OPTICAL TECHNOLOGY FOR EXPERIMENTS AND APPLIC
IN CISLUNAR SPACE

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OPTICAL TECHNOLOGY FOR EXPERIMENTS AND APPLICATIONS IN CISLUNAR SPACE

Requirements for new optical devices and techniques arise in many sectors of the space program. They include applications in astronomical, meteorological, and geophysical satellites, as well as uses of lasers for space tracking and communication. Indeed, the range is so wide that only a few can be mentioned here in substantial detail, but they will be suggestive of the challenging task of applying the new optical technology in space. We will also attempt to outline briefly how NASA is approaching the solution to some of these requirements, without restricting in any way the fields in which Industry's ingenuity and technical know-how are still urgently sought.

Space Astronomy

An obvious and interesting question which one asks of an astronaut or instrument sent into space is, "What do you see?" Astronomers, especially, are anxious to be freed from this shifting and concealing fog we call our atmosphere, and orbiting astronomical observatories promise to yield some of the most exciting scientific results of the space program. From the earth, stellar radiation at wavelengths to each side of the visible spectrum, i.e. most of the infra-red out to the submillimeter and microwave region, and most of the ultraviolet, out to the gamma-ray region -- cannot be detected because of atmospheric absorption. Even at wavelengths for which the atmosphere is transparent, its turbulence blurs images, hides details of galactic structure and multiple star systems, and prevents study of high resolution spectra. The hope of correcting these

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defects of earth-bound astronomy has inspired plans for Orbiting Astronomical Observatories, Manned Orbiting Telescopes, Manned Orbiting Research Laboratories, Apollo Telescope Mounts, Lunar Observatories, etc. All of them ask for diffraction-limited large-aperture reflecting telescopes.

Since the degrading effect of the atmosphere is not present in space, optical performance will be limited only by the diameter of the mirror, which determines minimum diffraction image size, by the accuracy with which the mirror surfaces conform to their true theoretical shape, by the degree to which the detector remains in the focal plane, and by the steadiness with which the instrument is pointed at the target and the image is kept still on the photographic plate or spectroscope slit, while the exposure is being made. Our goal is to place a 3-meter diameter astronomical telescope in orbit. The ideal image would thus have an angular size (at 5000A) of 4×10^{-7} radians, or 0.08 seconds of arc. Corresponding mechanical tolerances would require keeping the 120-inch, diameter mirror surface within .5 micro-inches of a true parabola, and the pointing axis within 0.01 arc seconds of the target star, while the spacecraft has to cope with thermal effects of sunshine, earthshine, and cold space, and the dynamical perturbations of gravity gradients, solar wind, micrometeoroids, and possibly an astronaut puttering around on-board. Formidable specifications: required only in space, hopefully soluble in space.

Several studies are seriously devoted to these problems, with encouraging progress on paper and in the laboratory. We can't launch a solid, perfect, 3-meter telescope, and expect it to maintain specifications in orbit. (We can't even make and test one, on earth.) We must develop a large telescope whose optical figure is adjustable in minute increments, invent a sensor which can automatically diagnose its deviations from perfection, and provide an active servo control to keep the image diffraction limited. One realization of such a scheme is shown in Figure 1. The 3-meter mirror would be composed of seven smaller hexagonal mirrors, each, perhaps, an off-axis parabolic section made of "egg-crate" fuzed quartz. (We can make smaller diffraction limited mirrors.) The diagnostic tool is a helium-neon laser. If the mirror is perfect, a laser beam directed at it from its center of curvature will be reflected back in phase from all portions of the mirror. An interferometer is formed, sensors monitor the interference fringes, an on-board analyzer then instructs actuators to adjust the mirror sections until the correct interference pattern is formed, and the mirror is effectively "perfect". Similar results could be obtained by deforming a thin mirror, or by introducing judicious thermal gradients by means of imbedded heaters, to control the mirror figure. An 18-inch, 3-segment example of an actively controlled mirror has already been shown to maintain its optimum quality under a wide range of perturbing influences, using the above technique, as shown in Figures 2 and 3.

The problems of pointing the telescope are not new, even though more severe than before. The Orbiting Astronomical Observatory has already been designed to point to 0.1 arc seconds, and the Stratoscope II 36-inch balloon-supported telescope successfully locked onto a 9th magnitude target and tracked to within .016 arc seconds. It seems sensible to correct the pointing of the main telescope and satellite, by means of a fine adjustment transfer lens which can compensate for perturbations at rates up to 100 Hz, instead of trying to slew the entire spacecraft to compensate for small drifts and perturbations.

The Role of Man

We expect some of these perturbations would be due to the presence of a man, whose duties will be vital to such a complex spacecraft which must continue to operate for many years. He must assemble the equipment initially in space, start and evaluate its operation, and then visit it periodically for repairs, as in Figure 4. An astronaut could change mirror elements, perform re-coating operations, and replace experiments and detectors. There will also be very interesting technological questions for him to answer. For instance, "What is the scattering environment in the immediate vicinity of the spacecraft, due to debris and vapors travelling along with the ship?" Of course, we will have to trace and correct any such degrading influence.

The Growing Importance of Lasers in Cislunar Space

The properties of lasers: their very high intensity and spectral purity, our ability to focus them into narrow beams, to modulate them and detect single photons, have suggested important applications in the space program. The most dramatic of these is not within the scope of this discussion, i.e. their use in wideband optical communication links with planetary spacecraft, and beyond.

However, lasers are already being used to very good advantage and are being contemplated by NASA for other purposes. We shall see that, by developing the technology for these more immediate applications, valuable in themselves, we are simultaneously laying the necessary groundwork for the deep-space optical link.

Pulsed Laser Satellite Ranging

In October, 1964, NASA launched the first of the satellites with arrays of fuzed-quartz cube corner retroreflectors to act as cooperative targets for laser radar stations (Figure 5). The quartz prisms reflect a maximum amount of the incident light back toward the transmitter. Shortly thereafter, we demonstrated the technique and achieved ranging precision of about 1 meter, using the ground station in Figure 6. There are now five such satellites orbiting the earth: three launched by the U.S. (Explorers 22, 27, and 29) and two by France (D1C and D1D). Such precise tracking permits better determination of satellite orbits than ever before, location of tracking stations on a global scale, studying the shape of the earth, detecting continental drift, and calibrating other tracking systems. Figures 7 and 8 illustrate the quality of data being obtained regularly. Interest in using this type of laser tracking as a standard geodetic tool is now growing fast: the Smithsonian Astrophysical Observatory, the Air Force, Coast and Geodetic Survey, the French, and NASA are all considering making them permanent parts of their tracking and mapping networks. Satellites whose experiments require accurate position information can easily add retroreflectors to their surface, because they are cheap, lightweight, completely passive, and last indefinitely.

Figure 9 is a block diagram of Goddard's tracking station. In addition to some of the elements of a rudimentary radar station, there are some features that are pertinent to our discussion of optical technology. The laser itself is a Q-switched ruby laser, which can still benefit from improvement. Typical present laser performance may be transmission of one joule of energy at 6943 Angstroms in a burst 20 nanoseconds long, into a beam about 1/4 degree wide, and then this is further narrowed down to one milliradian by our transmitting antenna optics. We hope to improve our range resolution by another factor of 10, so we would like sharp, single-pulse outputs, with rise times of 1 nanosecond. Higher power and narrower divergence should give us higher brightness and permit our technique to be used with smaller satellites and/or to greater ranges. Suitable materials for components such as beam splitters, transmitting antenna lenses, and mirrors must be found which will withstand radiation intensities as high as 500 megawatts/cm^2 without damage. Photomultiplier response and electron transit-time spread are introducing significant limitations to our range measurement resolution, and time interval counter stability and clock precision are also becoming critical.

