039

1. INTRODUCTION

This is the final report for NASA Contract NSR 09-015-039 awarded to
the Smithsonian Astrophysical Observatory (SAO) to procure and evaluate a
prototype laser satellite-tracking system. This report describes the activity
from 1 January 1967 to 30 September 1968.

1.1 Historical Background

The most important advantage of a laser over most other satellite-
tracking systems is that the data obtained are more precise than those gener-
ated by previous systems (Plotkin, 1964). The increase in precision amounts
to an order of magnitude. The resulting increase in the accuracy of computed
orbits is sufficient to open up new fields of scientific investigation. The laser
has other advantages: The data reduction is easily performed, and the precise
results can be available within minutes; the satellite can be photographed under
reflected laser illumination, thus providing simultaneous values of range and
angular position, or the complete three-dimensional coordinates of a satellite;
and range measurements can be performed when the satellite is invisible (i. e.,
when it is in the earth's shadow or when the sky is brighter than the satellite).

To measure the range from a station to a satellite, a very short pulse of
light in a narrow beam is projected from the laser toward the satellite. The
light reflected back to the station is detected photoelectrically. The range
is then calculated from elapsed time, with due corrections for atmospheric
and other effects. The intensity of the light returned from the satellite is
vastly enhanced if the satellite carries cube-corner reflectors. The

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installation of such retroreflectors on 1964-64-01 (BE-B) opened the way for the first experiments with laser observations. Five more satellites with retroreflectors are now in orbit: 1965-32-01 (BE-C), 1965-89-01 (Geos 1), 1967-11-01 (D1C), 1967-14-01 (D1D), and 1968-2-01 (Geos 2).

Prompted by the successful launch of BE-B, SAO took steps to test a laser instrument in conjunction with a Baker-Nunn installation. The program[*] was initiated in the spring of 1965, when a system developed by the General Electric Company was moved to the SAO observing station near Las Cruces, New Mexico. The first successful observation, made from this site on 19 June 1965, obtained simultaneously both photographic and photoelectric data (Anderson, Lehr, Maestre, Halsey, and Snyder, 1966).

As experiments progressed, the system was refined in various ways. By late 1965, it was capable of routine range measurements during twilight conditions when the satellite is visible and the laser can be pointed toward it. This limitation imposed by the adapted gun mount holding the laser was acceptable on an iterim basis because the Baker-Nunn normally operates during twilight conditions. Thus a continuing schedule of observations for the satellites with retroreflectors was begun in December 1965, even though the equipment had many experimental features.

The numbers of successful laser observations through 1966 are listed by months in Table 1. The data themselves are published periodically in SAO Special Reports, and the data on the Geos satellites are submitted to NASA's Geodetic Operations Control Center (GOCC).

These data were combined with Baker-Nunn observations, and satellite orbits were computed.

Since the number of laser observations was much less than the number of Baker-Nunn observations, the orbits were determined mainly by the data from the cameras. Further, the geopotential coefficients were derived from

Table 1. Laser observations 1966

	BE-B 1964-64-01		BE-C 1965-32-01		Geos 1 1965-89-01		Total	
	Passes	Returns	Passes	Returns	Passes	Returns	Passes	Returns
January			3	7	3	10	6	17
February			1	3	4	22	5	25
March	3	12	8	23	10	52	21	87
April	5	10	9	44	26	83	40	137
May	1	2	19	101	17	128	37	231
June	4	15	4	21	3	15	11	51
July	2	15	29	114	18	71	49	200
August	1	1	2	4	10	64	13	69
September	1	2	9	43	5	21	15	66
October	2	12	9	27	3	23	14	62
November			7	23	8	75	15	98
December			13	64	1	4	14	68
Total	19	69	113	474	108	568	240	1,111

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Baker-Nunn data alone. Consequently, the residuals between the computed
orbits and the laser observations reflected the accuracy of the cameras
(of the order of 10 m) rather than the accuracy of the laser (expected to be
of the order of 1 m). The residuals did show, however, that the laser observa-
tions were at least as accurate as those of the Baker-Nunn camera (Lehr,
Maestre, and Anderson, 1967). No unexpected source of error showed up.
But the single station did not provide nearly enough data for a refined inter-
pretation of the geopotential coefficient.

For geodetic and geophysical studies by the dynamical orbit method,
it is essential to have, in addition to high tracking accuracy, both a variety
of satellite orbits and a good geographic distribution of observing stations.
In 1965 NASA launched BE-C and Geos 1, and in 1967 the French launched
D1C and D1D. By 1967 the French had three laser stations in operation —
at Haute Provence, France; Stephanion, Greece; and Colomb-Béchar in the
Sahara. The Goddard Space Flight Center had one station. There were
five satellites with retroreflectors in orbit, and five laser stations in
operation. Since no single agency in any country had a wide distribution of
laser stations, an international pooling of laser resources was coordinated
by SAO in the spring of 1967. There resulted eight data files, each of about
1-month's duration, with hundreds of laser data points from the five laser
stations. The data from the SAO New Mexico station are listed in Table 2.
The calculation of orbits using data from the five stations is now under way
at SAO. The computed orbits, enriched by data points from the Baker-Nunn
camera and from other electronic systems, will form one of the bases of the
SAO 1968 Standard Earth.

During 1968 the SAO laser network was increased to three stations. The
8-MW laser system was moved from New Mexico to Hawaii. A 100-MW laser
system was established at SAO's observing station in Greece by the National
Technical University (NTU). And the 500-MW prototype laser[*] was the
first instrument to be installed at SAO's new Mt. Hopkins Observatory in

Table 2. Laser observations during saturation tracking intervals in 1967

	BE-B 1964-64-01		BE-C 1965-32-01		Geos 1 1965-89-01		DIC 1967-11-01		DID 1967-14-01		Total	
	Passes	Returns	Passes	Returns	Passes	Returns	Passes	Returns	Passes	Returns	Passes	Returns
January			13	47	12	100					25	147
February			12	51			3	6	1	1	16	58
March	3	19	2	7	6	16	7	19	9	28	2	89
April	2	3	8	33	4	18	5	13	1	2	20	69
May	6	15			6	38	17	113	27	209	56	375
June			16	68	12	99	13	56	1	2	42	225
Total	11	37	51	206	40	271	45	207	39	242	186	963

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Arizona. In January 1968, NASA launched Geos 2, the sixth retroreflecting geodetic satellite; its orbit has a 106° inclination, which is distinctly different from that of the other laser satellites. Soon after, SAO set up laser tracking intervals for coordinated international observing. There were now seven laser stations: NASA's stations in Maryland and Virginia, Centre National d'Etudes Spatiales' (CNES) stations in France and Spain, SAO's stations in Arizona and Hawaii, and NTU's station in Greece. Other groups in Australia, Czechoslovakia, and Japan have efforts under way and can perhaps take part in the last phases of the international program.

Besides strengthening the dynamic orbital computations, the international program has yielded simultaneous observations from the stations of the SAO/French triangle in Europe. A recent discovery of the French showed that the reciprocity effect in photography favors (rather than hinders, as originally believed) the photography of satellite returns under laser illumination (Bivas, 1968). Consequently, the simultaneous operation of a Q-switched laser and a Baker-Nunn camera is feasible when the satellite range is not too great; therefore, collocated camera and laser can determine the three coordinates that completely define the satellite's position at a given epoch.

1.2 Concept of the Prototype

The concept of the SAO prototype system was based on the requirements for future geodetic and geophysical investigations. One requirement is that observations be well distributed on the satellite orbits. To meet this requirement there must be a number of laser stations well distributed geographically, and each station must be capable of observing the maximum possible number of satellite passes. The mount of the prototype system has a mechanical simplicity desirable for operation in remote geographical locations; it also has the capacity to acquire satellites when the sky is too bright for visual observation or when they are in the earth's shadow. The current observation rate is limited to 1 or 2 points per min. For present purposes, this rate is sufficient, and the relative economy of such a system allows more units at distributed sites for the same cost as fewer units with automated tracking.

