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LASER TRACKING AND COMMUNICATION WITH SATELLITES

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ABSTRACT

While the potential value of space communication using the optical spectrum is rapidly being developed, tracking of satellites with pulsed lasers has already been yielding valuable data for several years. Four U. S. satellites equipped with special passive retroreflectors are now being tracked, by ruby lasers, to a precision of about 1 meter. They are being used for evaluation of other tracking systems, improvement of satellite orbits, and consequently improvement of our knowledge of station locations and the earth's gravity field. Further expected advance in precision, to study lunar motion, continental drift, earth wobble, etc., requires better lasers, detection systems, and telescopes. Satellite experiments with continuous lasers such as argon and carbon dioxide are also leading to new optical tracking and satellite navigation techniques. More important, they constitute the next logical steps in the development of optical space communication. Areas requiring immediate attention include study of atmospheric effects on the communication channel; improvement in the efficiency, stability, power, lifetime, and tunability of candidate lasers; development of wide-band radiation-cooled mixers at 10 microns; and development of techniques for acquiring and tracking satellite communication terminals, both from satellites and on the ground.

PROGRESS IN LASER SATELLITE TRACKING AND COMMUNICATION

I. INTRODUCTION

The potentials of optical communication for space application have been discussed, both pro and con, in many studies (References 1, 2, 3). Translation of these potentials into practice must depend upon successful development of each component and subsystem of a component space link, plus a considerable body of field experience. From satellite experiments we develop ability to deal with the practical operational problems of this new technology, obtain the necessary knowledge of the channel properties, and gain confidence and maturity in applying optics and lasers to useful projects of immediate interest. This paper will describe some field experiments at Goddard which have tried to keep pace with the component technology and which have begun to indicate to NASA areas in which lasers may play important space roles. The emphasis will be upon systems aspects, applications, such results as we already have, and plans which are to go into effect in the immediate future.

The application of lasers which now seems most firmly established in the space program is that of satellite ranging. We shall review recent results in tracking the retroreflecting satellites now in orbit, discuss the precision being achieved and its significance in geodesy, orbit analysis, and calibration. Prospects for expanding the network of operating stations have become very real. The technique will undoubtedly be applied also to accurate measurement of the moon's motion and to synchronous satellites in a program of measurements for fundamental physics, astronomy, and geo-physics.

The first applications of continuous lasers to satellite experiments have so far involved the use of argon lasers on the ground and detectors in space. They resulted in valuable experience and data on the ability to point laser beams and the effects of the atmosphere. They shall be described briefly. The same ground stations will soon be receiving continuous reflection from orbiting spacecraft and measuring radial velocity by doppler frequency shifts. Finally, we shall consider the variations required to apply similar techniques with the carbon dioxide laser at 10.6 microns. This will bring us to the difficulties and advantages of heterodyne detection, first on the ground and then on the satellite itself. A set of communication experiments at 10.6 microns between spacecraft and ground is in the preliminary planning phases. These are setting the stage for wide bandwidth laser communication links between near-earth satellites and ultimately to deep space probes.

II. RECENT RESULTS IN PULSED LASER RANGING TO PASSIVE REFLECTING SATELLITES

The techniques and equipment of laser ranging to satellites has been described in detail in a number of references. (References 4, 5, 6, 7, 8) After a brief review, then, it only remains to relate some of the results of the last year and to comment on the prospects for continued growth in the number of laser tracking stations and in the fields to which such data may be applied.

There are now six satellites in orbit which were supplied with arrays of cube-corner retroreflectors designed for laser ranging. These are the U.S. satellites Beacon Explorers B and C (Explorers 22 and 27), (Figure 1), GEOS-I and II (Explorers 29 and 36), (Figure 2), and two French satellites D-1C and D-1D. The reflector arrays are composed of accurately polished fuzed silica cube-corners, which reflect incident radiation generally back toward its source, with relatively high efficiency. They are fairly inexpensive, lightweight, and passive in nature which, coupled with the real value of the laser tracking results, may explain why there are plans to place more of them in space and why more organizations are becoming interested in turning to lasers.

Even the ground station equipment is relatively modest (Figure 3). It consists of a laser transmitter and a receiving telescope aligned parallel to each other on a tracking mount. The system at the Goddard Space Flight Center uses a pulsed ruby laser which fires once per second with an energy of 1 to 2 joules and a pulse duration of about 20 nanoseconds. After collimation through a 5 inch telescope, the transmitted beam has a total divergence of 1 milliradian, and it is this that determines the accuracy with which the instrument must point toward the satellite. Note that this is equivalent to an antenna gain of greater than 70 db. Our tracking accuracy must be within 1 minute of arc in order to illuminate the target. This can be accomplished with a programmed drive based upon a predicted satellite trajectory, aided when possible by an operator viewing through an auxiliary telescope. The satellite range is measured by the time interval between the departure of the transmitted pulse and reception of the echo with a photomultiplier at the focus of a 16 inch aperture cassegrain telescope.

During the past year, we have improved the resolution of our time-of-flight measurement. Figure 4 shows the state-of-the-art in the form of laser range residuals from a short arc during a typical pass. The plotted points are differences between individual laser observations and the range calculated from an analytic orbit adjusted to a least variance fit. The RMS scatter about this smooth curve is less than one meter.

Such plots allow us to estimate the "precision" of our technique, as distinguished from "accuracy". Aside from calibrating the system against carefully measured distances on the ground, an estimate of possible systematic errors and biases is not so easy to obtain, since we have no suitable available standards. However, several recent tests may help to give us a degree of confidence.

The GEOS-I satellite was also being tracked by other networks during the period when laser measurements were being made. One of these was the network of TRANET radio-frequency doppler stations operated for the Navy. Two days of doppler data on GEOS-I, collected from a worldwide distribution of stations were combined into an orbital solution. This was then compared with laser observations during a pass within that two day period. The differences are plotted in Figure 5. A similar test was carried out using measurements made during those same two days by the worldwide photographic network run for NASA by the Smithsonian Astrophysical Observatory. The differences between laser observations and the orbit derived from those photographic measurements alone, are also plotted in Figure 5. Remember that we are now comparing the laser system against measurements on the same satellite by two completely independent networks, with stations all around the world, none of them near the laser station. Errors in station location, time synchronization, gravitational models, as well as equipment bias will all influence the comparison. In view of this, the resulting agreement is remarkable.

The Table in Figure 6 summarizes the results of four typical tests of the type described above. For purposes of description the errors were assumed to consist of a constant range bias (or "zero-set") and a term depending upon range-rate (equivalent to a "timing error"). This would give the residual plot the form of a sloping straight line. The column labelled "random" is the RMS scatter about that straight-line approximation. The zero-set difference with the optical photographic orbit averaged 4.1 meters and with the doppler orbit, the average was 5.9 meters in the other direction. Apparent timing errors averaged around 3.4 milliseconds. By independent analysis of the laser system we feel that the range uncertainty at this stage is about 1 meter.

Another type of laser test which has been performed during the past year is illustrated in Figure 7. For this purpose we moved our station to Wallops Island, where it was in close proximity to an FPQ-6 Radar, an FPS-16 Radar, and Army SECOR (Sequential Correlation of Range) station and a photographic camera. All of these systems could track GEOS-II simultaneously, so that their intercomparison would not suffer from the uncertainties in station location and orbit dynamics which degraded the tests described above. To display our results this time (Figure 8), we start by fitting a short arc to the laser data for a particular pass, and then plot the difference between that reference orbit and the ranges observed at the same time from each of the systems being tested. Figure 8 shows the disagreement between 3 of the other instruments and the laser orbit, and Figure 9 summarizes the comparisons for 6 typical passes. Again, the errors are interpreted in terms of a "zero-set" bias and an apparent timing error. The general agreement between the radars and the laser was very gratifying.

III. EXTENSION OF PULSED LASER SATELLITE TRACKING

A precision and accuracy of less than one meter, and the prospect of decreasing the uncertainty to a fraction of that, has stimulated interest and participation among many groups. Laser tracking can improve knowledge of satellite orbits, the fine details of the earth's gravitational field, or the position of the tracking station with respect to other stations and the earth's rotation axis. In addition to NASA's first station at Greenbelt, Maryland, a mobile station has been built, and will soon begin a series of intercomparisons like the ones we described. The Smithsonian Astrophysical Observatory has been operating stations at Mt. Hopkins in Arizona, Mt. Haleakala on the island of Maui and in Athens, Greece. They hope to add to this network with lasers at such places as Brazil, Argentina, and Ethiopia. The French also have been laser tracking at two or three stations and are reported planning to enlarge the number. The data collected over the past two years is already serving to improve world models, station locations, and calibration of other trackers. Other countries which have participated in geodetic programs may be expected to join the laser ranks soon.

We need not restrict pulsed laser tracking only to low altitude reflective satellites such as the six now in orbit. Several synchronous satellites would be excellent for mapping studies, because stations could range simultaneously and eliminate the need for calculating orbits. Since reflector arrays are so easy to add, we expect that some future synchronous communication or meteorology satellites might consider their value.

One other application of pulsed laser ranging which promises to keep us busy for sometime is that of ranging to a retroreflector placed on the surface of the moon (Reference 9). We hope that one of the early Apollo trips will permit an astronaut to deploy a special array on the lunar surface. Because of the greater distance, all the elements of the tracking system are being drastically improved for this project. The laser pulse must be both more energetic and shorter in duration, limited only by the ability of materials to withstand the extremely high peak powers. The divergence of the transmitted beam must be much less, in order to get the maximum of intensity onto the target. The retroreflected rays must not spread more than necessary. We are planning to use a 60-inch aperture telescope for both transmitter and receiver. In this experiment, the Goddard Space Flight Center is working with a team of co-investigators led by Professor C. O. Alley of the University of Maryland. With frequent measurements of precise range to the lunar reflector, over a period of years, we expect to improve our knowledge of the detailed motion of the moon, its libration and precession, its radius and moment of inertia, the earth's rotational rate and wobble, and the position of the tracking station. After 8 to 10 years, we may be able to say something definite about the slow change in the gravitational constant, which is predicted from some cosmological theories. Thus, such an experiment can have great significance in fundamental physics, astronomy, geodesy, map making, and timekeeping.