In order to point our laser beam at the satellite, the mount is controlled by a computer which continuously compares shaft angle encoder values with a programmed tape prepared previously from the predicted satellite trajectory. The computer, incidentally, also operates a "range gate", restricting the detector effectiveness to a short time interval during which the echo is expected. This, together with a narrow pass-band color filter, gives us considerable discrimination and allows us to operate in high ambient backgrounds. If the predictions were correct, and the servo control accurate, the satellite would always be illuminated by the laser beam, which now has a spread of about one milliradian. (We fire it at a rate of once per second.) We would then be able to operate both day and night, without having to "see" the satellite. Actually, we cannot yet rely on the programmer accuracy, so we limit our operations to twilight, and use an observer at a boresighted telescope to correct the program drive and keep the visible satellite in the laser beam. Here is an obvious area of needed improvement. We should be able to generate better predictions, based upon our more accurate tracking data; we should be able to autotrack on the reflected laser radiation once we have acquired and hit the satellite. Both of these improvements will soon be incorporated.

Continuous Laser Satellite Tracking. An Earth Laser Beacon

In the near future, we may thus expect regular pulsed laser satellite ranging, with precision of about 15 cm, at data rates up to 5 measurements per second. What then? The next step is to track these same passive reflecting satellites with continuous lasers. A ground station similar to that already described is being built around the Ionized Argon laser. Four watts of power at 4880 Angstroms will be intensity modulated with a tone of 136 Mhz and beamed at the satellite. In the reflected light, the modulation tone will be doppler shifted, giving us a measure of radial velocity.

A measurement of range rate, such as this, is certainly very valuable for orbit determination, and justifies the necessary development of field-worthy transmitters, modulators, detectors and tracking electronics. However, as we stated earlier, development of this capability also goes a long way toward providing techniques that will be needed later for deep space optical communication. In this case, the Argon laser directed toward a satellite represents precisely the "up-link" prescribed in most versions of ground-to-spacecraft laser telemetry links. It provides a beacon, to which we expect the planetary probe will have to direct its very narrow optical or infrared beam, with its high data rate information. The Argon radiation from the earth can also carry commands and information to the satellite. The Argon laser was chosen as the best available for this purpose, but it requires considerable improvement in lifetime, stability, and power output.

It is important also to study the effect of the atmosphere upon such laser radiation, if we are contemplating the use of ground stations in optical communication with spacecraft. In addition to several experimental studies of propagation across horizontal test paths, the projects using passive satellite reflectors, described above, give us an opportunity to measure perturbation due to the entire atmosphere, without requiring an active transmitter in the spacecraft. We have already been studying the fluctuations in intensity, direction, and time delay of the pulsed laser reflections from the Explorer satellites. On GEOS-B, which is now being built, we will go further. Not only will there be an array of retroreflecting prisms, but also a photomultiplier detector (Figure 10) which will measure the intensity of Argon laser radiation reaching the satellite, and transmit the data to earth via its radio telemetry system. We should then be able to analyze and compare the modulation depths and frequencies in the up-link, and in the round trip, as a function of atmospheric conditions and beam aperture. Such information will be important for the optical communication applications.

Infrared Laser Experiments

The effects of the atmosphere may be even more serious when we try to use coherent receiving techniques on radiation arriving from space. The most attractive laser source for spaceborne transmitters, in terms of efficiency, power output, and stability, is now Carbon-Dioxide, which radiates at 10.6 microns. Corresponding detectors are well on the way to being developed, but it appears that in order to overcome intrinsic background noise, we shall have to use heterodyne receivers, with strong local oscillators. This means that the beam passing through the atmosphere must conserve its phase across the aperture of the receiving telescope. Satellite experiments are being prepared to test the extent to which this is true.

Figure 11 is a block diagram of an infrared transceiver to be used with passive reflecting satellites. Unfortunately, the special reflecting arrays already in orbit will not be suitable, because quartz does not transmit 10.6 micron radiation. However, the high power radiated by CO_2 lasers permits us to obtain usable reflections from one of the Echo balloons. Later, we would like to launch an open, front-surface reflecting cube-corner into a synchronous orbit for these experiments. The figure illustrates some of the technological problems that must be solved in any ground station used for this purpose. A carbon-dioxide laser here acts both as transmitter and local oscillator. Visible light from the satellite target is used by a star-tracker to aim our 24-inch telescope, but to make sure that the received signal is accurately superimposed with the local oscillator on the mixer/detector surface, an additional image-motion compensator will correct for any remaining deviation of the incoming radiation from the optical axis. In this experiment, we will study the phase coherence of the signal and learn to cope with doppler shifts greater than 1000 Mhz, changing at rates of many Mhz per second.

Other Laser Experiments in Cislunar Space

As indicators to future technological developments, we have discussed activities in tracking satellites with pulsed and continuous lasers, studies of atmospheric properties, and experiments preparing the way to optical space communications. There are many other proposed valuable applications of lasers to NASA projects. Some of these deserve to be mentioned, at least briefly, in a summary of this type.

NASA's achievements in photographing the earth, moon, and Mars, from the vantage point of space, demonstrate the excellence of our equipment and techniques in that area. However, in order to add an accurate scale to such photographs, some linear dimension must be precisely known. A pulsed ruby laser radar system on the satellite, boresighted with the camera, can determine its altitude above the surface with a precision of two meters, giving that necessary information. With some refinement of this equipment, a spaceborne laser could also measure cloud heights from above, particle density and size, perhaps even clear air turbulence.

An exciting scientific experiment in which there is now a great deal of interest, is the precise measurement of the moon's motion by means of pulsed laser ranging. It is now entirely feasible to set up a passive reflector on the moon, and to measure its range from a ground station, with a precision of 10 to 15 cm. Thus, over long periods of time, we can study the intricacies of the lunar orbit, libration, precession, and changes in period, with accuracies far greater than ever before. A wealth of information concerning the structure of the moon's interior, the gravitational fields of the earth and moon, and the theories of relativity and gravitation can ultimately be derived from such an experiment.

Optical Ground Stations

Most of the laser programs that have been described in this article require a new brand of ground station. Superficially, the equipment may look similar to that at an astronomical observing site. For instance, the lunar experiment and satellite communication experiments must utilize telescopes larger than 60 inches in diameter. However, the manner in which such a telescope is to be used imposes design specifications which are not normally required in astronomy.

Since bulky laser transmitters and receivers must be attached to it, we must henceforth restrict the design to Coude or Coelostat type structures, in which the focal point remains stationary. The narrow laser beams and detector fields of view, several seconds of arc in diameter, must be aimed very accurately from the ground, even when the target is not visible. This implies rigid structures, precise angle encoders, computer-controlled servo systems, and sophisticated scanning and acquisition routines. Some of the satellite experiments even require receivers to be displaced from the transmitter, and accurately slaved together.

Figure 12 is an experimental 24-inch aperture telescope at Goddard, which is being used to explore the technology of the new optical ground stations. It will be used for the 10.6 micron experiment described previously, which has the most critical pointing requirement so far. However, it is very clear that a new facility is required, in an area of good "seeing", to realize the potentials of the new optical technology.