For future purposes, the higher cost of a greater rate may become justifiable. The present mount has a provision for tracking motors that could be added in converting to a computer-driven system at some later date if the requirements arise.

The accuracy of the range measurements becomes increasingly important as geophysical objectives advance. The system's high power output, static pointing capability, and high-resolution range counter all increase the system's potential accuracy. The 500-MW power level was chosen to compensate for prediction errors initially and to increase range and accuracy eventually.

1.3 Applications for a Laser Network

There is a need for the orbital accuracy that reflects the use of the laser observations. An example of an operational need is the fact that satellites that measure the magnetic field need accurate position determinations that tax the state of the orbit calculations today. Future oceanographic satellites with ocean-to-satellite altimeters will place severe requirements on orbital accuracy. Station positions for deep-space tracking have need for a precision that can be derived from laser observations of earth satellites.

As far as scientific investigations based on tracking data are concerned, new horizons begin to open up as tracking accuracy increases. A few of these are described below.

Determinations of the geopotential will improve with increased tracking accuracy. Only the most recent and accurate geopotential representations have had sufficient resolution to begin exhibiting recognizable correlations with geological features. More meaningful interpretation of the geopotential awaits still greater resolution. Time variations of the geopotential with seasons, solid-earth tides, or other causes are being actively sought; they seem to be just within the limits of present accuracy but within easy reach of laser accuracy.

Geometrical geodesy, i. e. , determination of accurate positions on the surface of the earth, can make the step from 10- to 1-m accuracy by use of laser data. If for no other reason, this will be necessary in the course of atmospheric, geodetic, and geophysical investigations. If decimeter accuracy is eventually attained, crustal motions can be sought over reasonable time spans.

Among the opportunities for improved science is atmospheric research. Short-period perturbations have already become apparent in the orbits of high-drag satellites when the analysis includes the SAO Standard Earth parameters. Clearly, greater tracking accuracy and broader coverage promise improved accuracy and time resolution in determination of atmospheric changes. The measurement of small secular changes in inclination is another subject that requires accurate analysis; some investigators have attributed this to high-altitude winds, but this interpretation is not certain.

There are several other opportunities. The interface between geometrical geodesy and oceanography must be studied. At the decimeter level oceans depart from an equipotential surface because of currents, tides, atmospheric pressure, and other factors. By satellite tracking, the location of sea-level gauges can be related to a common coordinate system and geopotential.

The phenomena related to transmission of light through the atmosphere must be examined to see whether there are atmospheric properties that can be profitably studied by laser signals between the ground and a satellite.

More detail on the applications of increasingly accurate orbits was brought out in a series of seminars at SAO (Lundquist and Friedman, 1966). A review of these applications was concurrent with the proposal for the construction of the prototype laser system.

1.4 Conclusions

The 1965 and 1966 laser tracking was in an experimental stage. Continued effort through 1968 led to the development of a system that will be the prototype for those that will eventually comprise a worldwide network.

Data have been accumulated steadily over these years. The SAO orbits computed in 1967 used these data (Lundquist, 1967). And the 1968 SAO Standard Earth will have used much laser data. As the range measurements were received, they were made available through NASA's GOCC and through SAO's special reports.

2. DESCRIPTION OF PROTOTYPE LASER RANGING SYSTEM

The integration of the system is outlined in Figure 1. Figure 2 shows the equipment in its location next to the Baker-Nunn camera at the Mt. Hopkins Observatory, which is 40 miles south of Tucson, Arizona. Figure 3 is a closeup of the system. It shows how an observer stands to set in the predicted azimuth and elevation coordinates. The components of the system are described in the following sections.

2.1 Static Pointing Pedestal

The static pointing pedestal (see Figure 4) is a rotatable mount for pointing two instrument packages, a photoreceiver and a laser transmitter, to an overall positional accuracy of better than ±1/2 arcmin. It employs a T-type elevation-over-azimuth configuration and is operated manually.

The azimuth-axle housing is driven by means of a worm-drive assembly located at the top right side. A Veeder-Root counter is used for coarse readout, and a goniometer for fine readout.

Another hand-driven worm-drive assembly, which drives the elevation axle, is located near the left end of the elevation-axle housing. The goniometer for fine readout of elevation setting is mounted on the opposite end of the housing.

As seen when facing the pedestal from the operator's position, the left end of the elevation axle is flat to accommodate the photoreceiver mounting plate. This plate provides for a ±2° elevation adjustment of the photoreceiver. By means of opposing adjustable screws, which between them accept a lug on the tube saddle, the position of the photoreceiver can be set with respect to the axle elevation.
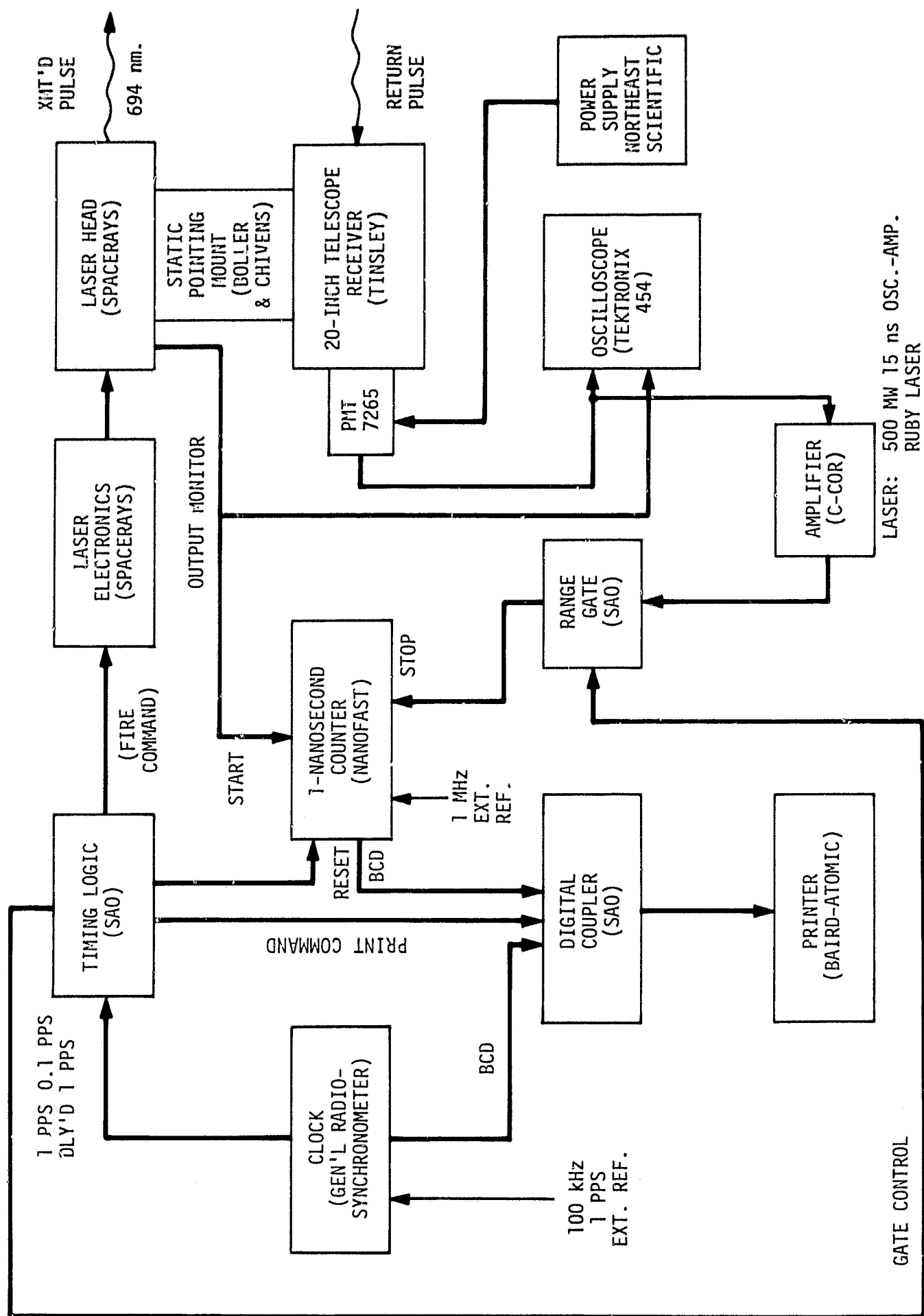
Figure 1. The laser ranging system.

