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SUMMARY

This lecture deals primarily with the areas of satellite design in which difficulties arose in the development of the Orbiting Astronomical Observatory (OAO).

A brief account is given of its history, which started late in 1958 when several scientists and engineers met to discuss the concept of a space observatory. Preparation of specifications began in 1960, and were based on the use of the Vega rocket. The NASA decision to fly the OAO on the Atlas Agena instead necessitated the development of a completely new shroud system for the OAO.

A description of the OAO follows, including an account of the star trackers, and the problems encountered in their development, the rate gyroscopes which control the satellite after separation, the systems to control its angular rate, and the command and data handling systems. The use of redundancy in the OAO is stressed, in particular in the command and data handling system. The test facilities are then dealt with, including three specially designed for the OAO.

The last part of the lecture is mainly concerned with the scientific experiments selected for the first three OAO spacecraft: the first OAO contains two experiments, one by the Smithsonian Astrophysical Observatory and the other by the University of Wisconsin, the second an experiment by Goddard Space Flight Center, and the third and experiment by Princeton University. The lecture concludes with a brief mention of tentative planning for the future.

LIST OF FIGURES

THE ORBITING ASTRONOMICAL OBSERVATORY[†]

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The Orbiting Astronomical Observatory (OAO) is probably the most complicated of the satellites at present being developed. In describing this satellite I shall touch on a number of areas that may be covered in greater detail by other lecturers in this course. Primarily, I shall concentrate on the areas of satellite design in which difficulties have arisen, indicating how these have been solved, if they have been solved. We are some distance from time of launch and there are still a few problems which are worrisome.

Some remarks on the history of the Orbiting Astronomical Observatory are appropriate. Actually, the history is comparatively long for a space project. When plans were being formulated for the International Geophysical Year, the U. S. National Academy of Sciences asked various scientists to describe the experiments which they would like to perform in a satellite. Among the astronomers who replied to this question were Dr. Arthur Code of the University of Wisconsin, Dr. Fred Whipple from the Smithsonian Astrophysical Observatory, Dr. Lyman Spitzer from Princeton University, and Dr. Leo Goldberg of the University of Michigan (now at Harvard University). It was immediately obvious that none of the experiments which these astronomers proposed could be conducted on the very small satellites planned for the VANGUARD program. With the birth of NASA late in 1958, these four astronomers and several other scientists and engineers interested in a space astronomy program met to discuss what NASA should do to implement the need for an astronomical satellite. We asked ourselves what an astronomer needed in a satellite and concluded that what was required was a space analogue of a ground-based observatory that would provide a number of functions common to any type of observations and which could be modified by a particular astronomer to provide the detailed information which he needs. For example, it was obvious that any astronomical observation in space would require a power supply, a command system, some way of storing the data and transmitting the information, a structure, thermal control and all of the other components of a normal spacecraft. In addition, astronomers re-

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quired a way of pointing the spacecraft to any selected astronomical object and of maintaining this pointing with an accuracy which was high by space standards. We decided that it would be possible to design a spacecraft which would serve any of a large number of astronomical instruments, but in contrast to the situation in a ground-based observatory we did not feel that it was practical to design a common set of optics for each experiment which an astronomer might wish to conduct.

Most of 1959 was spent discussing with engineers within NASA and in industry the requirements of such a space observatory. In 1960 our ideas were sufficiently well formulated to enable us to ask a group at one of the NASA centers (the Ames Research Center in California) to prepare specifications for this satellite In the meantime they had started to work on a stabilization and control system. Since astronomical objects are both small and faint, this spacecraft would be required to point to a particular object accurately for a long period of time. After the specifications were prepared the engineers and the astronomers sat down to go over the specifications one by one to decide whether the astronomical needs were satisfied, and if not whether they could be satisfied by any engineering specification within the foreseeable state-of-the-art.