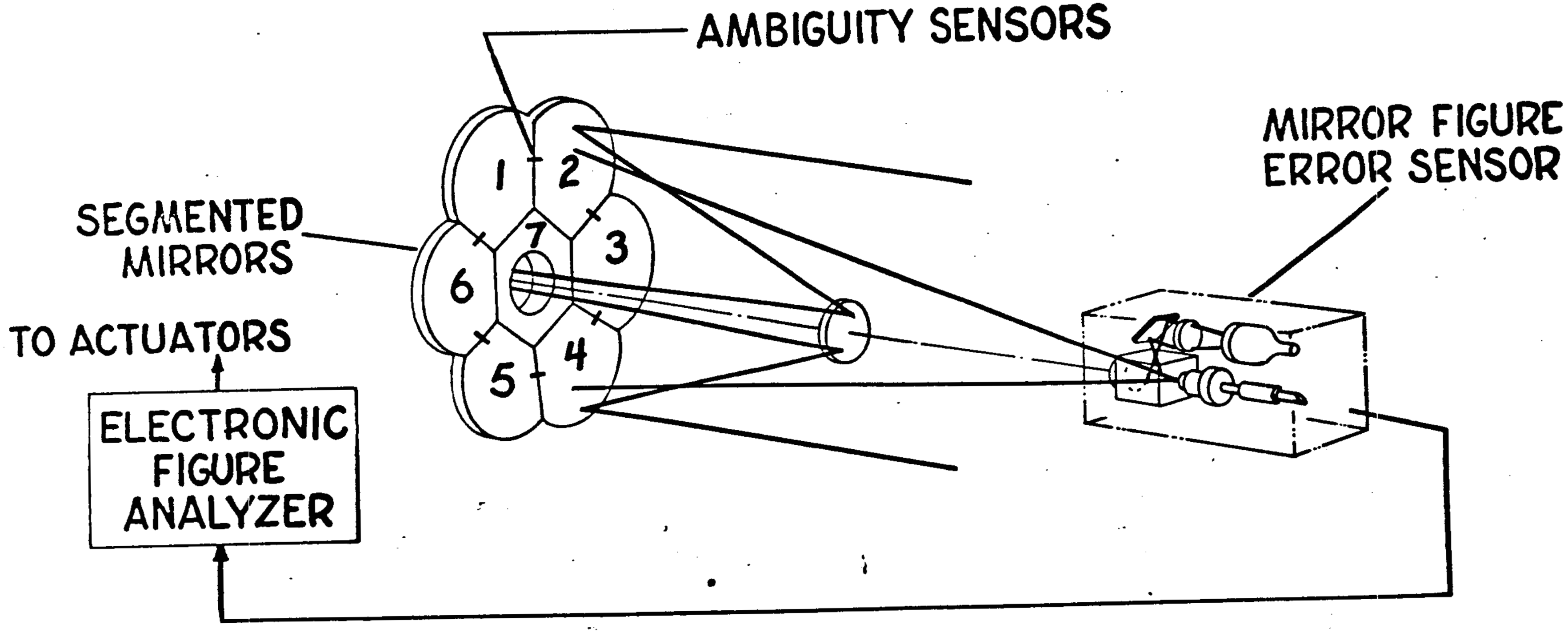


FIGURE 1. CONCEPTION OF AN ACTIVELY CONTROLLED 3-METER DIAMETER SEGMENTED MIRROR FOR SPACE ASTRONOMY. (COURTESY PERKIN-ELMER)

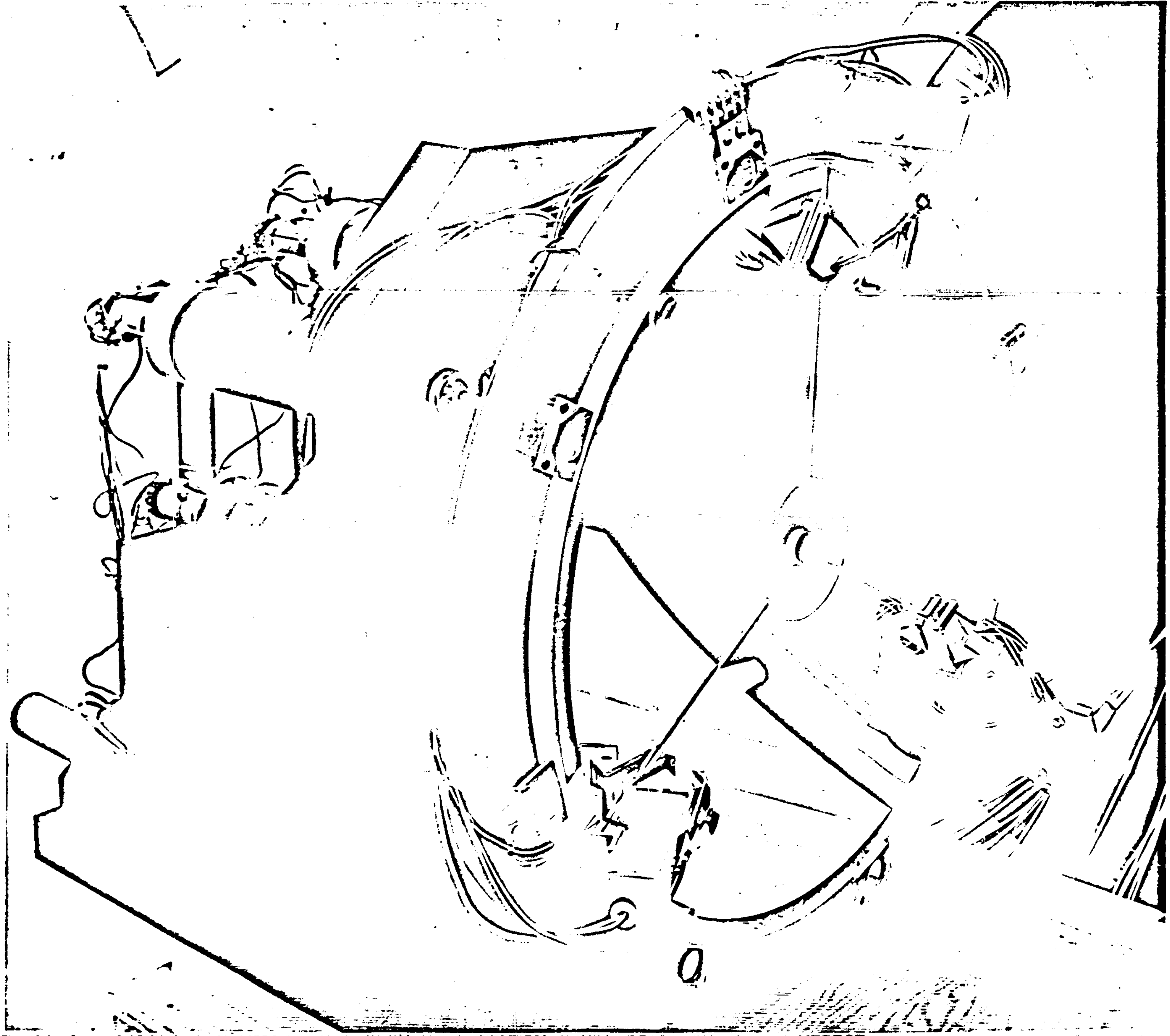


FIGURE 2. LABORATORY MODEL OF 3-SEGMENT ACTIVELY CONTROLLED TELESCOPE MIRROR.
(PERKIN-ELMER)