Figure 2.   The laser system (left) beside the Baker-Nunn
camera (right).

Figure 3.   The laser system on Mt. Hopkins.

PHOTORECEIVER MOUNTING PLATE

ELEV. CLAMP

ELEV. DRIVE & READOUT

AZ CLAMP

AZ GONIOMETER

AZIMUTH AXLE HOUSING

MOUNTING NUT ACCESS

ELEVATION AXLE HOUSING

LASER MOUNTING PLATE

ELEV. GONIOMETER

INDICATOR-LIGHT CONTROLS

AZ DRIVE & READOUT

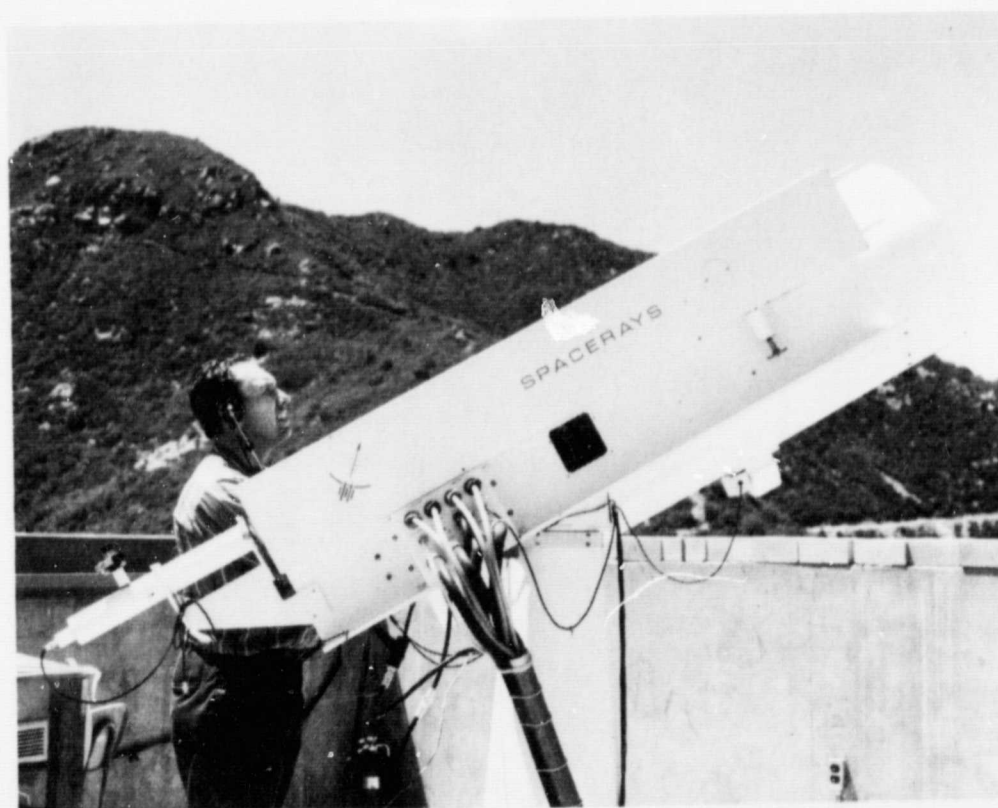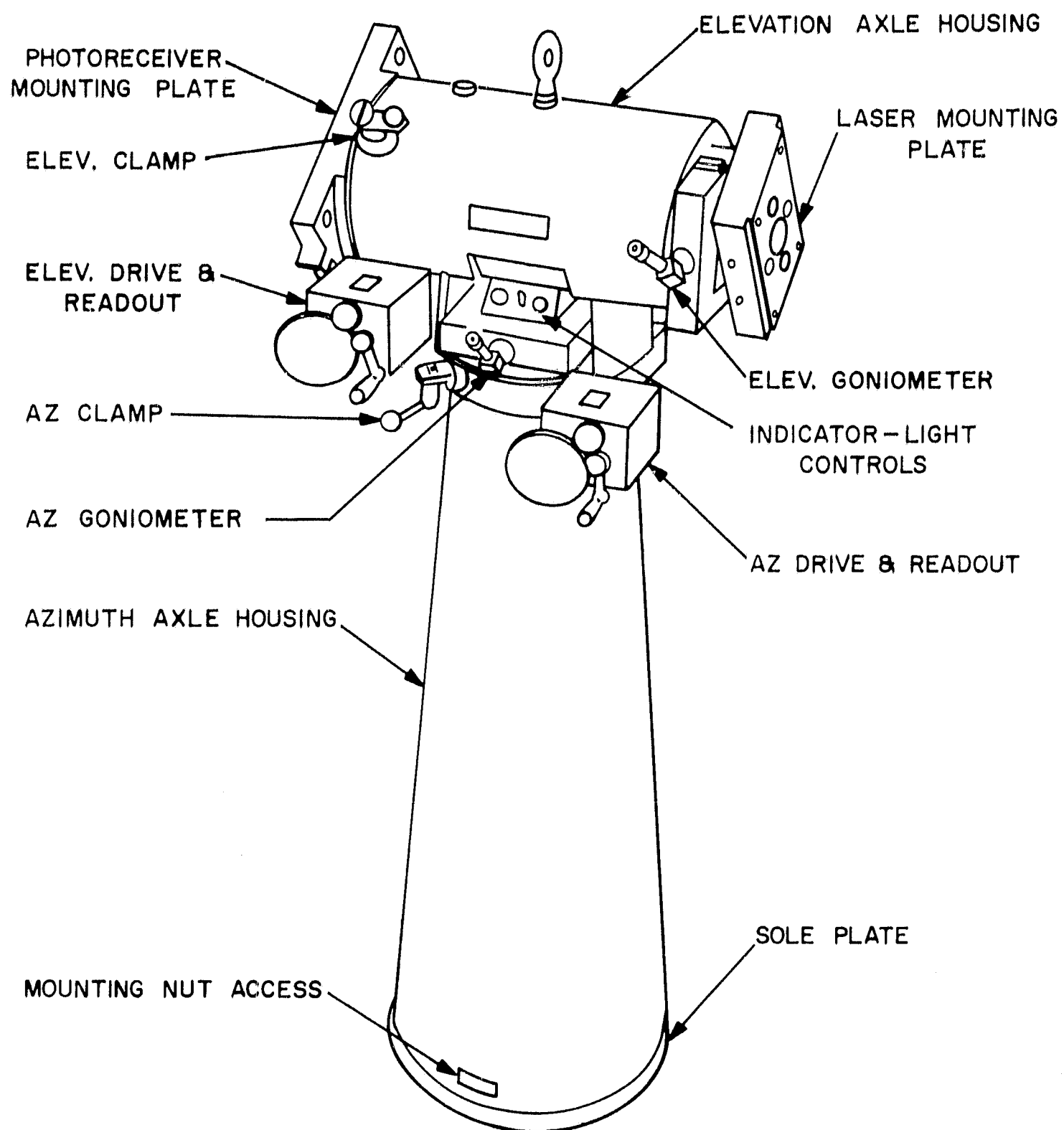SOLE PLATE

Figure 4. Laser static pointing pedestal.