IV. EXPERIMENTS WITH CONTINUOUS ARGON LASERS

Argon laser beams have been transmitted into space from several stations (Figure 10). The experiments normally require well collimated beams and accurate pointing. When the target is visible, the pointing problem is one of autotracking, similar to that experienced by astronomers, except that satellite rates can be much different from the angular motion of stars. The servo system for a 24-inch diameter telescope at the Goddard Space Flight Center can be controlled by a star tracker and keep the optical axis pointing toward the center of a visible target with an uncertainty of ±0.2 arc seconds. When the target is not visible, we must direct our laser beam or receiver field of view on the basis of computed angular coordinates and the readings of shaft encoders. Now, the corresponding aiming accuracy is degraded by structural flexure, bearing eccentricity, nonorthogonality of axes, encoder errors, pier tilt, atmospheric refraction, etc. To these we must add the inaccuracy of the trajectory calculation and uncertainty in time and in the station's position. With great care, the best we can now hope for in absolute or "a priori" pointing accuracy is 3 to 5 arc seconds.

All of this is prelude to a description of some of the space experiments using Argon laser beams, which require an advanced ability to point accurately. The first of these was in response to a suggestion by Professor C. O. Alley and D. G. Currie of the University of Maryland (Reference 10). The Surveyor VII spacecraft, when it came to rest on the surface of the moon, was able to direct its TV camera back toward the earth and transmit pictures of our planet as seen from that vantage point. In addition to the scientific measurements performed, we were therefore given the opportunity to test the visibility of argon laser beams.

In Figure 11 we see a globe which illustrates the aspect of the earth as seen by Surveyor VII during one of the tests. The sun was illuminating the earth from the right, as indicated by the shaded crescent. Each of the black dots shows the location of one of the stations which participated in the experiment. They consisted of Table Mountain, California (operated by JPL); Kitt Peak, Arizona; Goddard Space Flight Center, near Greenbelt, Maryland; Perkin-Elmer, near Norwalk, Connecticut; Raytheon, Waltham, Massachusetts; and Lincoln Labs, Lexington, Massachusetts. The position of the Surveyor was carefully pin-pointed with respect to the visible features on the moon's surface, and all the stations attempted to illuminate that spot so as to be seen by the vidicon camera.

Figure 12 is a typical resulting TV picture. In several trials, the beams from Table Mountain and Kitt Peak were observed unambiguously, while none of the eastern stations was ever seen with certainty. This result was repeated several times, but the experiment could not be continued long enough to learn the reason for the differences in performance. They might be traced to power radiated, collimation and aiming techniques, atmospheric conditions, or proximity of the sun illumination to the East Coast.

Even with the limited data obtained from Surveyor VII, a few valuable conclusions can be drawn. Each of the stations detected was transmitting about 1 watt after accounting for telescope losses, with a divergence of several arc seconds, limited essentially by atmospheric seeing. The spots appeared with an approximate equivalent star magnitude of -1, which corresponds roughly to the calculated power density. Thus, we established the feasibility of pointing such narrow beams and checked the transparency of the atmosphere to laser beams. It seems especially remarkable that the 1 watt laser beams appeared as bright stars from the moon, while the diffuse light from major cities was not observed.

The argon transmitter system of Figure 10 is also used for other experiments. The GEOS-II satellite (Figure 2) was provided with a detector sensitive to one of the strong lines (4880 Angstroms) of the Argon laser. If we could illuminate the satellite as shown in Figure 13, the detector could then measure the intensity of the light reaching it and scintillations introduced by the atmosphere, and transmit the information back via the normal telemetry channel. To aid in distinguishing the laser light from the very large earth background seen within the 80° field of view of the detector, in addition to using a spectral filter, the laser light is chopped at a 13 kHz rate. In the spacecraft, the amplitude of the 13 kHz component is amplified with a logarithmic compression amplifier to give us 3 decades of dynamic range.

In Figure 14, the upper trace is a typical record of the GEOS-II detector output. The receiver aperture had an area of about one square centimeter. The intensity shown corresponds to a received power of about 10^{-11} watts, with sufficient signal-to-noise to permit us to analyze such atmospheric parameters as attenuation, depth of scintillation, and frequency spectrum of scintillations. These can now be related to theories of atmospheric propagation. While publication of such results is now in preparation, measurements will continue through the active life of GEOS-II.

The continuous argon laser will also be used to track passive satellites in a manner analogous to pulsed ruby laser tracking. If the transmitted beam is modulated at a high frequency and reflected from the cube-corner array satellites, we can measure a doppler shift in the modulation frequency of the reflected light, giving us a measure of the satellite's radial velocity. The equipment for this task is now being assembled. Future applications of Argon lasers in space can benefit from the experience gained in the experiments we have described. Because of their high power and the ease of detecting the visible wavelengths, they will undoubtedly be used at least as beacons: for space navigation and for tying down the direction of narrow-beam communication systems.

V. CARBON-DIOXIDE LASER COMMUNICATION EXPERIMENTS

The carbon-dioxide laser has properties which are at present so attractive that it is being very actively studied for use in space communication systems. It is the most efficient of the lasers (greater than 20% power conversion to radiation), can be made to operate at high power in a single stable frequency, is rugged, compact, and potentially long-lived. The wavelength, 10.6 microns, is convenient because of a good atmospheric window and because the mechanical tolerances commensurate with diffraction-limited operation are easier to achieve than at visible wavelengths. Of course, the long wavelength leads to detection problems. The small photon energy means that detectors must be cooled and the signal must compete against thermal radiation in the background and receiving equipment itself.

Fortunately, the coherence of the laser and response characteristics of available detector materials allow us to employ heterodyne mixing techniques. It has been shown in many laboratories that by using local oscillator lasers to beat with a small signal, and by amplifying the resulting intermediate frequency, all extraneous noise can be overcome and our detectability becomes limited only by the photon nature of the signal light itself. Such utilization of the coherent nature of laser radiation gives optical communication its unique character and suggests developments and experiments that must be accomplished before we can safely evaluate its utility in space applications. In particular, we must study the conditions under which the atmosphere does not seriously perturb the phase fronts of the arriving waves so that mixing can be performed efficiently. We shall briefly describe two such experiments.

The first will attempt to receive CO_2 laser radiation which has been reflected from one of the geodetic balloon satellites now in orbit. The plan is shown schematically in Figure 15, and the equipment is shown partially assembled in Figure 16. A single frequency laser, radiating about 20 watts, will be used as transmitter source. By means of beam splitters, a small fraction of the output is used as local oscillator, while the bulk of the power is transmitted toward the reflecting satellite through a 12-inch telescope. The 10.6 micron reflected radiation is received by the large telescope and focused onto the cyrogenic mixer (mercury-doped germanium), where it is superimposed on the local oscillator radiation. The image motion compensator acts to superimpose the signal image on the local oscillator spot to within a fraction of its diffraction limited diameter, so that the phases will match. In this early experiment, information for the image motion compensator will come from a star tracker operating on visible light from the target. Later, angle-error signals must be derived from the CO_2 radiation itself.

Another difficulty arises from the doppler shift in the 10.6 micron radiation because of the motion of the reflecting target. In our experiment, this can amount to over 1 gHz, and will change at rates of several MHz per second as we track the satellite across the sky. Since the doppler shift is actually the beat frequency in our homodyne technique, we must have mixers which respond to such high frequencies, and tracking filters in the IF stage capable of following the rapid changes. All of these components have now been developed and are being tested in the laboratory in preparation for the experiment.

Assuming that this passive satellite experiment has been performed successfully, and that we have demonstrated the ability to receive coherently through the atmosphere with large receiving apertures, the next step must be to launch and test complete active prototype laser communication systems: first from spacecraft to ground, and then between two spacecraft. Only when unanticipated problems are met and solved, and we can put quantitative values on success probabilities, will the technology begin to be applied in operational projects. Such a plan is now being considered very seriously. The experiment we shall be describing is only in a conceptual stage: it may finally take on a very different appearance from the one shown schematically in Figures 17 and 18. It is being proposed as an experiment which can utilize existing state-of-the-art, can be flown and operated on an available spacecraft at the earliest possible time, and yet will provide most of the answers needed by the designers of the next (operational) system.

The ATS-F satellite is planned for launch early in 1972. It will be placed in synchronous orbit and oriented so that a 30-foot microwave antenna is directed down toward ground receiving stations which will perform communication experiments. Its attitude will thus be known to an accuracy of about 0.1 degree. In order to establish an optical link, therefore, the spacecraft laser package will have a single flat mirror whose angles with respect to the spacecraft axes are determined from digital shaft encoders, and which can be slewed by command.

The transmitted laser beam will be sent through a fixed 5-inch diameter telescope antenna and then reflected from this flat mirror, so that the optical link may be independent of the other functions of the spacecraft. The same optical system is also used as the receiving antenna for radiation from a similar package at the terminal. The received signal is focused on two mixer elements, which are also illuminated by a separate local oscillator laser. One of these mixers produces the video IF signal which is then processed for the communication information, while the other is an angle-error sensor. The latter provides feedback information to a small image motion compensator which is then automatically controlled to keep the signal superimposed with the local oscillator on the mixers. Since the transmitted beam also makes use of the image motion compensator, this also insures that the transmitted beam will be accurately directed toward the other terminal.

In order to isolate the transmitted and received signals at each terminal, we may arrange to operate on different lines of the CO_2 rotational spectrum, so that they will be separated by at least 55 gHz. In each channel, the local oscillator can be offset by 20 MHz from the signal frequency so that the IF frequency could accommodate information bandwidths of more than 5 MHz. Such details as tuning the laser by piezoelectric transducer mirror mounts, thermal stability, and acquisition techniques cannot be discussed here. They are covered in more detail in Reference 11. It should be noted that the detectors can be made of mercury-cadmium-telluride, which has acceptable properties at temperatures near 100°K. This could be accomplished on a spacecraft using a radiation cooler mounted on a surface always looking off into cold space.

It is clear that the system proposed for this experiment is only a very early indication of the potential of the CO_2 laser technology for space communication. The expected performance, however, will show an impressive capability for a relatively small package. A completely independent spacecraft optical system would weigh about 30 pounds and use about 30 watts. The antenna of 5-inch diameter would have an equivalent gain of about 100 db. The transmitter laser would radiate 400 milliwatts, with internal cavity modulation, while only 50 milliwatts would be necessary for the local oscillator laser. From synchronous altitude we expect 5 MHz of information bandwidth, with signal-to-noise of 26 db. This assumes that both terminals of the link have identical optical equipment.

We have thus seen that the tracking applications of lasers have at least found limited valuable operations and are expected to be extended considerably. On the basis of that kind of experience and remarkable progress in laser technology, there is every indication that optical communication will also find unique areas in which it is superior in performance and economy to other portions of the spectrum.