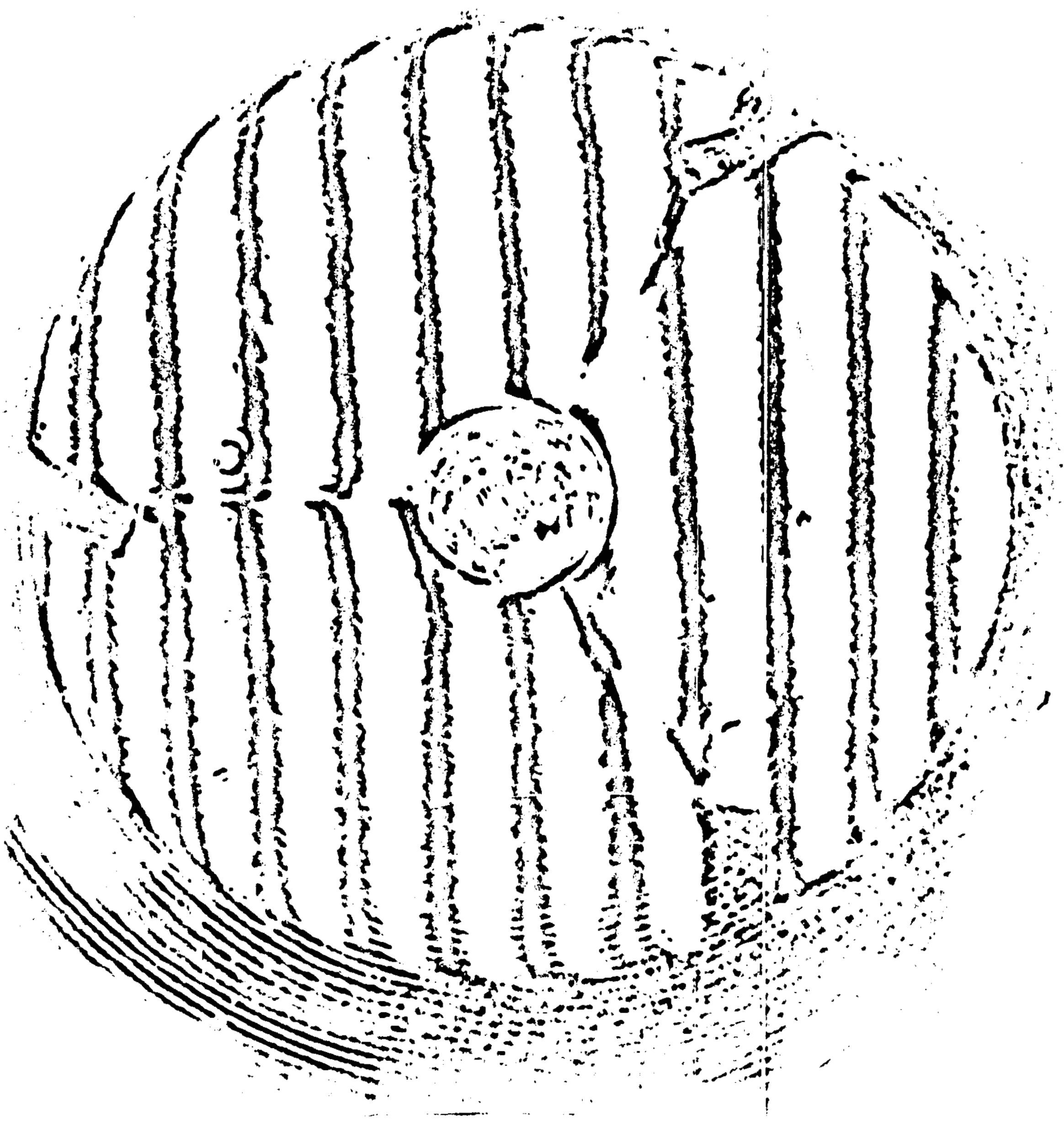
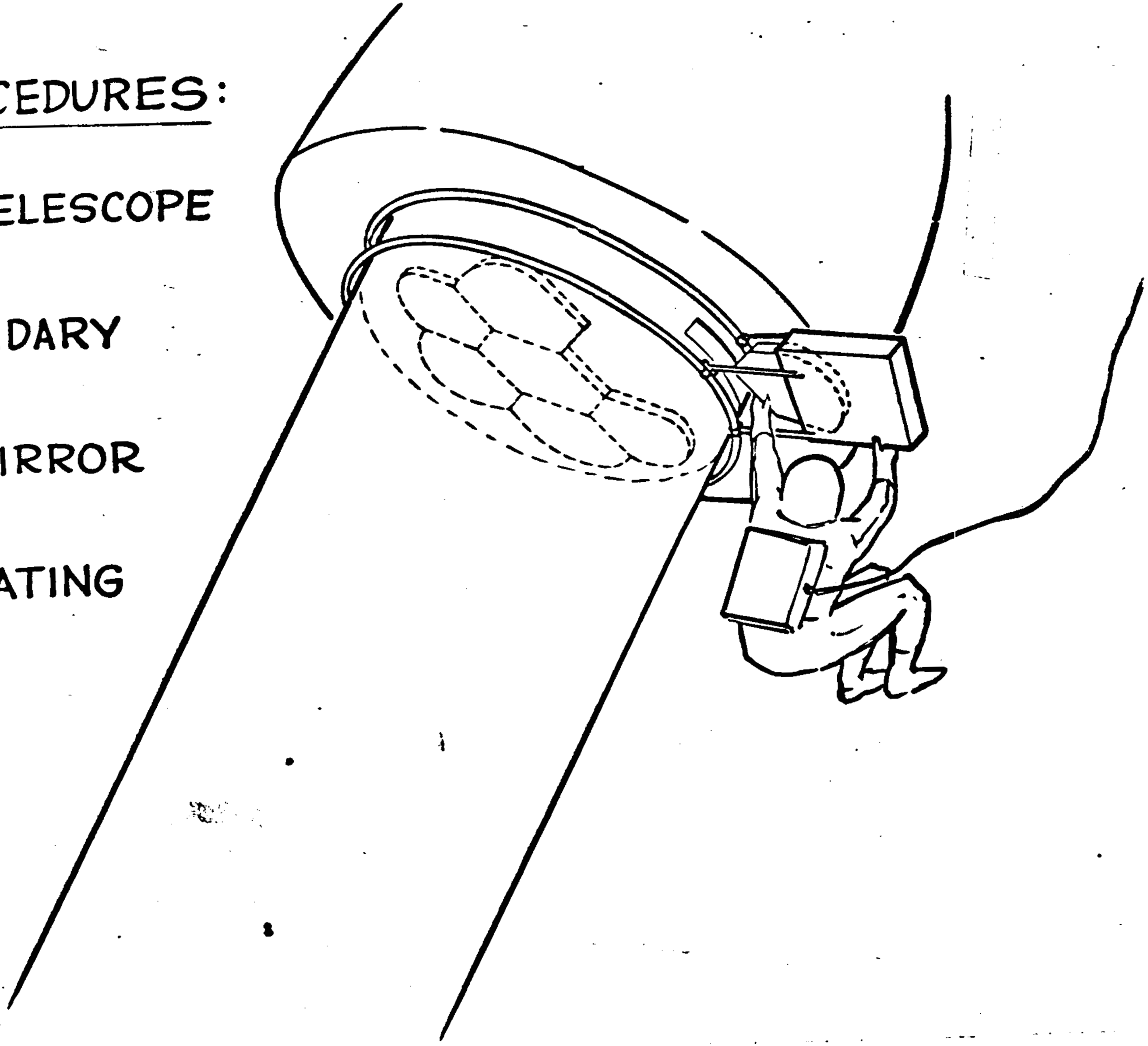


FIGURE 3. INTERFEROGRAM DEMONSTRATING PERFECT PLACEMENT OF MIRROR SEGMENTS, AFTER AUTOMATIC SENSING AND ADJUSTMENT.



TYPICAL EVA PROCEDURES:

1. ASSEMBLY of TELESCOPE STRUCTURE
2. CHANGE SECONDARY MIRROR
3. REMOVAL of MIRROR SEGMENTS
4. MIRROR RECOATING OPERATION

FIGURE 4. ASTRONAUT MAINTENANCE OF ORBITING TELESCOPE. ASTRONAUT IS SHOWN REPLACING MIRROR SEGMENT, AFTER IT HAS BEEN RE-COATED IN SPACE.