The right end of the elevation axle is machined concave to accept a matching spherical convex portion of the laser mounting plate. This ball joint provides a ±2° azimuth adjustment of the laser. The right end of the axle also carries the elevation-setting circle, which is adjustable for alignment with true horizontal.

2.2 Laser Transmitter

The laser transmitter system (outlined in Figure 5) is capable of providing a pulse rate of 4 per min. The transmitter package contains both an oscillator and an amplifier ruby-laser head, a Pockels-cell Q-switch, a Brewster stack polarizer, a rear reflector, optics for coupling the oscillator and amplifier rods, a set of beam-forming optics with facilities for boresighting, and an output monitor. All these units are mounted on an aluminum I beam. The ruby rods and flashlamps are water cooled, and the cavities are purged with dry nitrogen during operation of the laser. The entire unit is protected by a dustproof cover.

The oscillator head contains two 6-1/2-inch xenon flashlamps and a ruby 3/8 inch in diameter and 6-5/8 inches long. The lamps are located at the focal points of an intersecting elliptical cross-section silver-coated cavity; the rod is located at the common focal point. Both flashlamps and the ruby rod are contained within individual quartz water packets sealed with "O" rings. The amplifier cavity is arranged in the same way as the oscillator cavity, but utilizes a 5/8-inch-diameter, 7-inch-long ruby rod.

A Pockels cell containing a potassium deuterium phosphate crystal is used as the Q-switch. The Pockels cell is held at high potential to prevent firing of the laser until the proper time; then the potential is dropped to 0 V in about 30 ns. A giant pulse is formed up to 200 ns later.

Figure 5. Laser transmitter.

REAR MIRROR

POLARIZER

POCKELS CELLS

OSCILLATOR RUBY

EXPANDING TELESCOPE

AMPLIFIER RUBY

DIVERGENCE CONTROLLING TELESCOPE

FLASH LAMPS (2)

FLASH LAMPS (2)

AMPLIFIER CAPACITOR BANK

SERIES TRIGGER CIRCUIT

OSCILLATOR CAPACITOR BANK

SERIES TRIGGER CIRCUIT

DUAL CHARGING UNIT

THYRATRON

HIGH-VOLTAGE SUPPLY

DELAY GENERATOR

CHARGING & LAMP TRIGGER CONTROL ELECTRONICS

NITROGEN GAS SUPPLY

PURGE TO CAVITIES

FIRE COMMAND

INTERLOCKS

COOLING UNIT: RUBY BY REFRIG. LAMPS BY HEAT EXCHANGER

LAMP COOLING WATER

RUBY COOLING WATER

OUTPUT: 500 MW
15-ns PULSE
0.6 TO 6 mr BEAM DIVERGENCE
(OSCILLATOR OUTPUT = 100 MW)
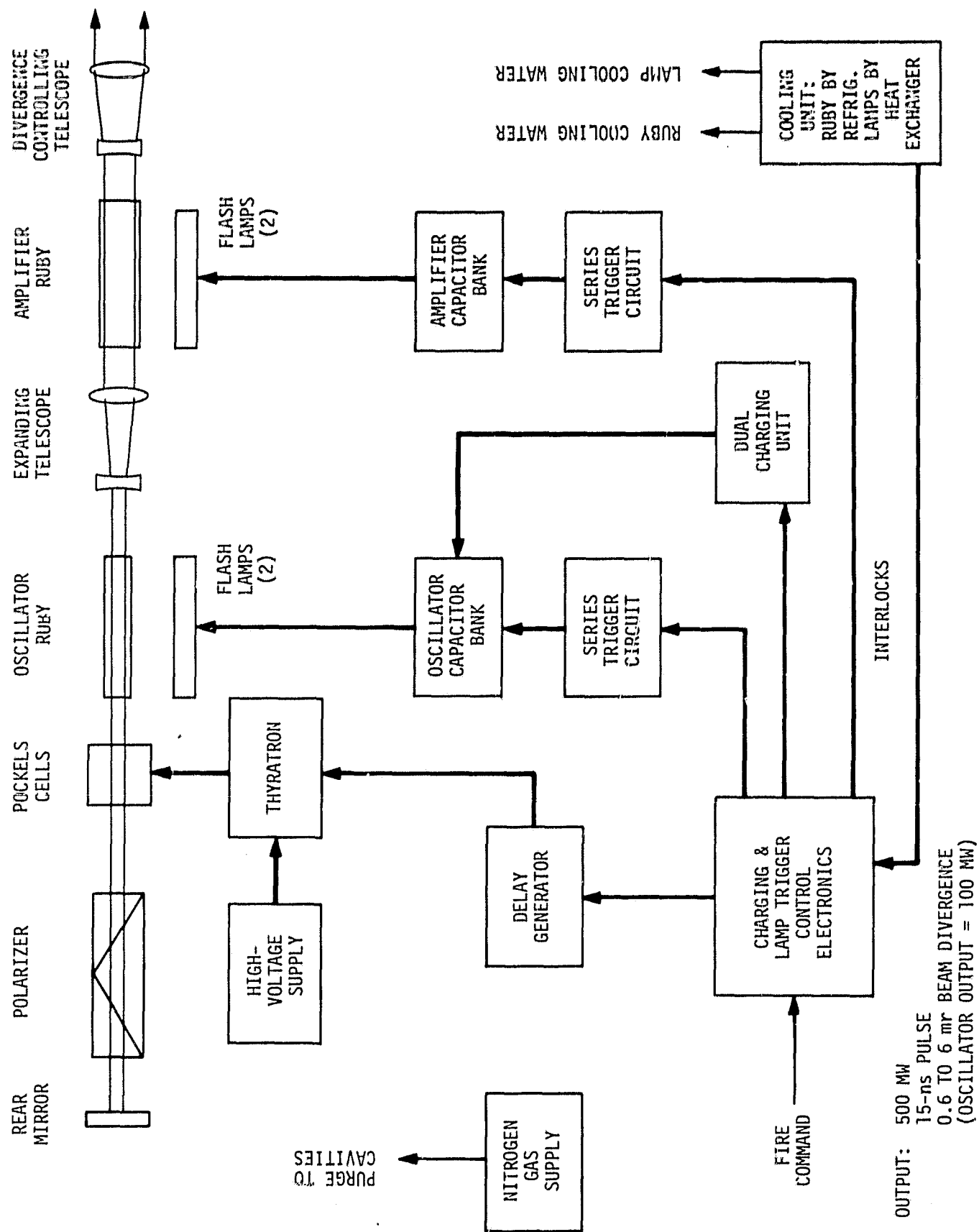
The beam-forming telescope consists of a Galilean lens and a 6-inch-diameter double convex lens. Both lenses are coated for maximum transmission at 694 nm. The Galilean lens is fastened to a movable platform and can be moved by a micrometer attached to a flexible cable to vary output-beam divergence from 2 to 20 arcmin.

The output pulse monitor is an ITT diplanar photodiode with an S-20 cathode driven at -1000 VDC. The monitor is arranged to look at laser light reflected from the rear surface of the 6-inch lens of the beam-forming telescope. The pulse from this monitor starts the time-interval counter.

An input to the oscillator cavity of 3000 joules and to the amplifier cavity of 6000 joules produces an output of 500 MW in a 15-ns pulse.

2.3 Telescope Photoreceiver

The telescope photoreceiver, designed primarily to be used with a photomultiplier tube (PMT), detects returning laser pulses. Equipped with an eyepiece, it permits visual checking of satellite positions, collimation of the receiver with the transmitter, and alignment of the readout devices on the pedestal with the receiver optical axis.