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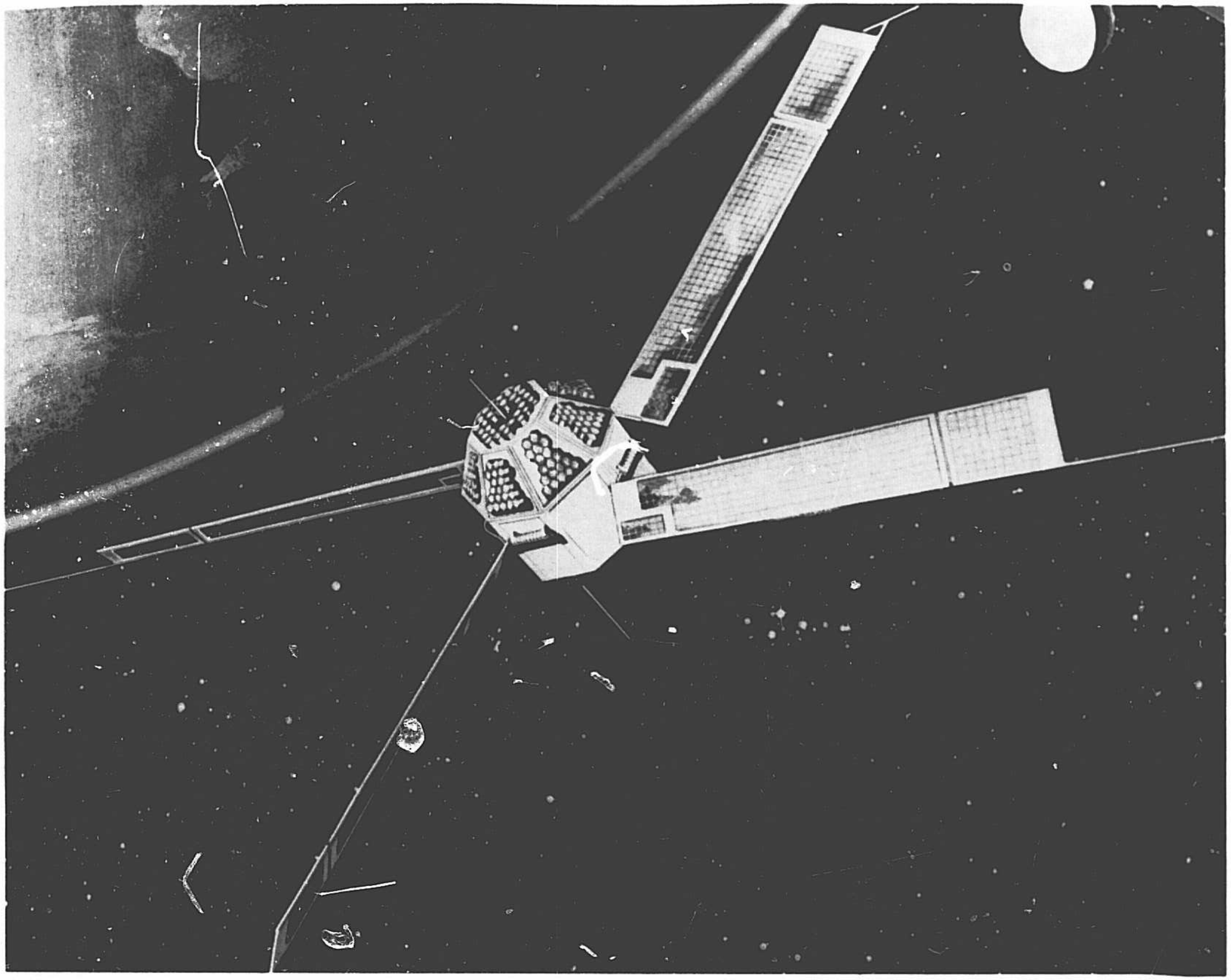

Figure 1. Beacon Explorer satellite. The reflector arrays are designed for pulsed laser ranging. The satellite is magnetically oriented so that, in the Northern Hemisphere, the reflector array points generally down toward the earth.

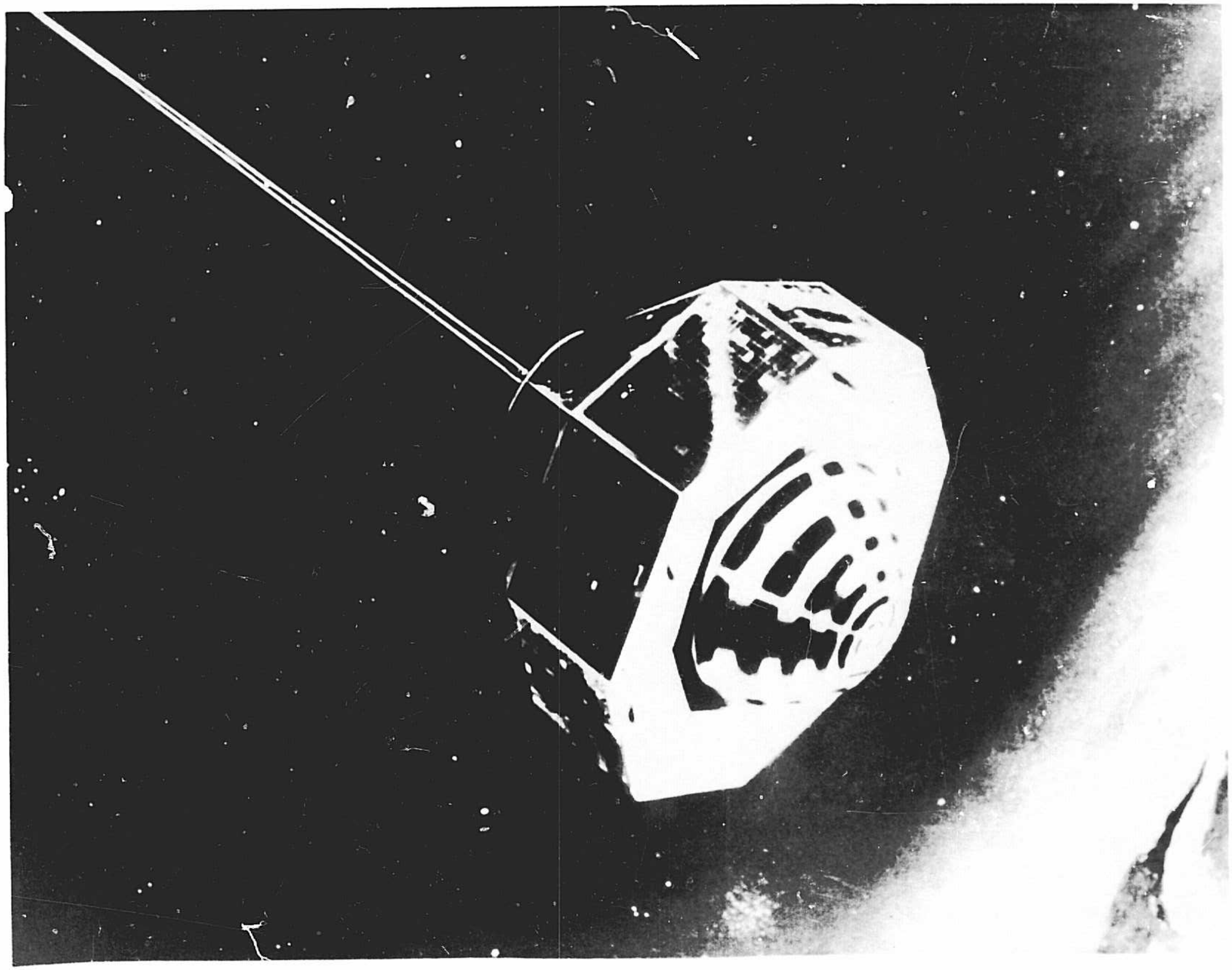

Figure 2. The GEOS satellite is gravity-gradient stabilized so that the array of fuzed-silica, cube-corners always faces the earth.

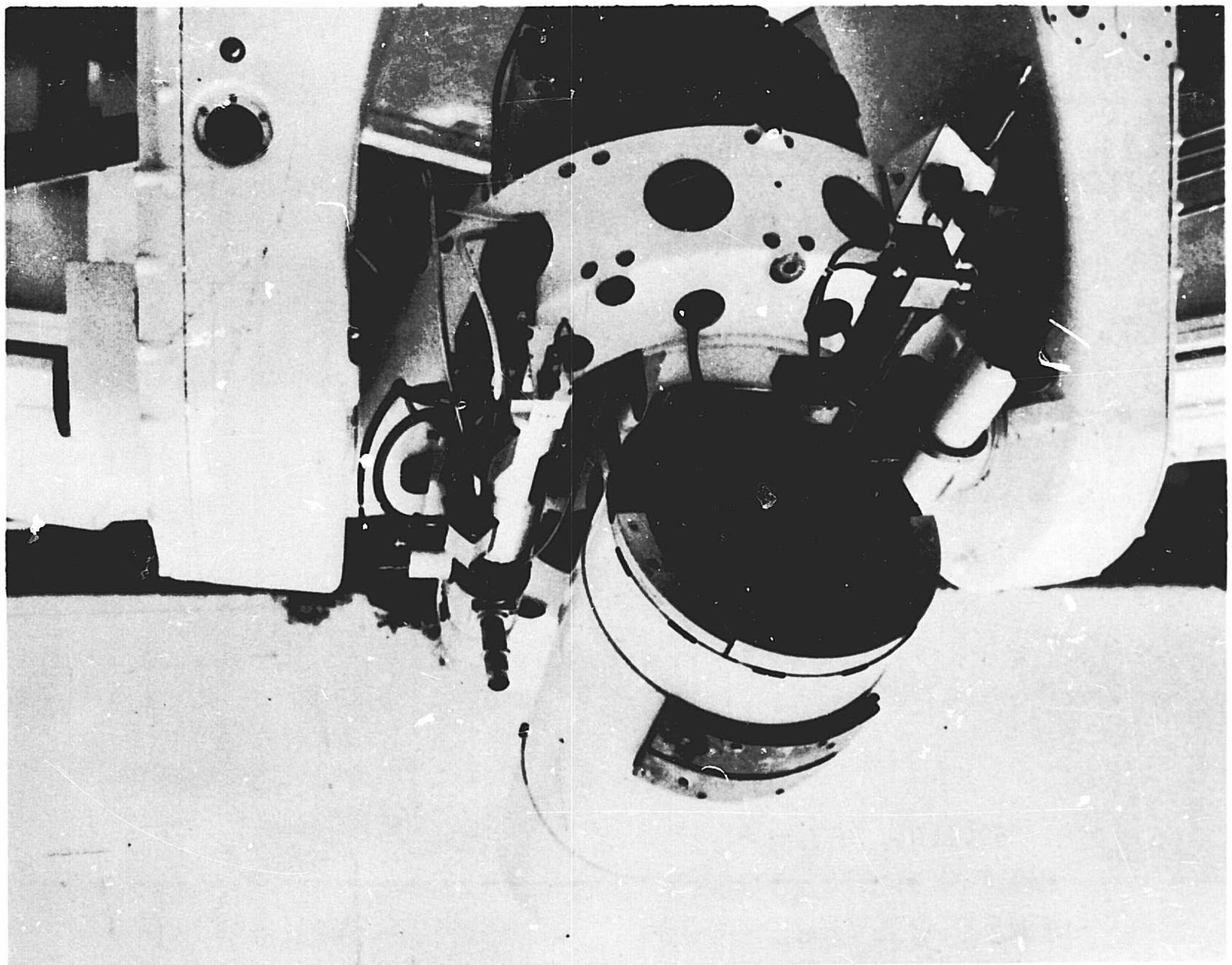

Figure 3. Goddard's laser satellite tracking equipment. On the azimuth elevation platform we have, from right to left, a pulsed ruby laser, a 10-inch cassegrain telescope with photomultiplier detector, and an auxiliary telescope for manual control.