At the time NASA was developing a rocket called the Vega, which was to be 10 feet in diameter. Since a 10-foot diameter for the satellite would permit the use of objectives up to approximately one meter in diameter and since other expected characteristics of the Vega appeared compatible with the spacecraft weight and altitude, our planning was based on the use of this booster. Not long after our specifications were determined NASA decided to abandon development of the Vega and to fly the OAO on the Atlas Agena. This change left us with a major problem. The Atlas is 10 feet in diameter but the second stage, the Agena, is five feet in diameter. By mounting a 10-foot spacecraft on this combination we obtained a configuration with two 10-foot sections separated by one only five feet in diameter. This shape is aerodynamically very poor for the region of high aerodynamical buffeting. The problem was finally solved by shrouding the entire Agena stage and spacecraft, thus providing a smooth 10-foot diameter profile for the entire spacecraft/launch vehicle configuration. This decision meant that a completely new shroud system had to be developed for the OAO. This shroud has not only been more expensive than that on any other spacecraft but has required appreciable development and testing. Recently performed separation tests on the shroud indicated that the problem has indeed been solved.

The astronomers wished the telescope to have a long lifetime, not only because it was to be an expensive instrument but because it also would have many uses and would be far from obsolete after a few months or even a year of operation On the other hand, it was impossible to design a spacecraft as complicated as this one which would last indefinitely. After much discussion on how to write an engineering specification that would be meaningful and would still convey the idea that we wished as long a lifetime as possible. we finally settled on a requirement that the spacecraft should have a 70 percent probability of lasting at least one year. Just before I left for this meeting I asked the project manager, Mr. Robert Ziemer, who has been deeply involved in all of the problems of getting OAO to work, how long he thought it would last. He replied that it was a mean question to ask anyone but he thought there was a good probability that the satellite would operate for at least six months. Since our experience with satellites has been, as you know, that they either last a week or less, or they tend to last several years, I was gratified by his reply. If he thinks it will last six months, I believe there is a good chance that the astronomers will be happy.

The astronomers visualized sitting at a desk on the ground watching on a television screen the part of the sky to which the observatory was pointing and using a simple control, such as a joy stick, to set the instrument on the proper star. Another simple set of switches would control the operation of their instrumentation in the same way that they would make an observation on the ground. For a number of reasons this concept proved impractical. For one thing, the satellite is over a ground station for only about 10 minutes out of each 100-minute orbit. For another, we were not at all convinced that we could obtain a television image which would be adequate to permit the astronomer to actually set on faint stars. Finally we were not convinced that the astronomer could control the spacecraft accurately and rapidly enough to conduct his observations effectively. Therefore, the astronomers have completely lost their battle for direct control of the spacecraft. The satellite will carry a television camera to show the astronomer where he is looking in case he does not trust the primary coordinate system, but all commands to the satellite must go through a large electronic computer and the astronomer is far removed from the actual operation of the spacecraft.

The astronomer wanted to point to any star in the sky with an accuracy of approximately one arc second. We were able to provide the flexibility of pointing and the desired accuracy when using the large aperture experimenter's optics as the fine pointing sensor. Astronomers wish to be able to store numerous television pictures. This is an obvious requirement if we are to use the satellite in a mode analogous to the photographic use of a terrestrial telescope, but proved to be impossible with the storage which we conceive of for this period. A single television image with 200 lines per frame and perhaps 10 levels intensity discrimination per point requires 4 x 10^5 bits of information; the data storage which we are building for the OAO has only 10^5 bits of storage, which appears entirely satisfactory for spectrophotometry.

As there were many requirements in common, for both stellar and solar astronomy, we hoped to use the same basic spacecraft for each. However, this proved impractical because the thermal problems presented in an instrument pointing at the sun are so different from the thermal problems presented when the sun never shines into the experiment tube. It, therefore, appeared to be more desirable to design a second spacecraft specifically for solar observations. There were many other compromises between the astronomers and the engineers in the course of the development of the OAO system but I have probably covered the primary ones and I believe they are sufficient to show the way in which the plans for the OAO evolved.