The receiver employs a coaxially folded, prime-focus optical system and has separate optical subsystems for the eyepiece and the PMT. The primary subsystem is a 20-1/2-inch parabolic mirror with a 6-inch hole in the center. The other is a 5-inch optical flat supported through a cored hole in the center of the mirror.

The eyepiece optical system (Figure 6) operates, in essence, as any standard viewing telescope, with the eyepiece focused on the prime-focus plane. The only departure from a conventional system is the addition of a pair of relay lenses that transfer the image from the prime-focus plane to the side of the telescope tube and the eyepiece. A flip mirror deflects the light through the relay lenses to the eyepiece.
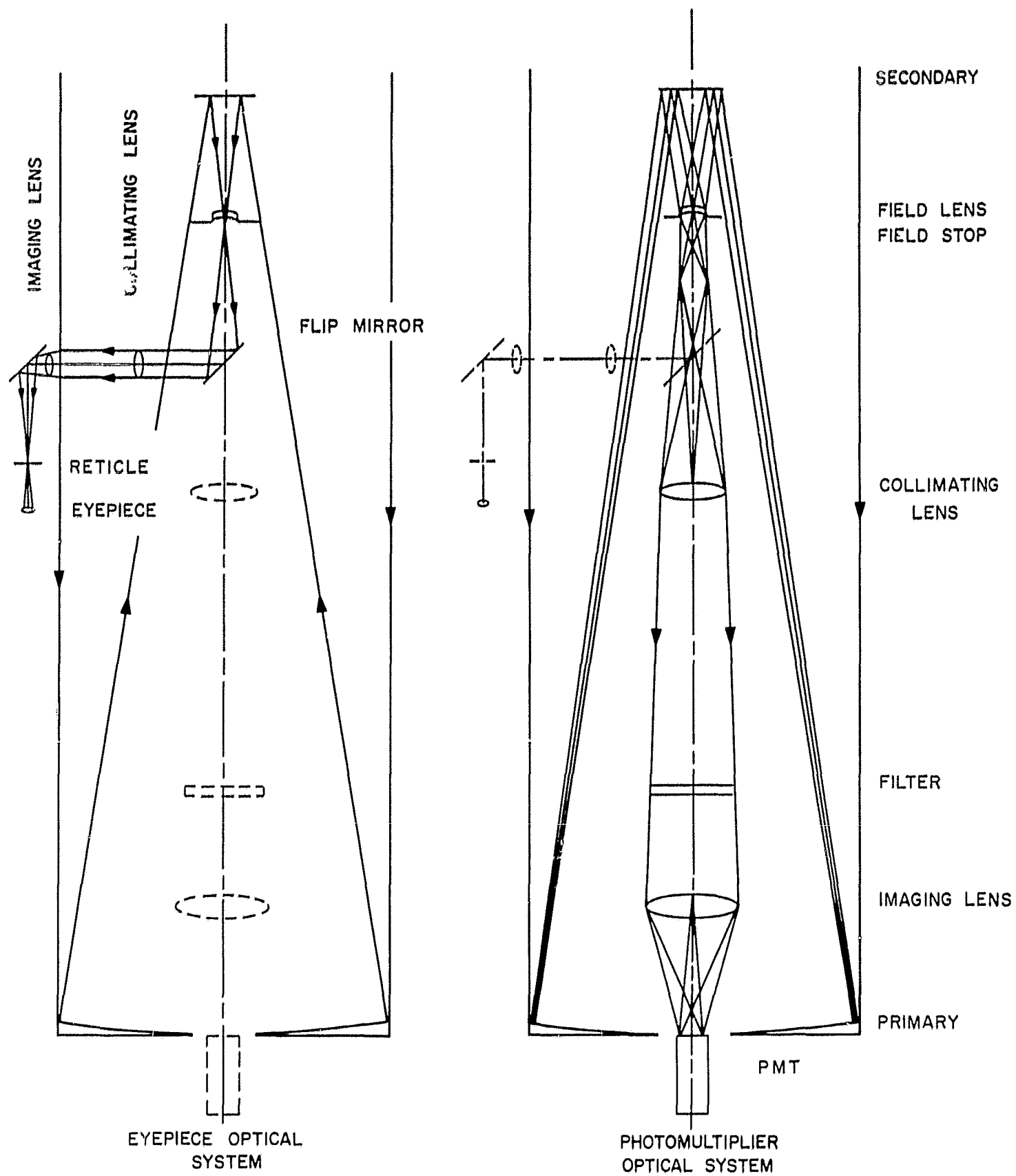
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Figure 6. Optical system and ray pattern for the telescope photoreceiver.

The optical system for the PMT (Figure 6) gives an image of the primary mirror at the face of the RCA 7265 PMT. Thus, instead of the PMT seeing a point image of the returning laser light, the detection of which might depend on where the image fell on the photocathode, the PMT looks at a donut-shaped image of the uniformly illuminated primary mirror. In this way, the laser return is evenly distributed across the PMT cathode.

In order to provide the image of the primary mirror at the PMT face, a positive meniscus field lens with a 2-inch focal length is placed in the primary focal plane. The field lens forms an image of the primary mirror at a point slightly more than 2 inches behind the field lens. This image is then transferred through the hole in the primary mirror to the PMT face by a pair of relay lenses, a collimating lens, and an imaging lens. The collimating lens also collimates the light bundle so that the angle of incidence of the rays passing through the interference filter, set just in front of the imaging lens, does not exceed 1°.

The field stops are located at the field lens position. The stops are holed disks that permit a field range from 2 to 20 arcmin in 2-arcmin increments.

An 0.6-nm passband interference filter is mounted into a tiltable holder inside the tube between the collimating lens and the imaging lens. The filter can be tuned by a micrometer (located at the back of the telescope), which adjusts the position of the tiltable holder.

The optical components in the system are coated to provide optimum performance in the spectral region in which they are used. The lenses in the eyepiece optical system are standard AR coated to provide good response in the visual region. The lenses in the PMT optical system have a dielectric "V" coating to allow less than 0.3% reflectance at each air-to-glass surface at 694 nm, the ruby-laser wavelength. The primary, secondary, flip, and diagonal mirrors are surfaced with aluminum overcoated with silicon monoxide. The efficiency of the PMT optical system, including the primary and secondary mirrors, is about 43%.

2.4 Ranging and Data-Recording Electronics

The fundamental accuracy of both the epoch of the laser-ranging pulse and its time of flight is derived from the standard station clock.[*] This clock is a VLF-steered crystal oscillator system (EECo Model ZA 34685), which produces a variety of precision pulse rates, with digital accumulation and display. The accuracy of the station clock is maintained by means of the SAO master clock[*] to within ±100 μsec of the UTC (USNO) time base. Short-term frequency stability is within 2 parts in 10^{10}.

For purposes of controlling and recording the epoch of the laser pulse, the 100-kHz output of the station clock is accumulated for time presentation by a timing synchronometer (General Radio Model 1121A). The synchronometer also produces timing pulses at rates of 1 and 0.1 pulse per sec. These pulses are used in coincidence circuits that permit automatic pulsing of the laser at uniform, predetermined intervals. In general, the epoch corresponds to precise 1-min markers of station time.

The control unit produces a pulse for the laser power supply, and 1.1 msec later, the laser is actuated. In addition, it provides appropriate pulses to reset the range counter and its associated range gate and to command the digital data printer. Figure 7 shows the control circuitry and other components of the system.

The range counter (Eldorado Model 796 or Nanofast Model 536) measures with high resolution (1 ns) the time interval between the emission of the laser pulse and the detection of a return signal. The start pulse, corresponding to the laser pulse emission, is produced by a photodiode monitor located near the laser optics; the stop pulse is the photoreceiver signal after amplification in a fast-rise, low-time-delay amplifier (C-COR Model 1375T). The range counter derives its counting accuracy and resolution from a 1-MHz frequency reference supplied by the station clock.