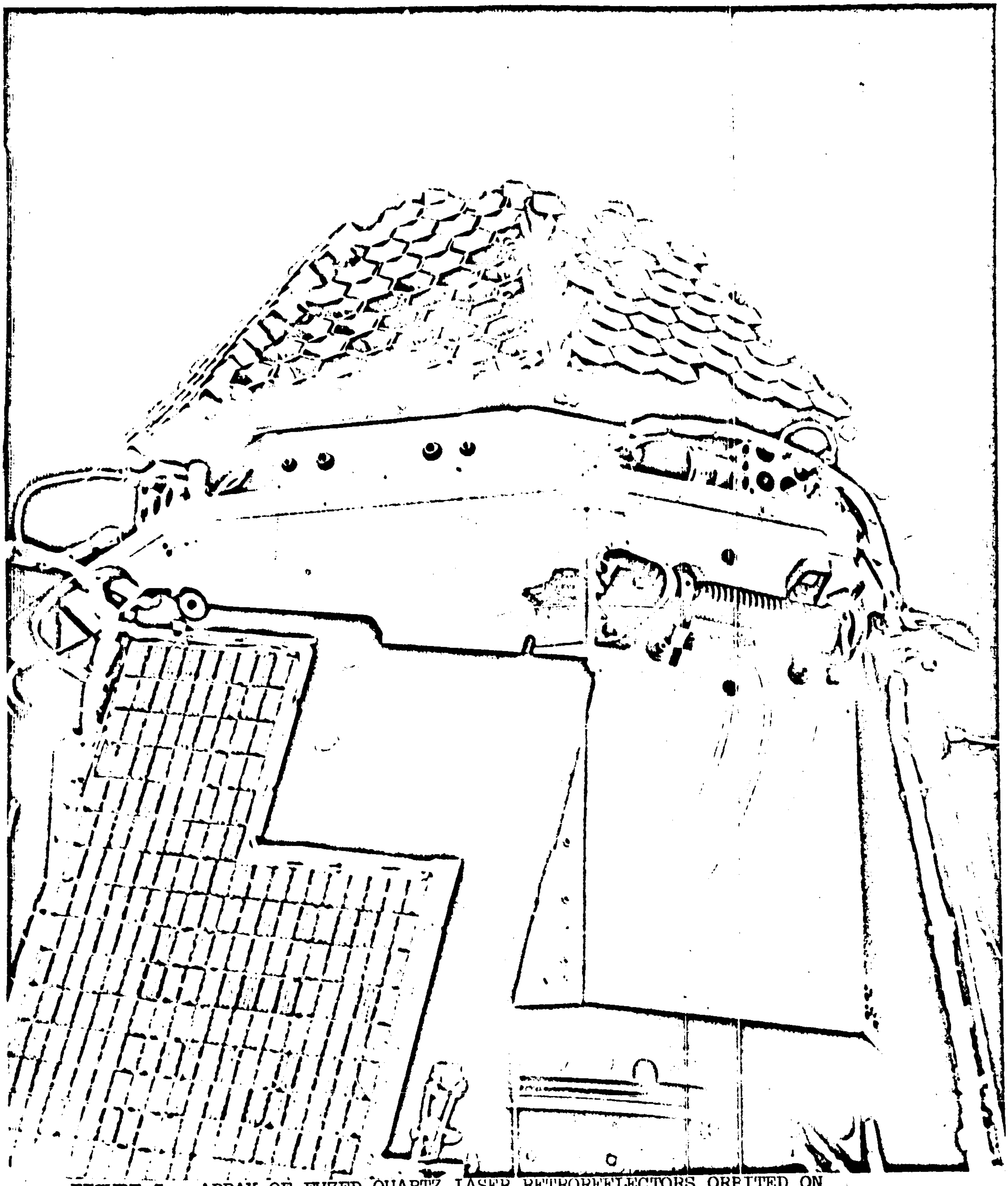


FIGURE 5. ARRAY OF FUZED QUARTZ LASER RETROREFLECTORS ORBITED ON BE-B AND BE-C (EXPLORERS 22 AND 27)