Figure 1 is an artist's conception of the OAO as it exists today. The basic structure is a tube 48 inches in diameter surrounded by an octagonal structure. Mounted on the outer structure are six star trackers which provide the reference system for satellite orientation. We have had a number of problems with the star trackers and they are one of the few components with which we are still not completely satisfied. One of the problems encountered was that scattered sunlight entering the star trackers, even when pointing far from the sun, obscured the guide star. To solve this problem we have put around each star tracker an oddly shaped sun shield, which we call a minaret, to cut down on light from the sun and the earth. Although the astronomers are still planning to use only the 30 watts they were promised at the beginning, the requirements of the engineers have increased steadily as the design has evolved. In addition, since the original design, we have recognized that both the natural and the artificial radiation belts will decrease the efficiency of the solar cells in time. Therefore, we have had to enlarge the solar cell area by adding additional paddles. We recognized from the beginning that the satellite would have to be carefully balanced inertially to avoid disturbance torques in the earth's gravitational field. It proved impossible to balance the satellite internally to the required degree of accuracy and hence two booms have been added for stabilization to provide proper moments of inertia. Figure 1 also illustrates the sun shield, which is closed at the time of satellite launch and remains closed until complete stabilization control has been achieved. Normally, during the observations the sun screen will remain between the sun and the optical tube to shield the primary instrumentation from both direct and scattered sunlight. However, it is possible to work with the sun shield in any other orientation if this should prove desirable. The spacecraft will be programmed to avoid pointing the telescope within 45° of the direction to the sun. However, if this system should fail the sun shield is designed to start closing as soon as the telescope points within 45° of the sun and be entirely closed at 30°. Since a finite possibility exists that it will be impossible to reopen the sun shield, pyrotechnic squibs have been provided to remove the shield completely in case of emergency.

Figure 2 illustrates OAO under construction. Both the central tube, which contains main optical instrumentation, and the equipment shelves are visible. You will also note cross-struts supplied for extra support. Basically the OAO is 118 inches long, and 80 inches across the flat end. The inner structure, which provides transverse sheer continuity and torsional stiffness along the satellite structure, is 48 inches in diameter and is made of aluminium alloy. Eight equal trusses form the backbone of the satellite system and absorb all of the loads. The equipment is mounted on shelves which are hinged so that the equipment can be swung out for servicing and adjustment after it has been mounted in the satellite The joints between the shelves and the structure have been designed so that thermal stresses will not change the alignment of the basic structure with respect to the instrumentation tube in the center of the satellite.

When the satellite is first separated from the Agena rocket it is likely to be tumbling in a random fashion. Three rate gyroscopes, one for each axis of the spacecraft, will activate a high thrust gas jet system to slow the spacecraft until it is tumbling more slowly than 3/4 of a degree per second in each axis. At this time a signal from several silicon solar cells, each of which has approximately a 180° field of view, will be used with the signal from the three rate gyroscopes to instruct the thrust system to slow the satellite to a tumble of approximately 0.03° per second in each axis and to stabilize it until the back end of the satellite is pointing within 2° of the sun line. A set of eight fine eyes, that is, solar cells with only a 10° field of view, are used to control finer gas jets to stabilize the satellite with the back end pointing within 1/4 degree of the s[illegible] When that has been done, one of the three rate gyroscopes will tell the sa[illegible]lite to start rolling about the sun axis slowly until the six star trackers on the satellite, which have been set previously at predetermined angles, simultaneously acquire a star. As each star tracker has a field of only about one square degree and can reach stars only brighter than a second magnitude they are unlikely to lock on to an incorrect configuration. Whether they indeed are observing the proper star field can be checked by the fact that if each tracker is tracking the proper star it should be pointing within one or two minutes of arc of a pre-computed angle. By means of these six stars we have then transferred the coordinate system of the satellite to the celestial coordinate system of right ascension and declination. The satellite carries a small computer to provide the conversion between these systems for controlling spacecraft motions.