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[*]Procured in May 1964 from Electronic Engineering Company of California (EECo) under NASA grant NsG-87.

Figure 7. From left to right: the EECo timing system, the ranging
electronics (including the time-interval counter, oscillo-
scope, control circuitry and printer), and two cabinets
housing the laser capacitor banks, the Q-switch driver,
and pulse-forming networks. The laser cooling cabinet
is not shown.

To eliminate backscatter and other noise problems, the receipt of the
stop pulse by the range counter is controlled by a range gate. The range
gate remains closed until it receives a timing pulse, which is delayed an
adjustable predetermined amount from the start signal. This delay may be
derived either from the synchronometer or from the internal counting logic
of the range counter. Receipt of the signal opens the gate, permitting
registration by the stop signal.

The epoch and time interval are printed on a two-channel digital printer
(Baird-Atomic Model QF-8).

The photoreceiver electronics consist of a selected photomultiplier of
high quantum efficiency (RCA type 7265) in a shielded, low-noise enclosure

(Nanosecond Systems Model 57265). Anode voltage between 2200 and 2400 V is provided by a regulated supply (Northeast Scientific Model RE3002). The waveforms of the returned signals can be recorded with a high-speed oscilloscope/camera system (Tektronix 454A with C-40 camera). These photographs are useful for confirming returns and for diagnostic purposes.

3. PROCUREMENT OF THE PROTOTYPE LASER RANGING SYSTEM

The four major components consist of the static pointing pedestal, ordered from Boller & Chivens (a Division of Perkin-Elmer Corp.) of Pasadena, California; the laser transmitter system, ordered from Spacerays, Inc., of Burlington, Massachusetts; the telescope photoreceiver, ordered from Tinsley Laboratories of Berkeley, California; and the ranging and data-recording electronics, assembled by SAO from components supplied by several vendors.

3.1 Static Pointing Pedestal

A negotiated fixed-price contract was awarded to Boller & Chivens in January 1967 for the static pointing pedestal. In early March, an engineering design drawing for the unit and calculations describing the errors to be expected in the pedestal were forwarded to SAO for approval, before fabrication of the hardware by Boller & Chivens.

In late March, SAO representatives T. E. Hoffman, Chief Engineer, and L. A. Maestre, Program Manager, visited the Boller & Chivens plant to review the design of the pedestal. This design review with the contractor led to a final version of the design, on which fabrication was started in early April.

At the beginning of July, a factory acceptance-test plan was sent to SAO by the contractor. This plan was found acceptable, and in late July, a preliminary acceptance test was conducted on the pedestal. On hand for the tests, which required integration of the entire laser system, were the telescope photoreceiver and the laser transmitter.

The tests showed a number of deficiences in the pedestal that prevented completion of the acceptance tests at that time. Boller & Chivens suggested remedies that were agreed to by SAO. Completion of the acceptance test was deferred until the shortcomings in the pedestal could be corrected.

In mid-October, the contractor was ready to continue acceptance testing. This time the tests proceeded without difficulty.

The tests were remarkably successful. The total error budget for the pedestal as stated in SAO's technical specifications was 0.5 arcmin. This error was to consist only of nonrepeatable, noncorrectable errors, since all other errors could be compensated for in the satellite prediction program. The factory tests showed that all errors, including correctable and non-correctable, repeatable and nonrepeatable, with the exception of wind-load-induced errors, would equal about 12 arcsec, or less than half the specified error budget.

Upon conclusion of the tests, Boller & Chivens was authorized to ship the pedestal to Mt. Hopkins, Arizona, by 13 November 1967.

3.2 Laser Transmitter

A negotiated, fixed-price research and development contract for the laser transmitter was awarded to Spacerays, Inc., in March 1967. Since the laser was fabricated with off-the-shelf components for the cavities, Q-switching-mechanism power supplies, and trigger circuitry, the design review that was held in April covered only the output and divergence controlling optics, the safety aspects of the equipment, and the few minor parts that required special design considerations.

Fabrication of the unit was completed in early June. A plan for the factory acceptance tests was provided to SAO by that time. The actual tests were conducted during the last week in June.

As in the case of photoreceiver and pedestal, the performance of the laser exceeded SAO's technical specifications. Deflections in the transmitter that might have an influence on the overall pointing accuracy of the equipment were unmeasurably small. Also, the transmitter's output was a reliable single pulse of 5-joule output in a single 10-ns pulse, with a pulse-to-pulse stability of ± 10%.

The acceptance tests were not completed until 15 July 1967, because wiring changes were necessary in the power supply to reroute the high-voltage cables. On 15 July, the transmitter package was sent to Boller & Chivens to be included in the pedestal acceptance tests. The remainder of the hardware was held at the Spacerays' plant until late October 1967, when it was shipped to Mt. Hopkins.

3.3 Telescope Photoreceiver

In February 1967, Tinsley Laboratories was awarded a negotiated fixed-price contract to construct the telescope photoreceiver. The design for the instrument as offered in Tinsley's proposal proved, under further analysis by the contractor's engineers, to be inadequate for our purposes; as a result, it was modified to include additional optical components. A set of drawings describing the changes was submitted to SAO for review in April. At the same time, SAO received a mathematical analysis of the deflections expected from the finished product. On the basis of this material, the design was accepted.

Fabrication of the photoreceiver proceeded without difficulty. By late July, the mechanical structure of the telescope was sufficiently advanced to permit it to be sent to Boller & Chivens for test mating with the pedestal.

3.4 Ranging and Data-Recording Electronics

Some of the ranging and data-recording electronics were standard commercial products; others were designed and fabricated by SAO.

Items purchased routinely included the synchronometer (General Radio Model 1121A), a photomultiplier tube (RCA type 7265) in a shielded, low-noise enclosure (Nanosecond Systems Model 57265), a high-voltage power supply (Northeast Model RE 3002), a high-frequency oscilloscope (Tektronix 454 with C-40 camera and accessories), a low-time-delay amplifier (C-COR Model 1375T), and a two-channel digital printer (Baird-Atomic Model QF-8).

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Initially, the range counter consisted of an Eldorado Model 783G with a resolution of 10 ns. As devices with 1-ns resolution became available, a ' Nanofast Model 536 was purchased. In August, an Eldorado Model 796 was obtained for evaluation, for checking the initial unit, and for use as a spare.

Concurrent with the above procurement, the timing logic, digital coupler, and range-gate units were under development and construction at SAO. As these units were required to perform specialized functions and, in the case of the digital coupler, to interconnect units with differing logic levels, development by the experienced personnel at the STADAD Engineering Division of SAO was more expedient than purchase.

Tests confirmed that the individual pieces described were capable of operating together as complete system.

3.5 Prototype System Installation

On 13 November 1967, the major components of the prototype laser system were delivered to Mt. Hopkins and installed. Final acceptance tests on the pedestal and photoreceiver, which largely required only assembly and minor adjustments, were concluded within 10 days. The acceptance tests on the laser transmitter system were more involved, requiring an almost complete repeat of the factory acceptance tests.

During the laser acceptance testing in December, the Spacerays' installation engineer encountered difficulty in providing a stable single-pulse output from the oscillator portion of the transmitter. His problems were characterized by the following: (1) At low ambient temperatures (15°F), the oscillator was operating in an unstable mode. Since the gain in the amplifier portion of the transmitter is very high, it is important that the output from the oscillator be quite stable. (2) The 40-ft cable between the Pockels-cell driver and the Pockels cell was affecting the switching time of the unit. Ringing, with

the time between pulses being about 80 ns, occurred in the cab. . This 80 ns
was approximately the same length as the Q-switched pulse buildup and
consequently caused multiple pulsing.