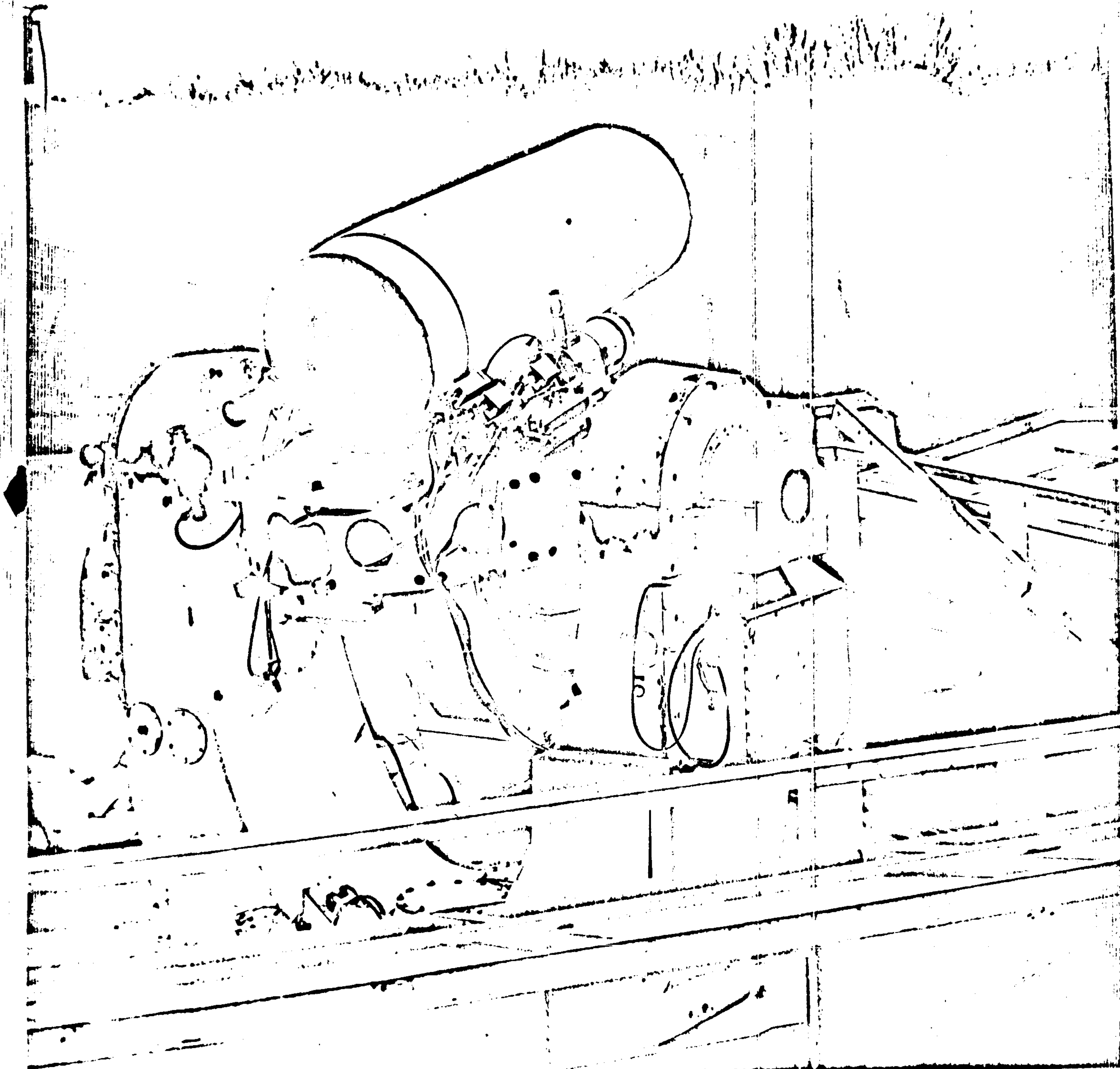


FIGURE 6. GODDARD'S EXPERIMENTAL GROUND STATION FOR PULSED RUBY LASER SATELLITE TRACKING

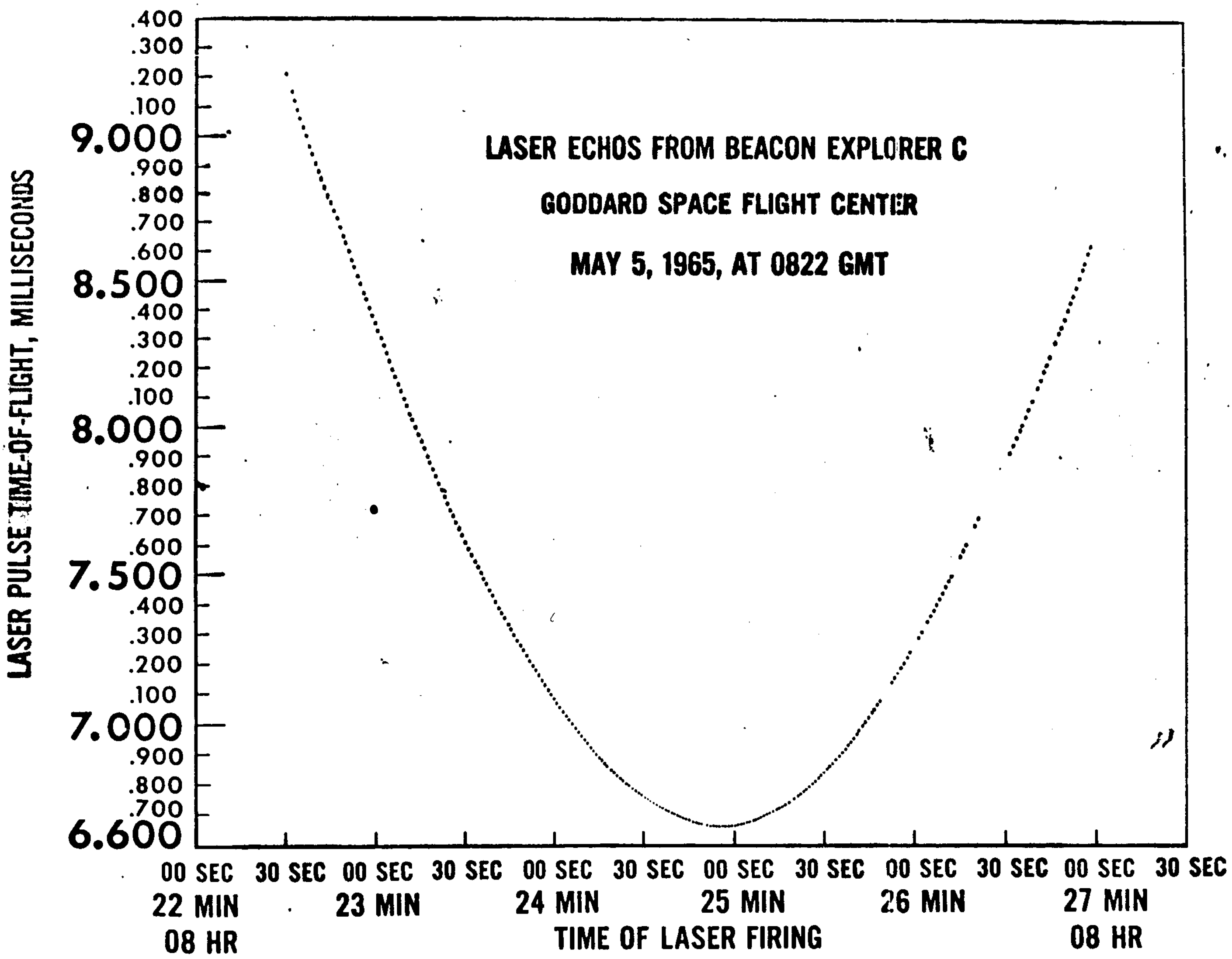


FIGURE 7. RANGE DETERMINATIONS ON BEACON EXPLORER C (EXPLORER 27) DURING A PASS OVER GODDARD ON MAY 5, 1965. EACH POINT REPRESENTS A LASER FLASH, RECEPTION OF AN ECHO, AND DETERMINATION OF RANGE FROM THE ROUND TRIP TIME OF FLIGHT. LASER WAS FLASHED AT THE RATE OF ONCE PER SECOND.

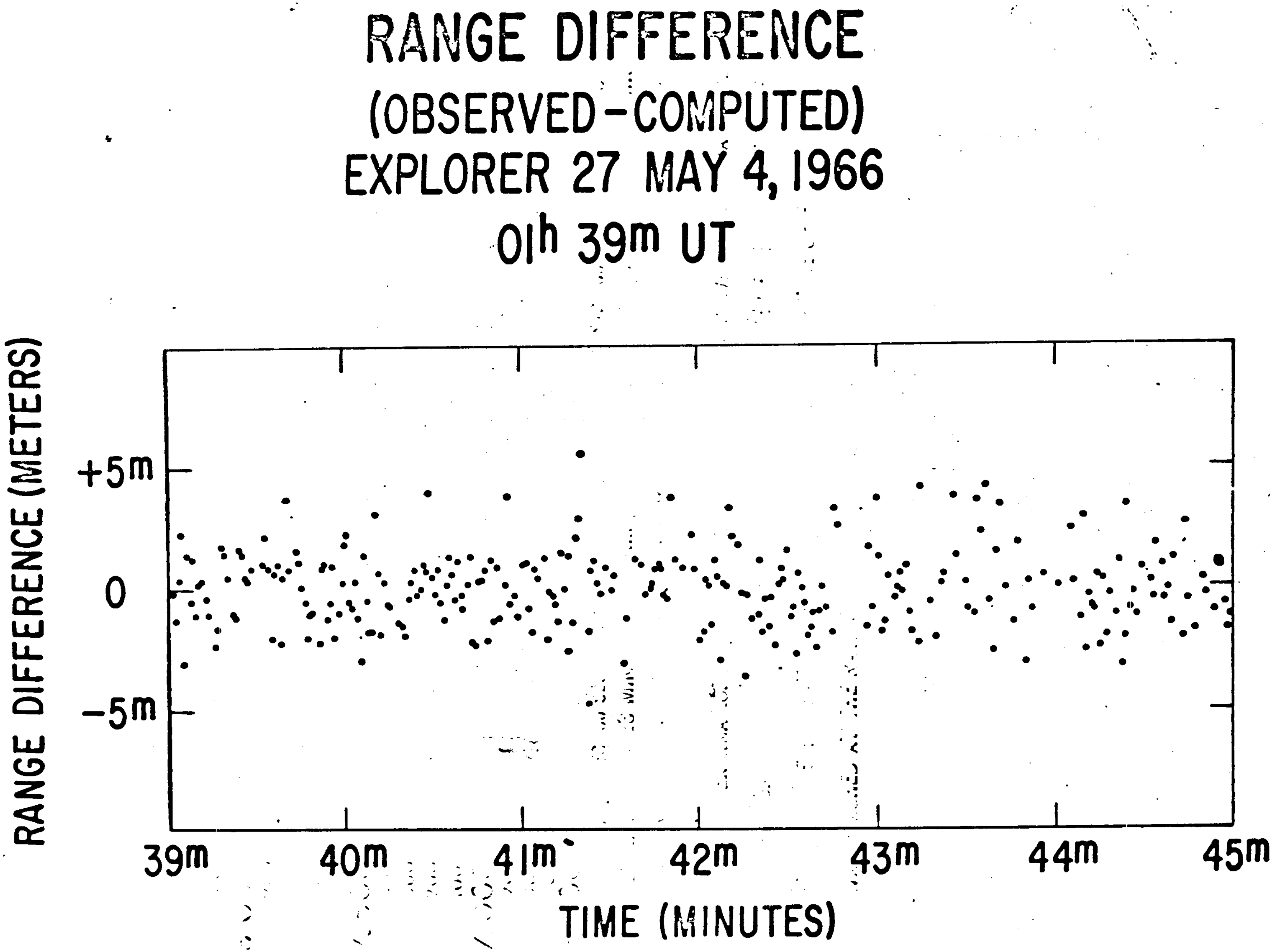


FIGURE 8. RESIDUAL ERRORS OF INDIVIDUAL RANGE MEASUREMENTS, AFTER COMPARING DATA WITH THE BEST-FIT COMPUTED SATELLITE ORBIT.