The satellite carries five systems to control its angular rate: the high-level jet system which is used in initial stabilization; a low-level jet system which is used to get rid of unwanted angular momentum in the satellite lifetime; a set of coarse inertia wheels; a set of fine inertia wheels; and a controllable magnetic field to interact with the terrestrial magnetic field. In normal operation the satellite will tend to drift slightly because of the various torques to which it is subjected. To remove this drift, the fine inertia wheels are activated to absorb the angular momentum of the satellite. Of course, these wheels cannot build up rotation speed indefinitely and a second system is required to change the angular momentum of the satellite. The fine gas jet system provides such a mechanism for removing angular momentum but its lifetime is limited by the amount of gas which can be carried in the satellite. Therefore, a magnetic system has been added as the primary mechanism for unloading angular momentum, and the gas system used entirely as a back-up system. In each of the spacecraft axes we have wire coils through which an electric current can be sent to produce a magnetic field. This field will then interact with the magnetic field of the earth to change the angular momentum of the satellite in exactly the same way as the fine gas jets. This magnetic system has been used on a number of satellites and has proved highly reliable.

The six star trackers and their associated logic provide the mechanism for pointing the satellite at any place in the sky and for maintaining the pointing to within approximately one quarter of a minute of arc for at least 50 minutes. Each star tracker is actually a telescope, approximately three inches in diameter, mounted on a double gimbal system (Figure 3). The angle at which each gimbal is set is determined by a phasolver. Each phasolver consists of two glass discs (Figure 4). On one of these half of a ring is coated with a conductor; on the other, is a ring consisting of a number of stripes. When the discs are then mounted close together a capacitance is set up between the two conducting rings. The half ring provides a coarse indication of the angle and the other disc with its numerous small segments of conductors then acts as a vernier. This system should measure each gimbal angle within a few seconds of arc. The star tracker system has, however, produced a number of problems. It proved difficult to design the star tracker system so that it would be insensitive to temperature distortions. This has now been solved. Since they are glass and cannot be strongly stressed it has been difficult to design a mounting for the phase solver discs in such a way that they would retain their proper position during the stresses of launch. This problem apparently has been solved also. In the latest test a shift of the star tracker axis was observed, but we believe at present that this shift did not occur in the star tracker itself, although we will not be sure until the system has been retested. I have already mentioned the problem of scattered sunlight. Even a little sunlight coming in the edges of the telescopes makes the star tracker think that another star is present in the field. As the star tracker tracks on the center of light of the field which it is observing the net result is a biased signal. We had originally planned to cover each star tracker telescope with a quartz dome not only to protect the star tracker during launch but also to permit the operation of the various moving parts in a hermetically sealed dry nitrogen atmosphere. This idea had to be abandoned, since tests showed that even the slightest bit of dust or the smallest scratch on the quartz dome scattered sunlight into the star tracker. The sun shield which has been added has a small hole to let in the desired star light. The edge of this hole has been polished to a knife edge to avoid scattering of light off of the edge into the tracker. Obviously it is particularly important to keep this edge clean and one of our current worries is how to avoid blowing some dust onto these tracker shields when the shroud is ejected. We do not know how to handle this problem yet, particularly since we have no way of testing the procedure on the ground.

As I have already mentioned, each star tracker tracks on the center of light of the object in its field. Therefore, we must avoid choosing as guide stars, double stars or stars in fields in which a second star is present unless the second star is appreciably fainter than the star on which we wish to track. By restricting ourselves . stars brighter than second magnitude and eliminating stars in which confusion might arise we have restricted the number of guide stars to approximately 40 stars.

We decided originally that if the astronomer needed to point his telescope with a higher accuracy than one minute of arc he would have to provide an error signal from his own experiment However, there are some experiments which require better pointing than one arc minute, but do not observe an object from which an error signal can be derived. For example, an astronomer may wish to observe a nebula, which is usually a broad diffuse region, possibly several minutes of arc in diameter, with no obvious features. To provide tracking for these experiments, as well as a back-up system to that provided by the six star trackers, we have added a special bore-sight star tracker which is carefully aligned with the optical axis of the experiment. This tracker has a field of view of ±5 minutes of arc and can be used to point the satellite with an accuracy of two seconds of arc. Since the astronomer may wish to observe a star fainter than that which can be tracked by this device or an unsuitably diffuse object, an offset capability has been provided so that any star within 90 minutes of arc of the center of the field can be used.