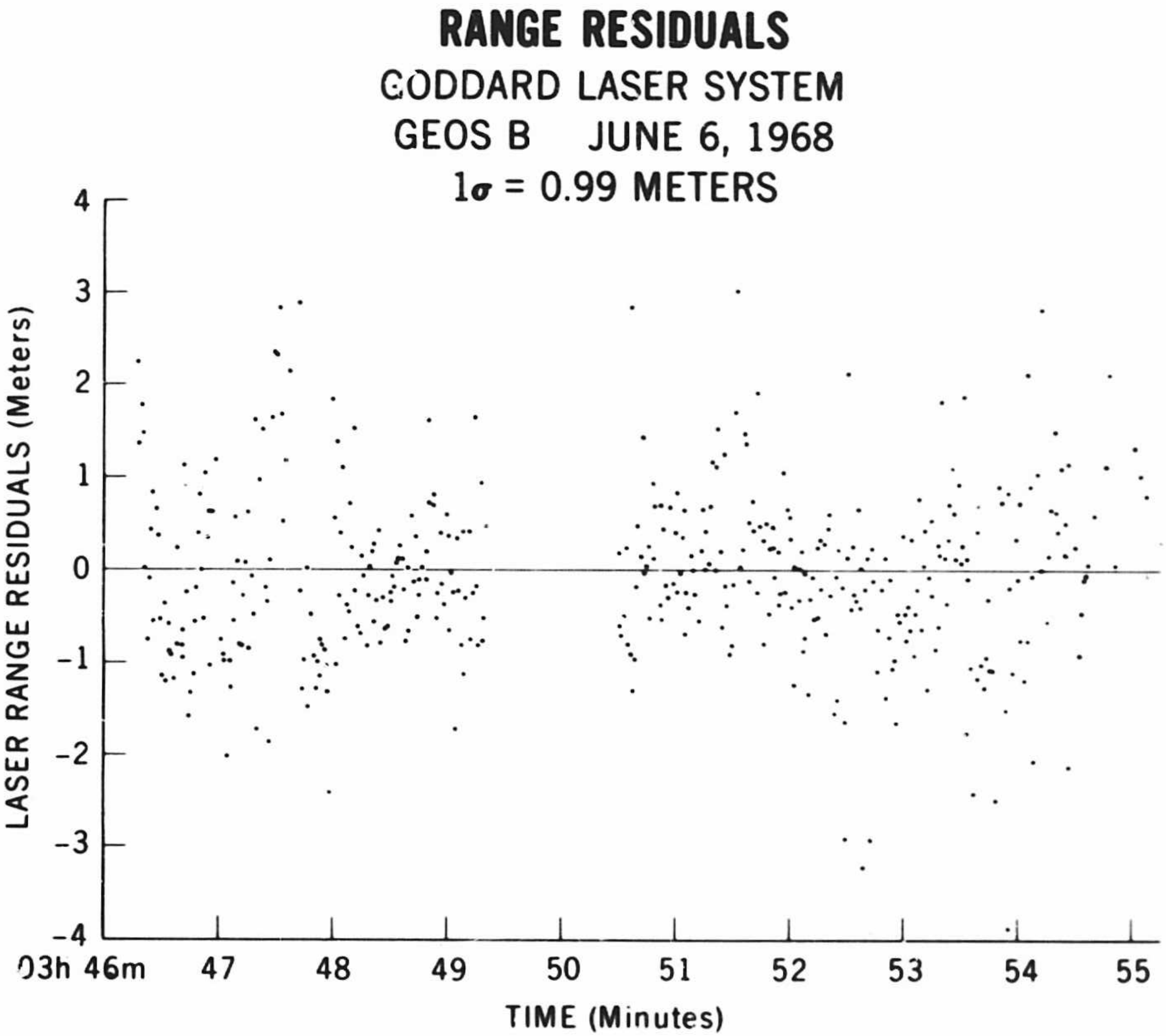

Figure 4. Residuals of satellite range measured with laser radar from an orbit fitted to the observations. The time interval between independent measurements is one second.

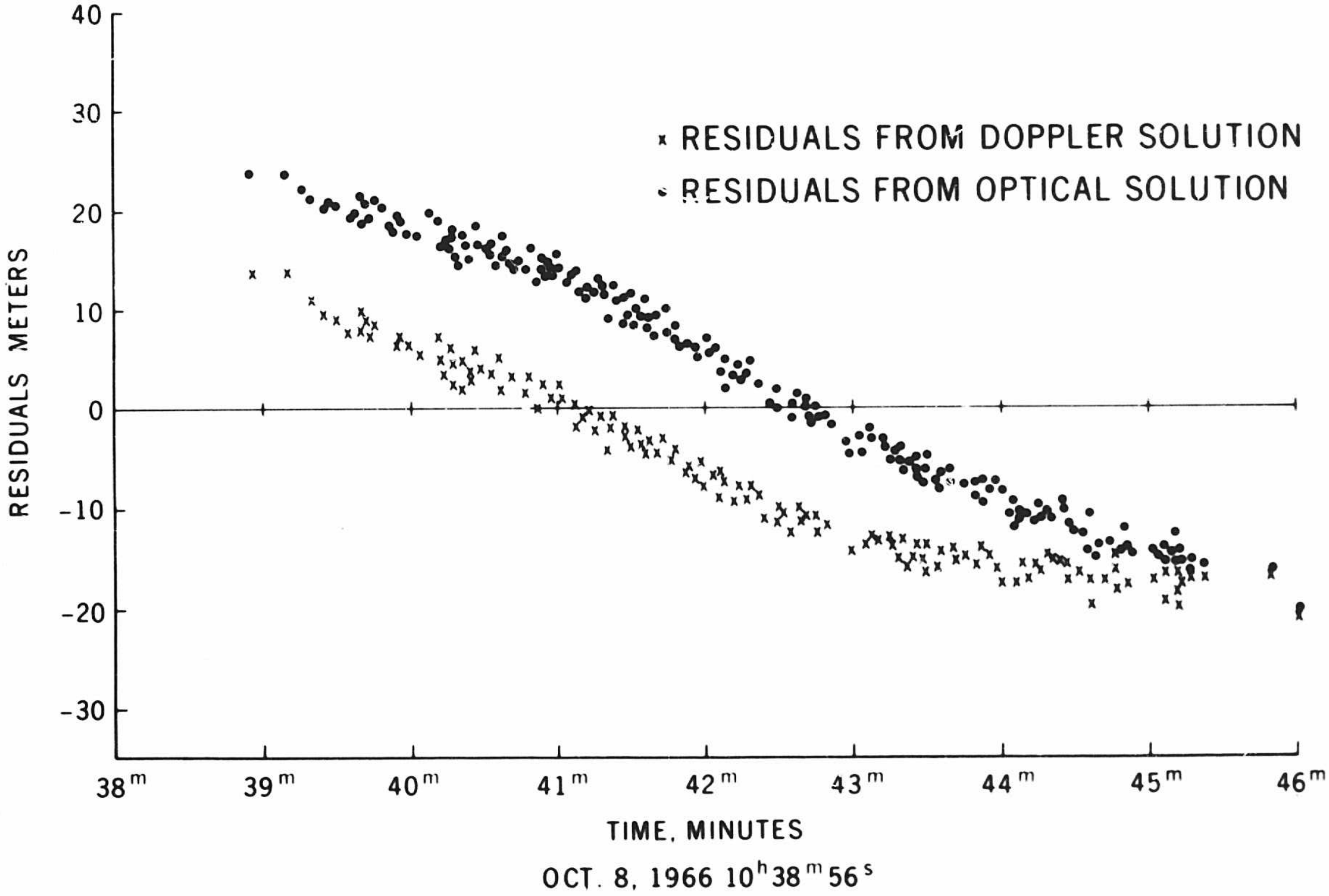

Figure 5. Differences between laser range measurements on GEOS-1 and orbits derived from two days of photographic data and two days of radio doppler data, respectively. The optical and radio doppler data were collected by independent world-wide networks of stations.

SUMMARY OF LASER RANGE ERROR ESTIMATES

2 DAY ARCS

TYPE OF SOLUTION	PASS		ERROR ESTIMATES		
	YYMMDD	HHMM	ZERO SET (m)	TUNING (ms)	RANDOM (m)
OPTICAL	661005	10 29	3.5	-4.1	1.8
DOPPLER	661005	10 29	-6.0	-1.8	1.8
OPTICAL	661006	10 31	6.9	-3.9	1.7
DOPPLER	661006	10 31	-3.3	-1.5	2.0
OPTICAL	661007	10 35	4.1	-6.4	1.9
DOPPLER	661007	10 35	-6.6	-2.4	1.6
OPTICAL	661008	10 38	2.0	-4.1	1.1
DOPPLER	661008	10 38	-7.9	-3.0	2.1

Figure 6. Summary of differences between laser range observations and orbits of GEOS-I based upon optical photographic tracking and radio doppler tracking.