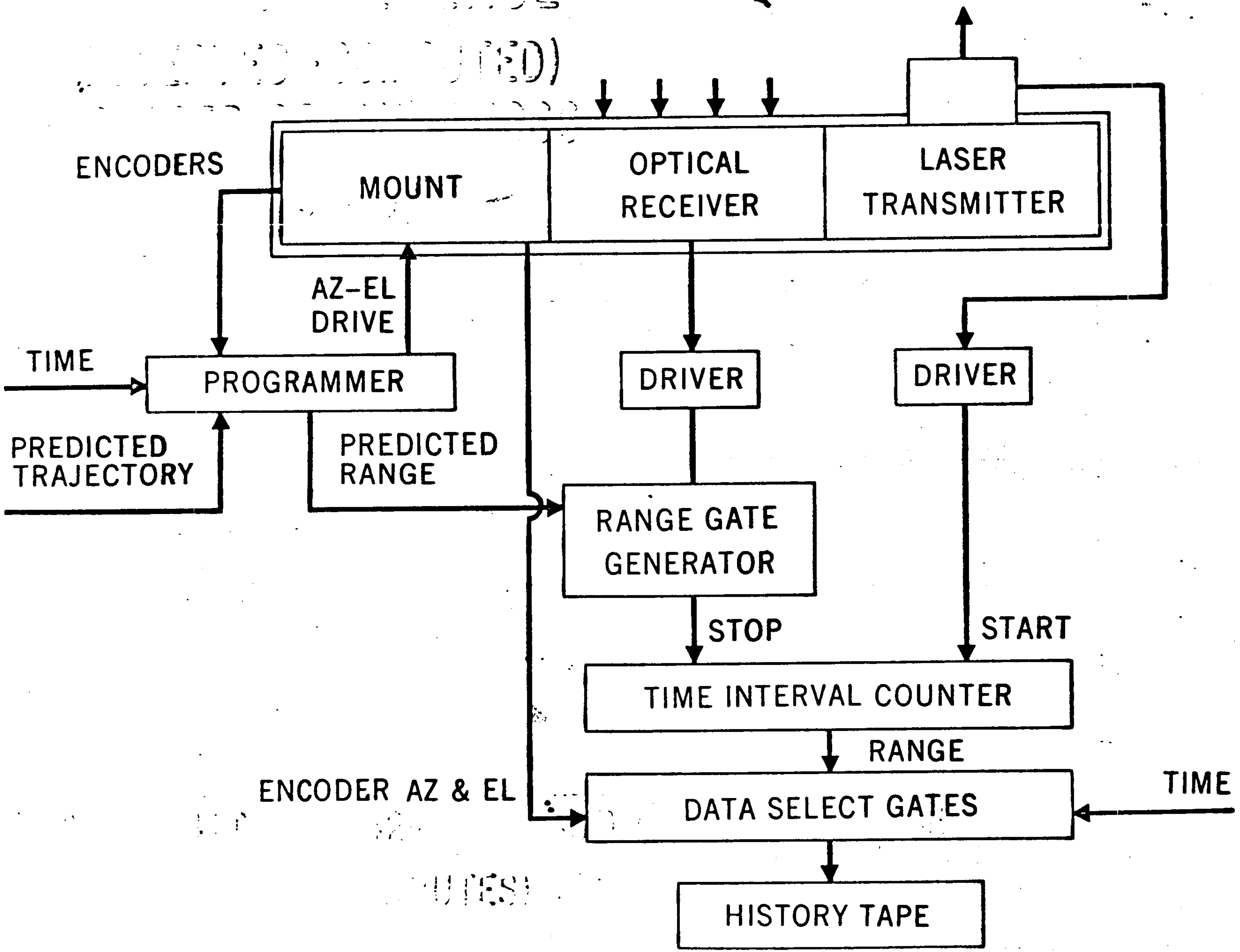


FIGURE 9. FUNCTIONAL BLOCK DIAGRAM OF GODDARD'S STATION FOR PULSED RUBY LASER SATELLITE TRACKING.

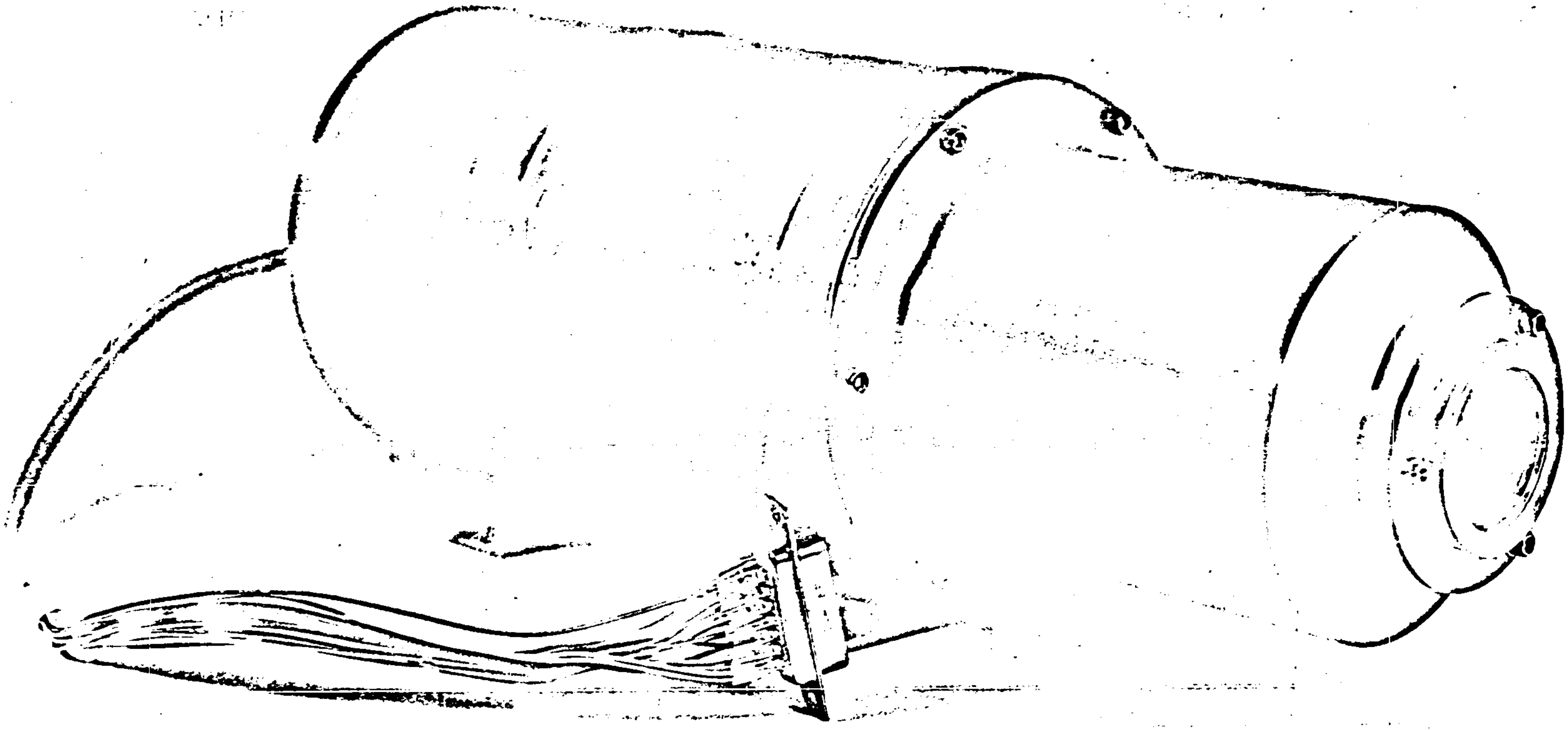
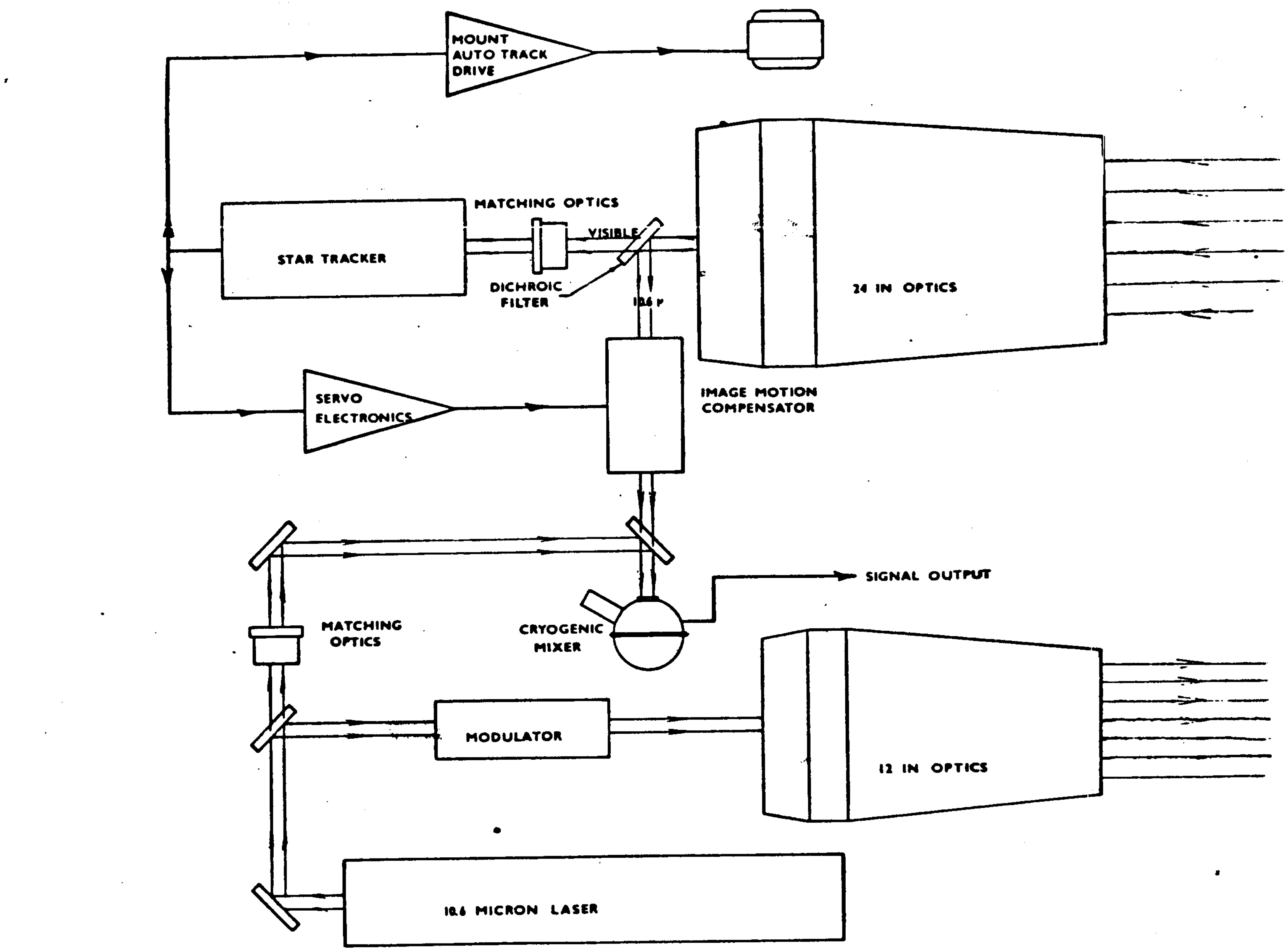