In January, the Spacerays' engineer modified his transmitter package to
rectify the problems of December (heavy snows on Mt. Hopkins in the last
half of December prevented continuation of the laser acceptance tests until
mid-January). He corrected the multiple-pulsing problem by removing the
thyratron from the Pockels-cell driver and placing it onto the transmitter
chassis. This change enabled him to shorten the cable length to 2 ft. The
instability problem was handled through application of a thermostatically
controlled heater to the Pockels cell. This heater maintained the temperature
of the cell at 90°F, no matter what ambient temperature prevailed.

With the two difficulties causing multiple pulsing and instability in the
oscillator corrected, the final acceptance test of the laser transmitter was
completed on 25 January 1968.

4. PROTOTYPE EVALUATION PROGRAM

4.1 System Evaluation

4.1.1 Goals

The primary goal of the evaluation program was, of course, to show how closely actual performance came to that anticipated or specified. The most critical test evaluated the system in actual operation by using the range measurements in the determination of satellite orbits and obtaining residuals for each data point. The results of this test were not immediate, however, because the magnitude of the residual depended not only on the range measurement itself, but on the accuracy of the orbit. This latter accuracy increases as additional laser stations go into operation as part of a worldwide network.

The evaluation program also undertook to answer four operational questions that bear on the concepts of a laser network:

1. How well did the system operate under the field conditions associated with a site of good atmospheric seeing conditions?

2. Were the laser power and receiver aperture large enough to compensate for errors in the prediction of satellite positions?

3. Did the system design effectively cope with random variations in the intensities of the returned signals?

4. To what extent was the system design successful in facilitating daytime operation?

4.1.2 Test program

The first satellite range measurements with the new prototype on Mt. Hopkins were obtained in Febuary 1968. These are indicated in Table 3 along with a tabulation of continuing performance. A visual check of the

satellite's position was not required in pointing the laser. Many of the returns were obtained with the satellite in the earth's shadow. All returns from June on were made with a range counter of 1-ns (15-cm) resolution.

The returns were received with a laser beamwidth and telescope beamwidth of 10 arcmin. Since this value is only one-half the maximum beamwidth permitted by the system, we see that the system is compatible with the prediction errors. In fact, a computation of the prediction errors shows that had the beamwidth been only 6 arcmin during February and June, 70% of the reported returns would still have been received. A study of the errors in the predicted range (obtained along with the angular predictions) shows that the range predictions increase the effectiveness of the system by increasing the accuracy of the values used in range gating and in allowing returns from noise pulses to be separated from actual returns before the differential orbit improvement program is run.

By letting stars drift through its field, an initial calibration of about 8 photons/mV was obtained for the receiver. This constant was used to compare the calculated values of the returned signal with two experimental values (the first from Geos 2 and the second from D1D). The fact that one return was 29 dB and the other was 10 dB below the calculated value is consistent with the random variation observed with the 8-MW laser system when it was in New Mexico.

Tests were run to determine the effect of the sky-background noise. Before the baffling of the telescope was improved, the noise was considerably higher than it was later. Even so, the receiver was operable when the sky was bright enough to make invisible all stars fainter than first magnitude. When the baffling was improved, the receiver was operated in full daylight, but the anode voltage was a little below the specified value. From these tests it can be inferred that the laser system will operate when the sky is to bright for the Baker-Nunn camera, but the permissible extent of sky illumination will not be known until further opportunities to obtain returns in twilight come about.

Table 3.   Mt. Hopkins laser observations 1968

	BE-B 64-64-01		BE-C 65-32-01		Geos 1 65-89-01		D1C 67-11-01		D1D 67-14-01		Geos 2 68-02-01		Total	
	Passes	Returns	Passes	Returns	Passes	Returns	Passes	Returns	Passes	Returns	Passes	Returns	Passes	Returns
February			3	5			1	1	2	6	4	7	10	19
June	1	2	1	3	1	6					2	11	5	22
August			2	4	1	1			2	2			5	7
September	2	10	6	10	5	19	3	6					16	45
TOTAL	3	12	12	22	7	26	4	7	4	8	6	18	36	93

4.2 Subsystem Evaluation

4.2.1 Static pointing pedestal

Acceptance tests performed on the pedestal verified that its performance was satisfactory in all major respects.   Only minor assembly errors had to be corrected before delivery and final acceptance.

This portion of the system has been found satisfactory for normal field operation.   Subsequent units will be of essentially the same design.

4.2.2 Laser transmitter

The laser transmitter has demonstrated that this configuration has the capability of supplying the specified 500 MW together with the appropriate beamwidths and pulse characteristics for system operation.

The laser represents the only portion of the system that taxes the "state of the art"; consequently, the problems that occurred can be considered normal for field operation of such a prototype.

In general, performance can be refined with greater cleanliness, improved mechanical construction of components and adjustments, and increased stability in the output of the pumping lamps. Necessary modifications of the maintenance procedures and the mechanical design have been recognized and will be implemented.

Future lasers will have the same general configuration as the present systems but will incorporate the necessary modifications.

4.2.3 Telescope photoreceiver

As delivered, the telescope photoreciver met or exceeded the design requirements. A few minor discrepancies disclosed during the acceptance test were corrected before delivery and final acceptance.

Several minor field modifications were incorporated as a result of experience; e. g. , a cylindrical light baffle was added between the flip-mirror assembly and the photomultiplier tube to reduce the ambient light level, and a temporary optical sighting system for rough aiming was added. These and other minor improvements such as a more positive stop on the flip mirror will be incorporated in subsequent units.

The telescope photoreceiver has operated in a very satisfactory manner and has proved to be of rugged design. Future units will be essentially identical.

4.2.4 Ranging and data-recording electronics

With the exception of the timing logic, digital coupler, and range gate, the ranging and data-recording electronics consist of standard commercial items. No trouble has been experienced with these units.

Slight modifications are planned in some of the noncommercial equipment to provide simplified operation in future field units. With these exceptions, future systems will be identical to the present prototype.

5. PREDICTION AND DATA-HANDLING PROGRAM

5.1 Predictions

The laser prediction program AIMLASER uses as input updated precise orbital elements together with selected passage times. The program provides look angles that have been corrected for the effects of short-period (up to J_2) zonal perturbations, tesseral harmonics, and lunisolar perturbations. The output of AIMLASER can be teletyped directly to the field stations without further modification. The program predicts the satellite's azimuth, elevation, and range. The program also designates whether or not the satellite is in shadow and whether or not the sky is dark enough for astronomical observations. Table 4 shows a predicted pass of Geos 2. The predictions are supplied on a weekly basis. The epochs are even minutes.

5.2 Data Handling

The reduction of the laser range observations can be accomplished easily and rapidly. Two corrections are needed. The first corrects for time delays in the system that make the reading of the range counter larger or smaller than that corresponding to the difference between the intersection of the mount's azimuth and elevation axes and the retroreflector on the satellite. The second corrects the velocity of the laser pulse, which is less in the earth's atmosphere than it is in vacuum.

The correction for the time delay is obtained by ranging on a target 2547 ft away from the laser system. The distance, determined from an accurate survey, is subtracted from the product of the counter reading and the atmospheric velocity of light. The difference is added to the measured range values.