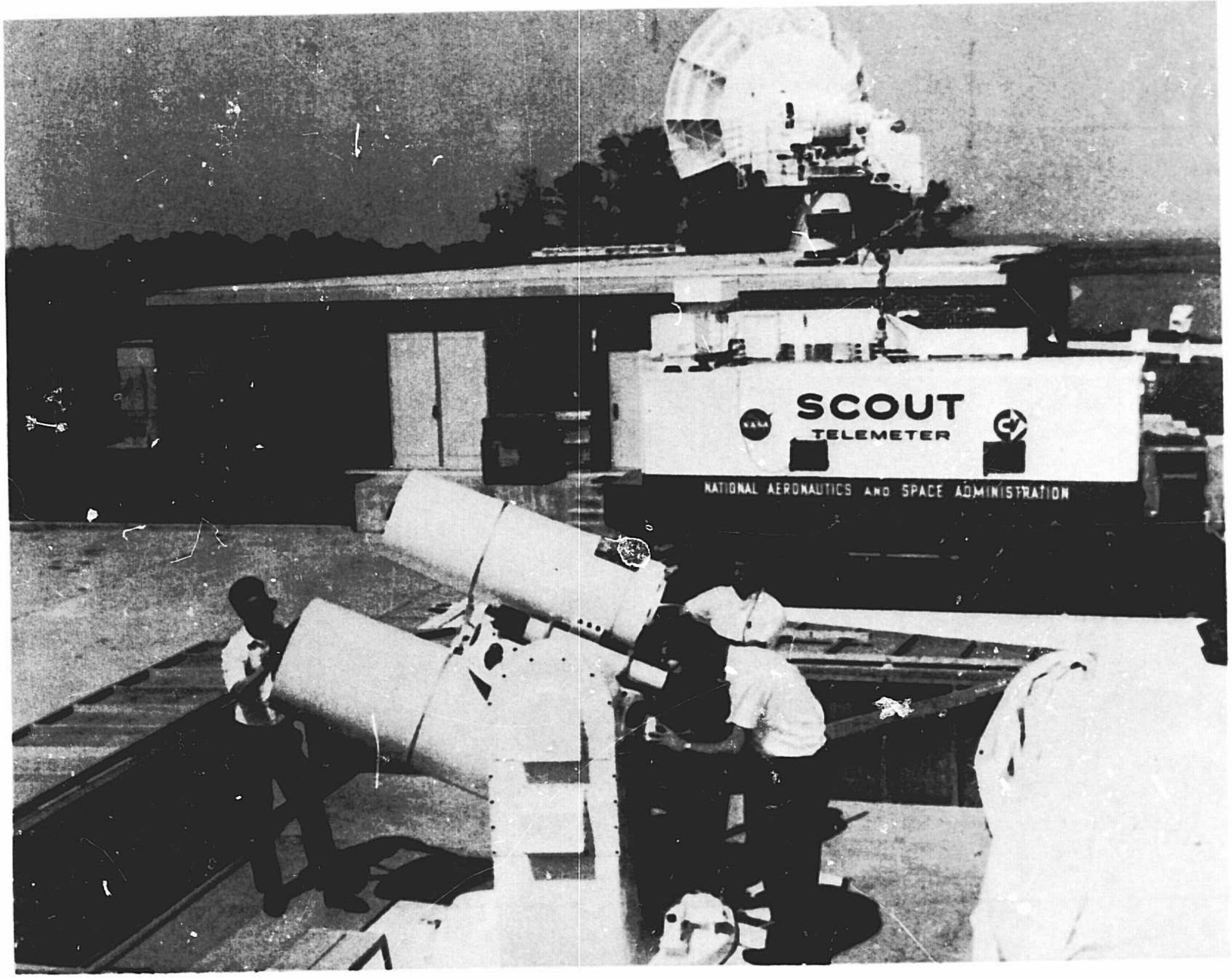

Figure 7 Co-location experiment at Wallops Island. The laser tracking station operated close to the FPQ-6 Radar (C-Band), both simultaneously tracking the GEOS-II satellite.

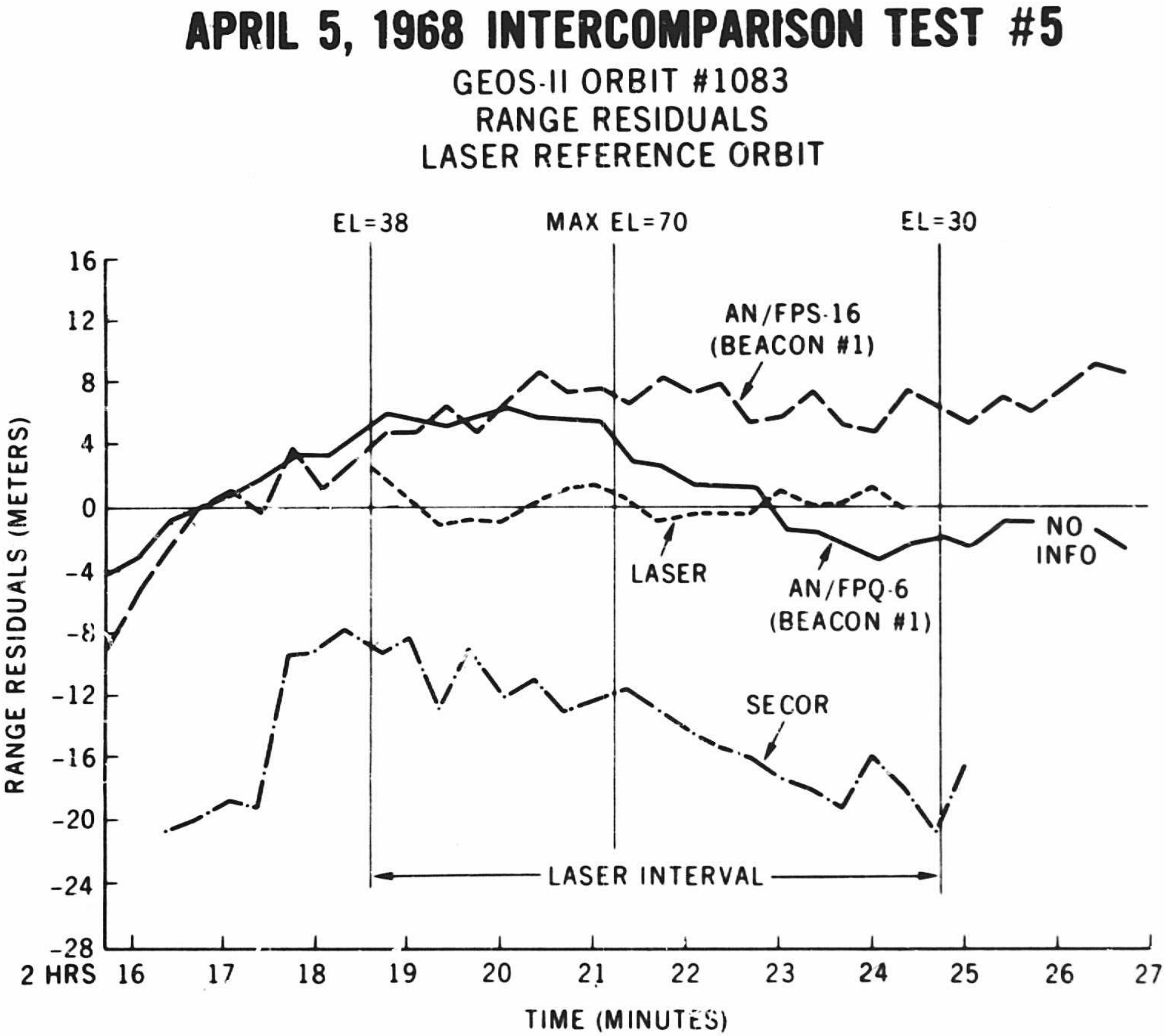

Figure 8. Comparison between three tracking systems at Wallops Island and the co-located laser tracker, all simultaneously measuring range of GEOS-II. Reference orbit is best fit to laser data.

RANGE DATA COMPARISONS

LASER SHORT ARC REFERENCE ORBIT

TEST #	RANGE (METERS)			TIME BIAS (ms)		
	SECOR	AN/FPQ-6	AN/FPS-16	SECOR	FPQ-6	FPS-16
2	-18.6 ± 3.2	-8.9 ± 1.6	-0.1 ± 1.6	-0.58 ± 1.09	-0.80 ± 0.52	0.67 ± 0.52
3	-6.1 ± 5.6	-0.3 ± 2.8	2.6 ± 2.8	-1.38 ± 1.61	-0.02 ± 0.80	-0.04 ± 0.80
5	-13.5 ± 3.2	1.4 ± 1.6	6.6 ± 1.6	-0.94 ± 0.91	-0.11 ± 0.46	-0.01 ± 0.46
9	-9.4 ± 6.3	——	1.2 ± 3.2	-0.35 ± 3.94	——	0.74 ± 2.00
11	——	5.2 ± 1.5	-1.9 ± 1.6	——	0.41 ± 0.46	0.26 ± 0.46
12	——	0.7 ± 1.9	-1.0 ± 1.9	——	0.52 ± 0.86	0.31 ± 0.84
AVERAGE	-11.9 ± 4.7	-0.4 ± 4.6	1.2 ± 2.8	-0.80 ± 0.39	0.32 ± 0.34	0.32 ± 0.30

Figure 9. Summary of six passes of GEOS-II which were simultaneously tracked at Wallops Island by the Laser, SECOR, and radars FPS-16 and FPQ-6l Differences listed are averages between a reference orbit fitted only to the laser data for each pass, and observations from each of the other tracking systems.

Figure 10. Argon laser beam being transmitted from the Goddard Space Flight Center. In this equipment, the laser is on a stationary platform and the beam is reflected through the hollow shafts of an azimuth-elevation mount.