FIGURE 10. DETECTOR PACKAGE TO BE FLOWN ON GEOS-B FOR MEASURING SCINTILLATIONS IN INTENSITY OF ARGON RADIATION DIRECTED TOWARD IT FROM GODDARD



FUNCTIONAL DIAGRAM OF 10.6 μ TRANSCEIVER

FIGURE 11. 10.6 MICRON TRANSMITTER-RECEIVER ARRANGEMENT FOR HETERODYNE DETECTION OF COHERENT RADIATION

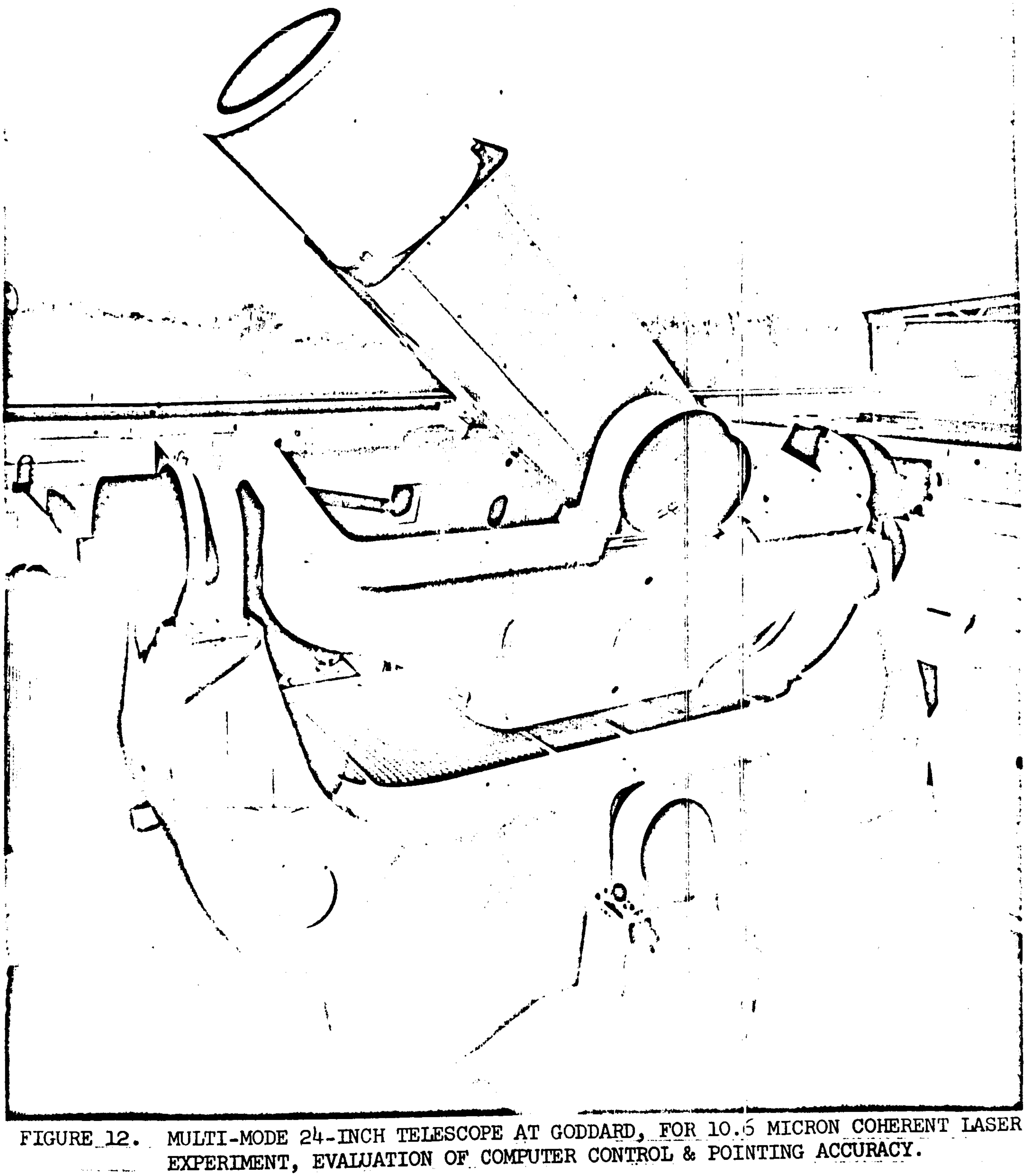


FIGURE 12. MULTI-MODE 24-INCH TELESCOPE AT GODDARD, FOR 10.6 MICRON COHERENT LASER EXPERIMENT, EVALUATION OF COMPUTER CONTROL & POINTING ACCURACY.