Table 4. AIMLASER prediction program

(DEGS)

HR	MN	SEC	AZIM	ALT	IN SHADOW	SKY
			7/7/68			
6	20	0.0	129.421	16.384	YES	DARK
6	21	0.0	125.869	21.325	YES	DARK
6	22	0.0	121.185	26.839	YES	DARK
6	23	0.0	114.800	32.909	YES	DARK
6	24	0.0	105.837	39.298	YES	DARK
6	25	0.0	93.124	45.307	NO	DARK
6	26	0.0	75.905	49.559	NO	DARK
6	27	0.0	55.777	50.458	NO	DARK
6	28	0.0	37.000	47.636	NO	DARK
6	29	0.0	22.499	42.383	NO	DARK
6	30	0.0	12.204	36.268	NO	DARK
6	31	0.0	4.956	30.236	NO	DARK
6	32	0.0	359.736	24.666	NO	DARK
6	33	0.0	355.861	19.643	NO	DARK
6	34	0.0	352.901	15.134	NO	DARK
6	35	0.0	350.583	11.071	NO	DARK
20	3	0.0	31.137	19.326	NO	LIGHT
20	4	0.0	33.851	24.979	NO	LIGHT
20	5	0.0	37.663	31.737	NO	LIGHT
20	6	0.0	43.470	39.892	NO	LIGHT
20	7	0.0	53.330	49.488	NO	LIGHT
20	8	0.0	72.222	59.338	NO	LIGHT
20	9	0.0	107.024	64.628	NO	LIGHT
20	10	0.0	143.454	59.832	NO	LIGHT
20	11	0.0	163.949	49.427	NO	LIGHT
20	12	0.0	174.507	38.928	NO	LIGHT
20	13	0.0	180.604	29.960	NO	LIGHT
20	14	0.0	184.527	22.567	NO	LIGHT
20	15	0.0	187.263	16.439	NO	LIGHT
20	16	0.0	189.286	11.265	NO	LIGHT

The correction for the earth's atmosphere comes from the work of Thayer (private communication, 1967). It is based on a model that uses the height of the observing station, the local temperature and pressure, and the elevation of the satellite.

If r_v is the travel time of the laser pulse multiplied by half the velocity of light in vacuum, and r_m is the "measured range" (i.e., r_v corrected for the effect of the atmosphere), we have

$$r_m = r_v - \frac{2.238 + 0.0414PT^{-1} - 0.238h_s}{\sin a + 10^{-3} \cot a} \text{, for } \theta_0 > 5°, \ \lambda = 694.3 \text{ nm,}$$

where

    r_m and r_v are range values in meters,

    P is the atmospheric pressure in millibars,

    T is the temperature in degrees Kelvin,

    h_s is the laser's elevation above mean sea level in kilometers,

    a is the elevation angle of the satellite, and

    θ_0 is the apparent elevation angle (i.e., the elevation angle uncorrected for atmosphere bending).

The standard error associated with this correction is 5 cm or less for elevations greater than 20°.

6. SAFETY PROGRAM

The basic safety hazards of the laser can be divided into three areas: mechanical, electrical, and optical. The optical hazards can be further subdivided into areas affecting operators and other station personnel and areas affecting persons not at the station. A copy of the laser safety regulations in effect at SAO installations is included in the Appendix.

The prime mechanical hazard is the possibility of explosion of the exciting flash lamps. In system tests and operation, they are enclosed in the laser cavities and thus cannot cause injury.

Electrical hazards exist in several areas in the laser system: the high voltage at high-energy levels for the exciting lamps; the high voltage at low-energy levels for the output monitor, the photomultiplier, and the Pockels cell; a short, very high-voltage pulse, approximately 30 KV, for the lamp trigger; and the normal supply-line voltages.

Protection from these voltages is provided by the use of enclosed, grounded metallic cabinets for mechanical isolation. Covers that are normally removed for servicing are provided with interlock switches to shut down the system and dump the high-energy storage capacitors. High-voltage cables between units are provided with adequate insulation and grounded external metallic covering.

The flash lamps and the laser output are both optical hazards. Since the lamps are normally covered by the cavities and a light-tight cover and because the time of firing is known to the operating personnel, the flash lamps provide a minor hazard.

Station personnel are indoctrinated in the safety program for their own protection. It is the responsibility of the laser operator to inform all station occupants when the laser is in operation to preclude their looking at the beam. An intercommunications system between the operations building and the camera house keeps all personnel advised of the status of the countdown that proceeds each laser firing.

Because the laser is mounted on a high point and seldom operated in a horizontal position, people in the area are never in the direct beam. The mount operator has the responsibility for interrupting the firing if an airplane is within range.

During alignment, when the laser is fired at a nearby target, trained operators with walkie-talkies are stationed at the target to operate the equipment and to ensure that no others are in the target area.

As the Mt. Hopkins Observatory expands and more people are in the area, the safety program will be expanded. Specifically, when the summit of Mt. Hopkins, higher than the laser location, is occupied, the warning system must be extended to this location.

Consideration has been given to adding audio or visual devices at strategic locations to warn of laser firings. The use of safety goggles is under consideration, although they cannot guard against the results of direct exposure.

Future laser equipment will have the same basic safety features as the present prototype. Additional stop buttons to terminate the firing sequence may be incorporated at locations such as the tracking pedestal.

7. CONCLUSIONS

SAO has been quite satisfied with the performance of its prototype laser system. All future systems will be of the same design as the prototype but will incorporate minor modifications that resulted from the evaluation program. The fact that the prototype laser was operated within a few days of its final acceptance test at Mt. Hopkins is an indication of the soundness of its design. Since February 1968, the prototype laser has supplied SAO with satellite range measurements that will be used in the calculation of precise satellite orbits. Since camera observations will still be needed to provide the necessary geographical distribution, these orbits will not be obtained until the Baker-Nunn measurements have been reduced.

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APPENDIX

LASER SAFETY REGULATIONS

When laser equipment is being operated at field stations, you should adhere to the following regulations and procedures.

1. Utilize firing procedures designed or approved by Headquarters, which will avoid accidental pulsing of the laser and/or electrical shock from storage capacitors, power supplies, etc.

2. Clear all station personnel not directly involved in operation from a reasonable distance on all sides of the anticipated path of the laser beam.

3. Discharge the laser beam into a background that is nonreflective and fire resistant.

4. Do not aim the laser with the eye.

5. Do not look into the primary beam at any time. Do not look at specular reflections of the beam, including those from the lens surfaces at any time.

6. Do not allow the laser beam to impinge on exposed skin surfaces.

7. Do not operate the laser unless the flash tubes are covered.

8. Operational voltages range from 1000 to 7000 V. These voltages are lethal. Exercise extreme care at all times.

9. Suspend operations at any time flying objects come into range.

10. When working with the laser, at times other than when ranging, maintain as high a degree of illumination as possible in the work area. Darkened areas cause the pupils of the eye to dilate, thus increasing the amount of laser energy that might inadvertently enter the eye.

In addition to the foregoing operational procedures, Station Managers are responsible for initiating and implementing a program of periodic eye examinations for <u>all</u> station personnel. Initial examinations must be followed by subsequent reexaminations every 6 months or immediately in the event of an exposure.

In the case of employees transferring from one laser station to another, station records of previous eye examinations must be forwarded to the new station prior to date of transfer. The manager of the new station is responsible for making appropriate arrangements to ensure that the 6-month cycle is maintained.

Eye examinations are compulsory for all station employees. In the immediate future, we will transmit recommendations as to appropriate exam procedures. These materials will be prepared by professional consultants. In the meantime, existing arrangements are to be continued without change.

Station Managers are responsible for sending a copy of each employee's examination record to the SAO Safety Officer. Results of each examination will be monitored and interpreted for Headquarters staff by medical consultants. Any positive findings will be promptly communicated to the stations, with appropriate recommendations.

Because of the severe inherent hazards involved in any laser operation, it is essential we initiate immediately a safety program consistent from station to station. The foregoing constitutes temporary steps pending formulation of a permanent, ongoing policy. Procedures outlined may be changed or augmented in the near future as we obtain additional information and equate it with our particular circumstances.

In the meantime, Station Managers are responsible for enforcing these regulations and procedures to ensure the safety of all operating personnel.