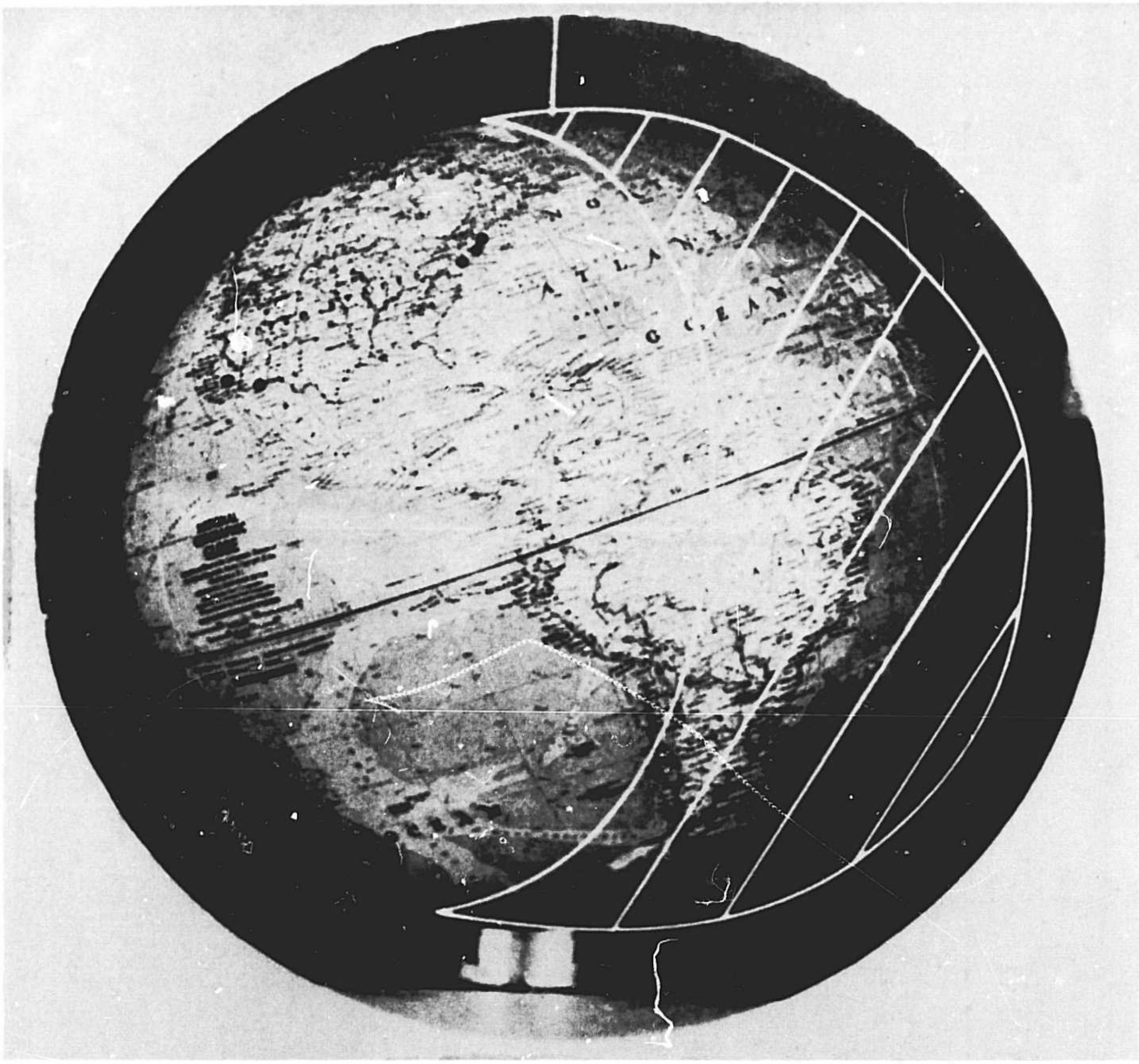

Figure 11. Globe showing the aspect of the earth during one of the Surveyor VII laser tests. The shaded area is the position of the sun-illuminated crescent, and the dots are the positions of laser transmitting stations which participated in the test.

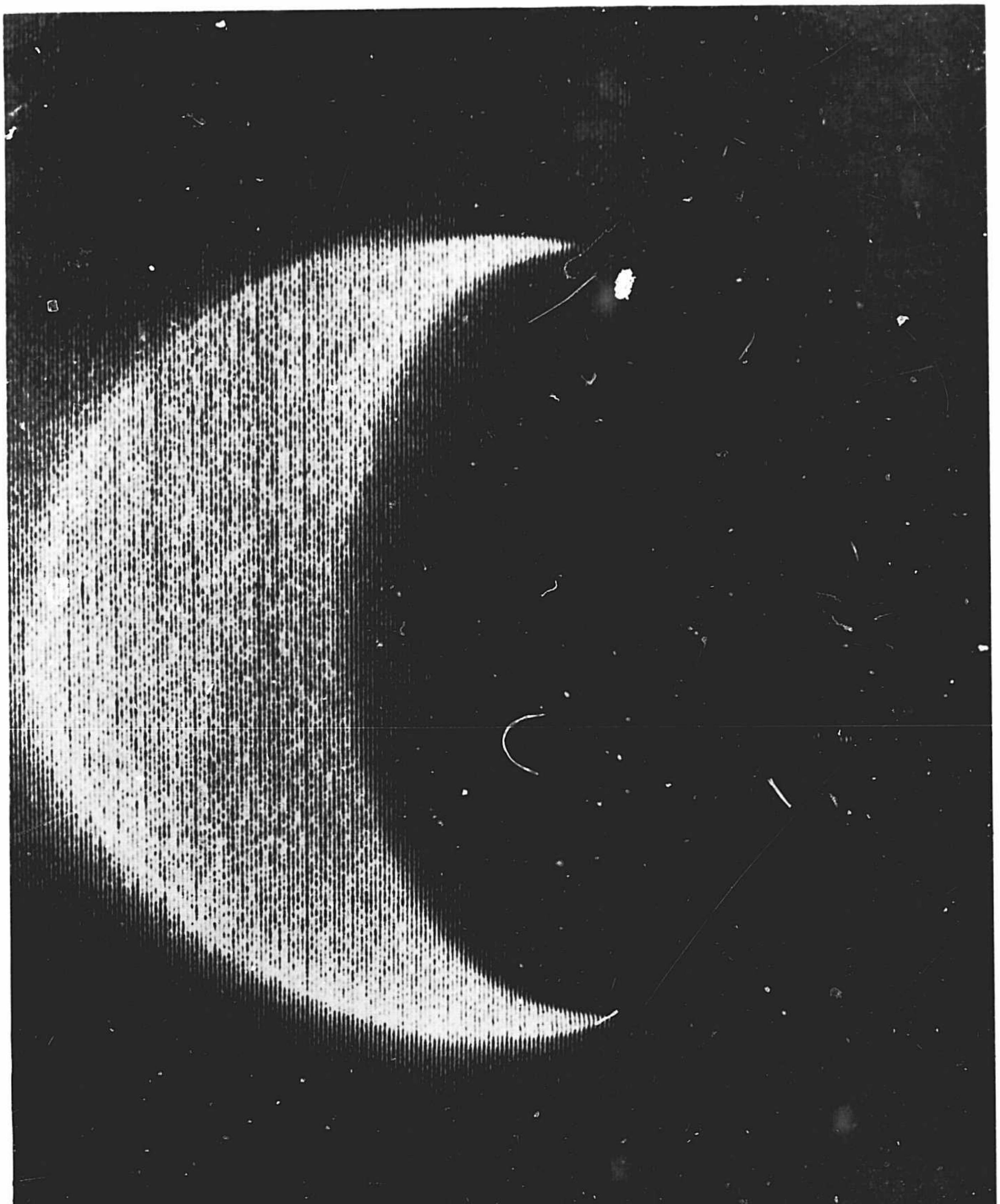

Figure 12. Vidicon TV picture of earth from Surveyor VII, showing laser radiation images from Table Mountain, California, and Kitt Peak, Arizona. Eastern U.S. stations indicated in Figure 11 were not observed with certainty.

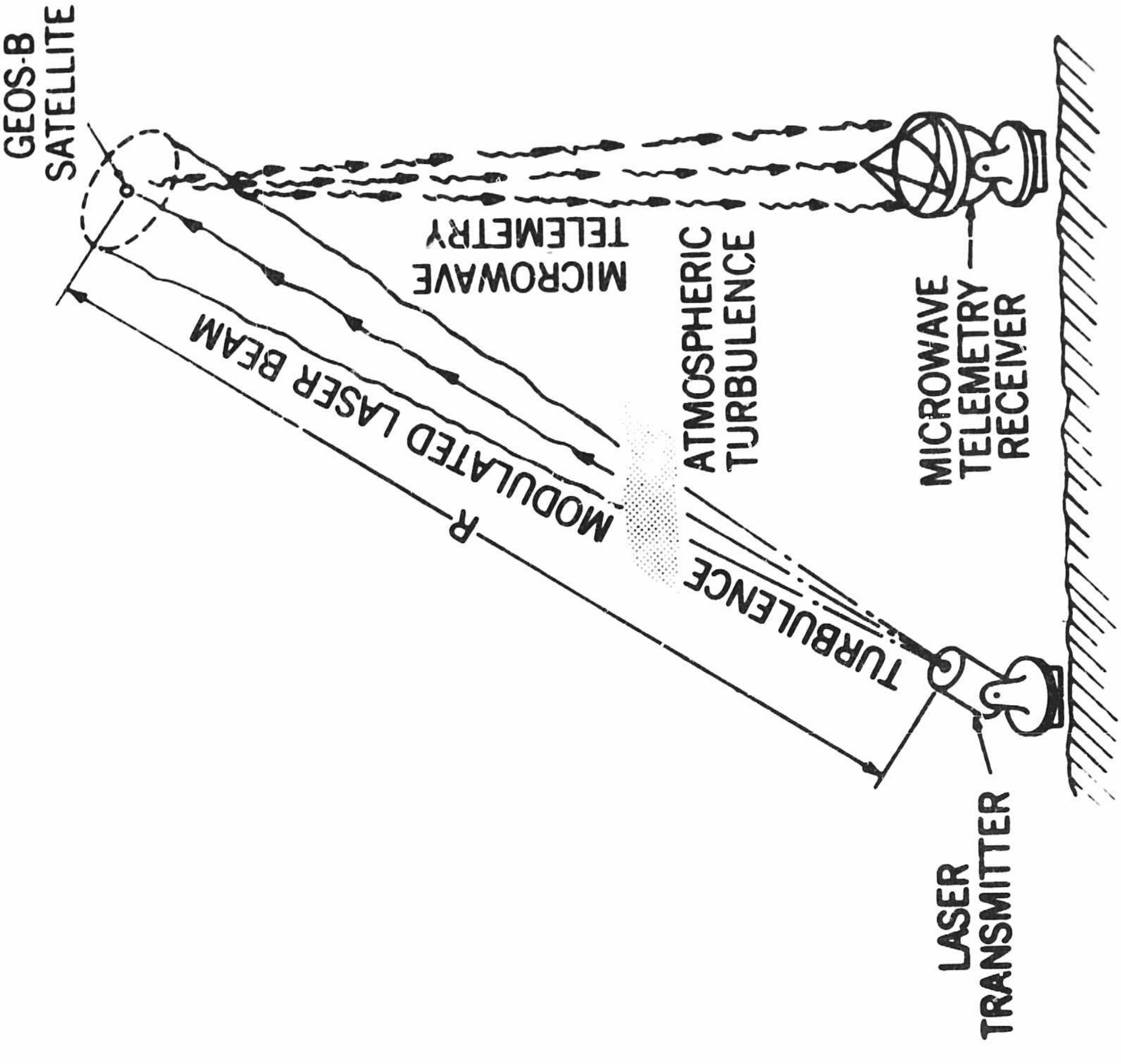

Figure 13. Plan for GEOS-II experiment for studying scintillation produced by the atmosphere on a laser beam transmitted into space from the earth.

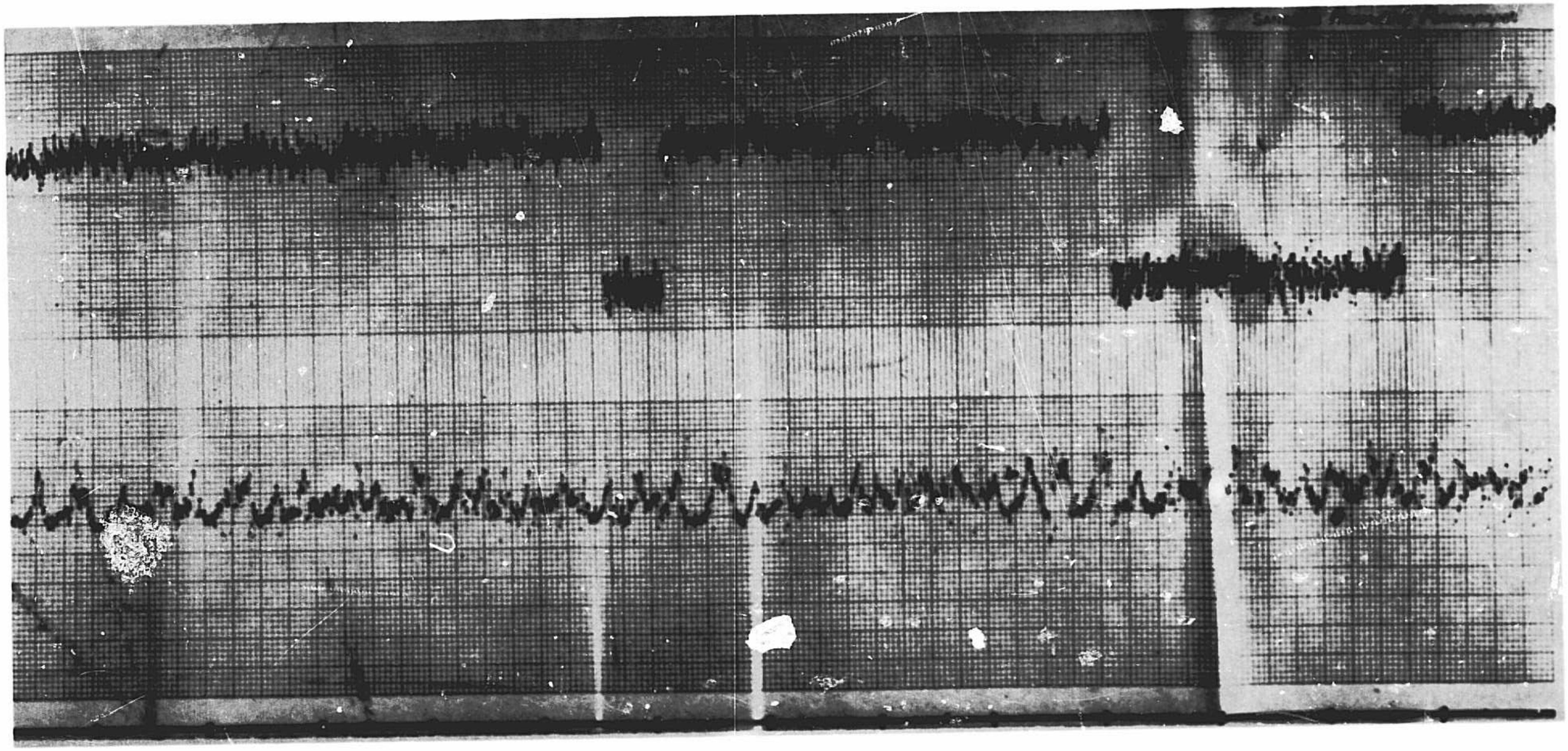

Figure 14. Typical record of incident laser intensity measured by GEOS-II. In upper trace, the long record is detected radiation when laser is on, the shorter gaps are the result of closing the transmitter shutter. Background signal within filter response is 2×10^{-13} watt, laser signal is about 10^{-11} watt. Vertical marks at bottom of record are one-second time ticks.

FUNCTIONAL DIAGRAM OF 10.6 μ TRANSCEIVER

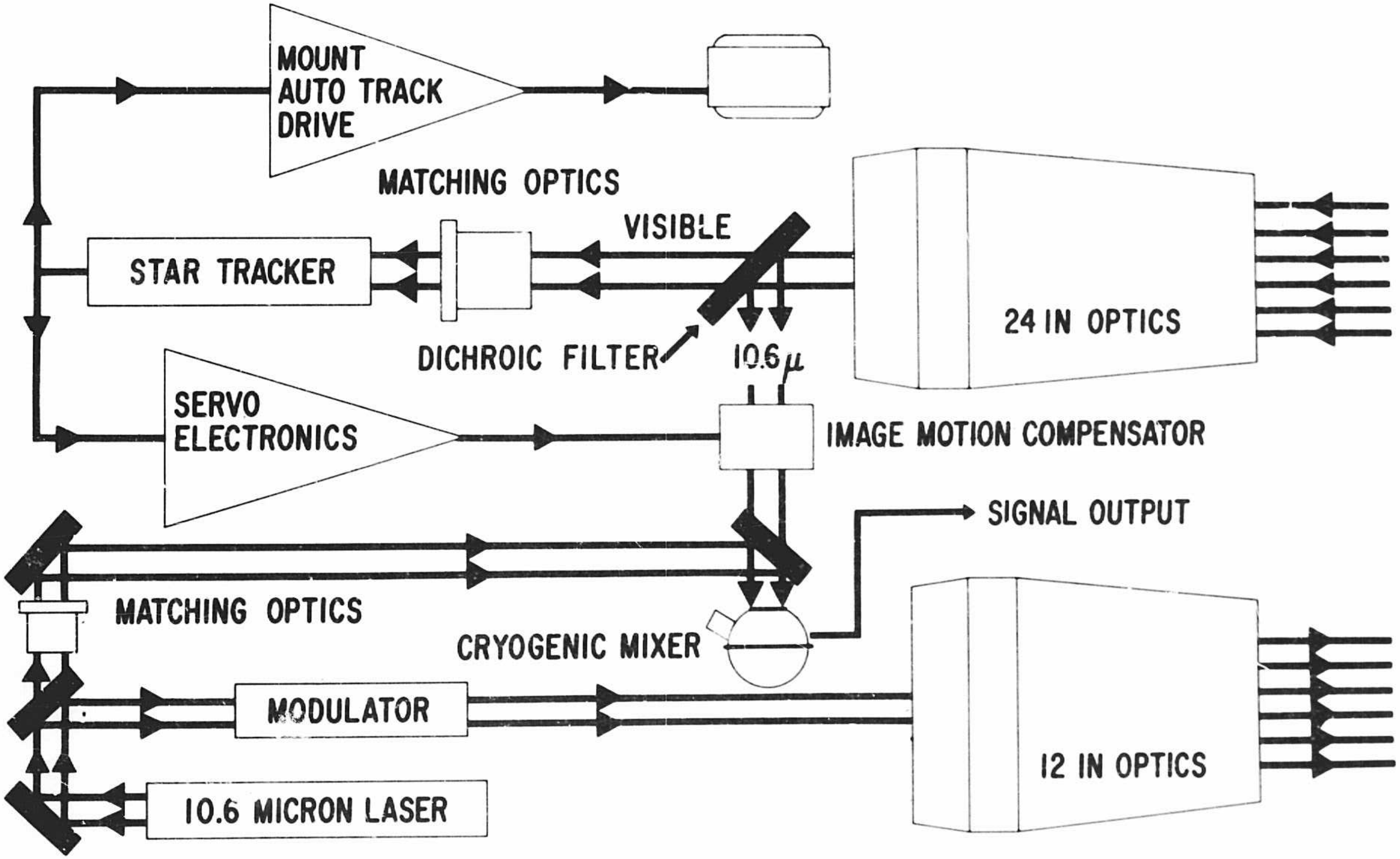

Figure 15. Functional diagram of 10.6 micron homodyne experiment with passive satellite reflection. The combination of star tracker and image motion compensator insures that the images of received radiation and local oscillator radiation are superimposed on the mixer.

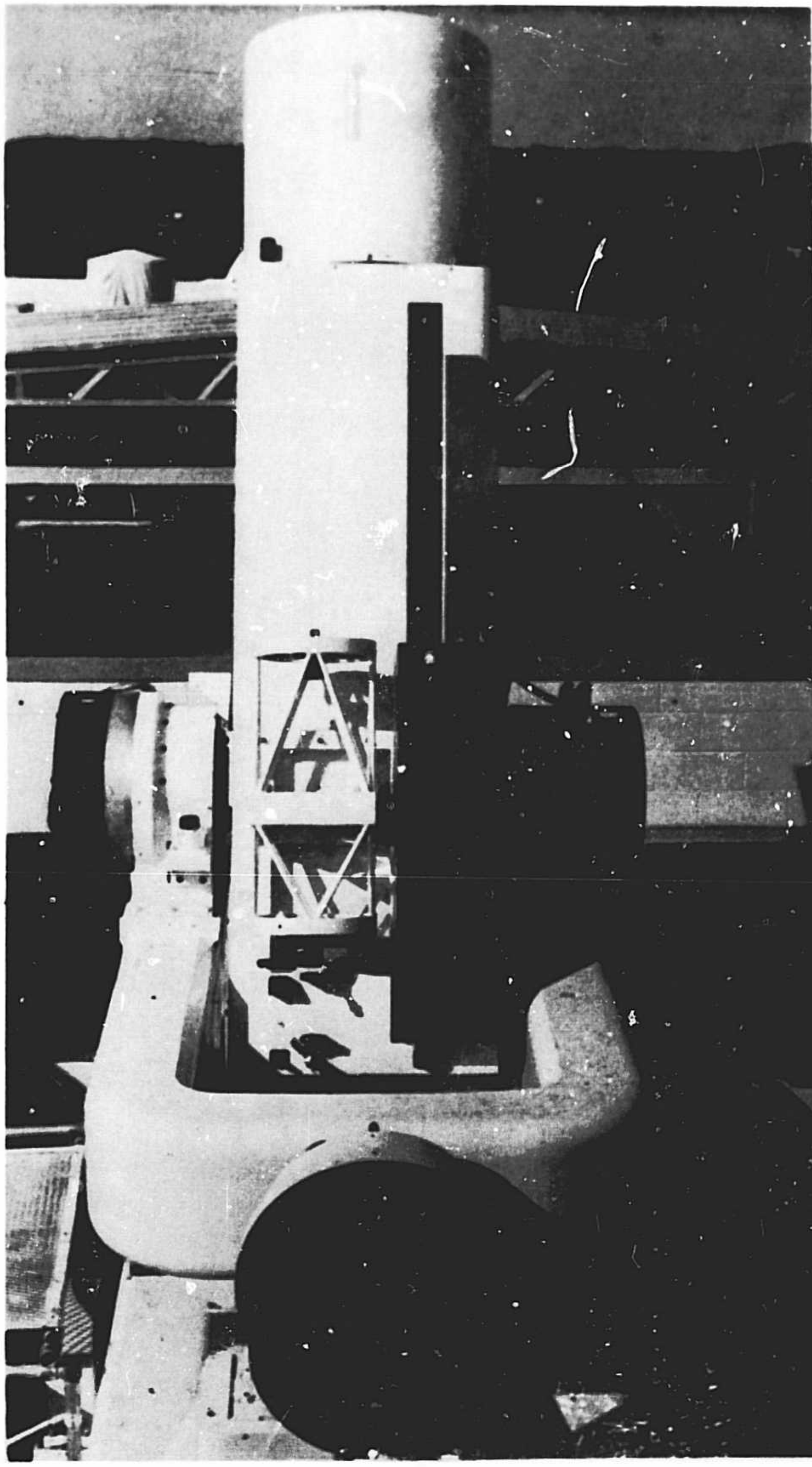

Figure 16. Carbon dioxide laser mounted on a 24-inch telescope at Goddard. The laser is 8-feet long, transmits through the "piggy-back" 12-inch antenna, while the large telescope is used as receiver. Cryogenic mixer and star tracker (not visible) are mounted on underside of telescope housing.

LASER COMMUNICATION LINK GEOMETRY

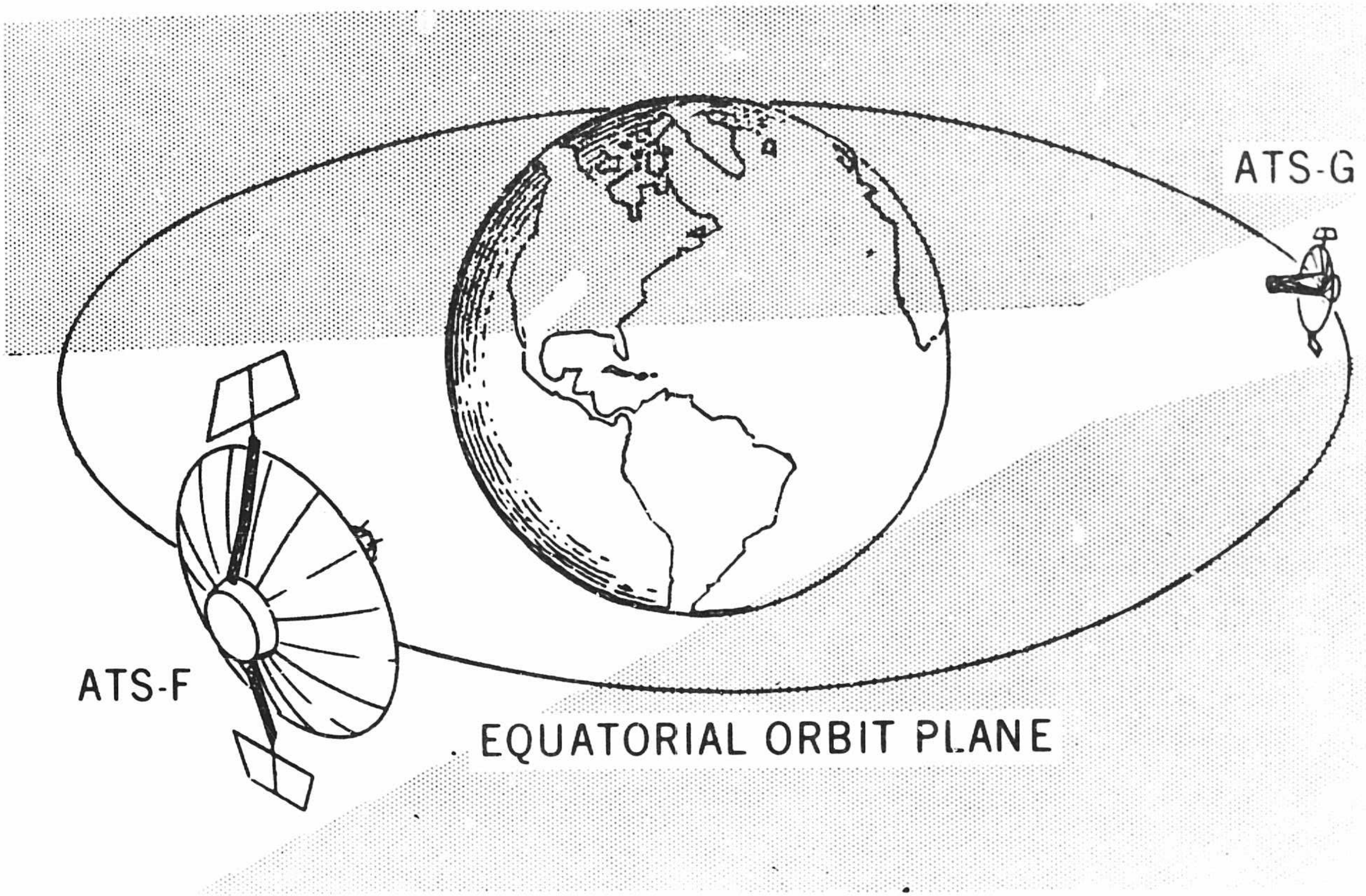

Figure 17. The Laser Communication Experiment proposed for the ATS-F spacecraft provides a prototype two-way optical link between a synchronous satellite terminal and ground stations. Design allows extension to link between ATS-F and ATS-G, when the latter is launched one year later.

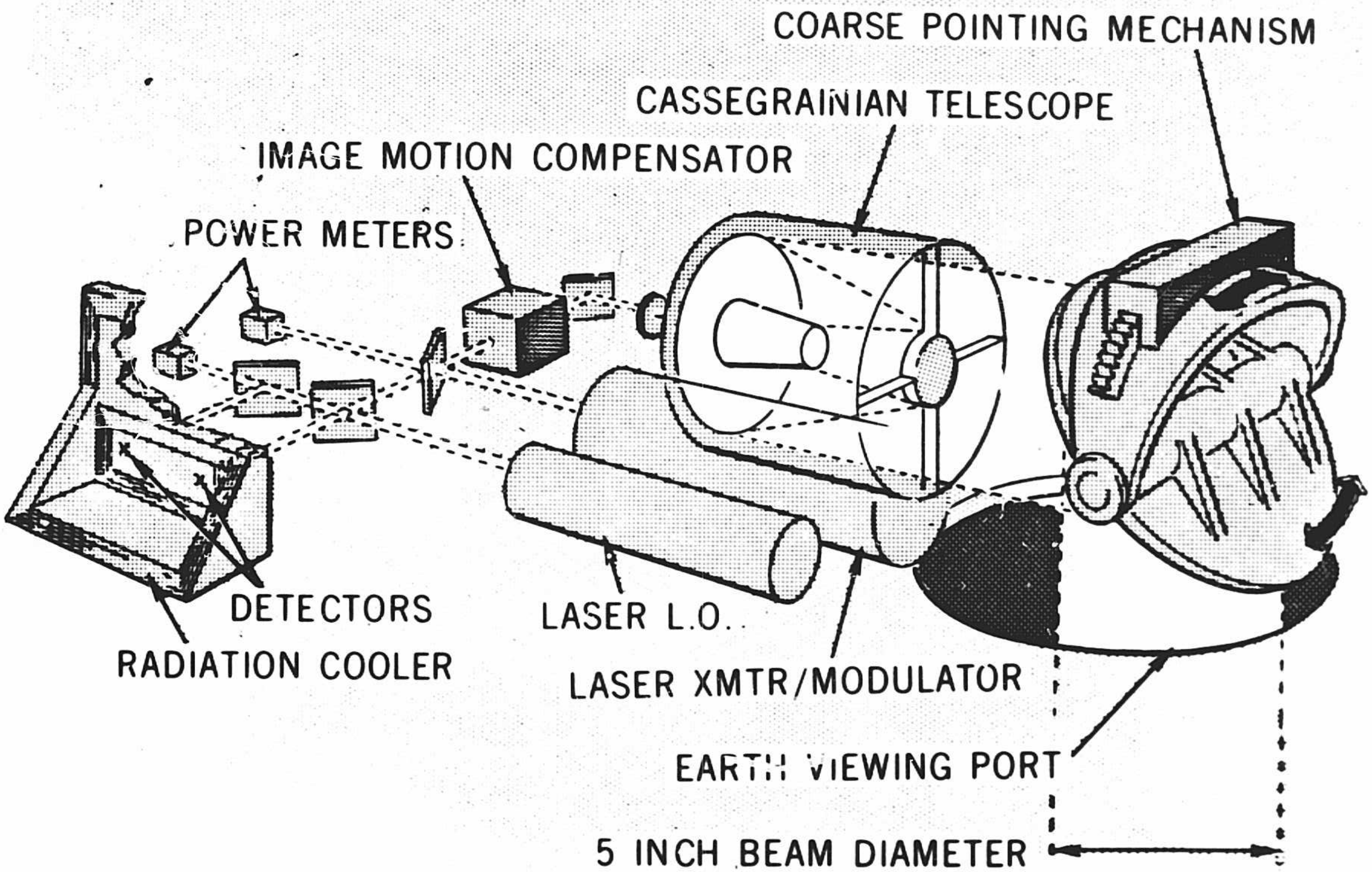

Figure 18. Concept of optical package aboard ATS-F. Coarse beam pointing is provided by flat mirror commanded from the ground, while sine adjustments are accomplished by automatic motions of small image motion compensator. Mixer elements for angle-error sensing and information signals are mounted in radiation cooler looking into cold space.