Once a series of observations on a given object has been completed it is necessary, of course, to repoint the telescope to another portion of the sky. The astronomer tells a computer on the ground the right ascension and declination of the object which he wishes to observe next. The computer translates this into the spacecraft coordinate system and determines how many degrees in each axis it is necessary to move the spacecraft. The computer also checks that the spacecraft will not in the course of the maneuver cross the sun or go through other undesirable orientations. The computer then generates the commands necessary to tell the satellite to move so many degrees in each of the three axes. Specifically, the command tells each of the coarse wheels in turn to rotate a specific number of times. For example, 80 rotations of a coarse wheel corresponds to a change in satellite direction of approximately one degree. Unfortunately, it is possible to move a satellite in only one axis at a time. This delays the transfer from one star field to another undesirably but was the only solution which could be found to how to avoid cross coupling between the various axes. As the satellite is moved the star trackers continue to track the same guide stars. However, their angle of motion is limited to $\pm 43^{\circ}$ and they cannot follow the same stars indefinitely. As a particular tracker approaches the limit to which it can turn, the ground-based computer tells it to stop tracking that star and change to a new gimbal angle which will permit it to pick up a new guide star. In theory, two star trackers are sufficient to determine the orientation of a spacecraft. However, not only might the angle between stars tracked by these two trackers not be ideal but the fact that at times a tracker will lose track because of earth occultation makes the use of at least three trackers necessary. The additional trackers have been added simply to provide redundancy, as the star trackers are expected to be one of the less reliable components on the spacecraft.

In original specifications we required that the spacecraft be able to move to a new position at the rate of 30° in three minutes. The necessity for moving in only one axis at a time raised the time required to nine minutes for a 30° slew. However, a much bigger problem has arisen. The spacecraft designer indeed met the specifications that it should be possible to move 30° in a given axis in three minutes, but he did not include in the three minutes the time that it takes a satellite to come to a dead stop. As this will require three to four additional minutes, as much as 25 minutes may be required to move the satellite 30°. We are unhappy about this length of time and are making efforts to decrease it, but it is unlikely that the time will be decreased significantly before the launch of the first or second satellites. For these satellites an effort will be made to restrict the observing program so that the telescope's position is changed by only a small amount from one observation to the next. We estimate that in contrast to the 25 minutes required for a 30° slew approximately five minutes are needed for a two-degree change in the position of the satellite.

One of the philosophies in the design of the OAO has been the use of redundancy wherever possible. We have used redundant components, redundant subsystems and redundant systems. There are obviously places where redundancy is not possible, for example, in a large optical system, but it has been used where it can be. In particular, in the command and data handling system four-fold redundancy has been used throughout. To the best of our knowledge this is the first time that this system has been used extensively, so that the spacecraft will essentially become a test vehicle for such a system. The four-fold redundant system works well on the ground. We are hoping it will work even better in orbit. The command and data handling systems deserve further comment. Because a tape recorder has moving parts which might upset the delicate pointing of the OAO, a magnetic core system was used. To save space and weight a new system was developed which is approximately ten times more compact than any core storage system that has been used previously. A storage system which can store 10^5 bits of information is contained in a box approximately 1/2 foot on a side. In each box there are 64 layers of cores. The spacecraft data handling system is completely digital except that a small amount of spacecraft data can be transmitted to ground in an analog mode. Some analog data may also be transmitted from the experiment but only in real time.

Redundancy is also used for the transmission of commands to the spacecraft. For each command, the command itself and the complement of the command is transmitted. Before the command is executed the spacecraft compares it with the complement. If they do not check, a signal is transmitted indicating that a valid command was not received. Both commands and data can be stored; therefore, the commands sent while the spacecraft is in sight of a ground station can be executed at any time during the orbit. Over a ground station the information in the data storage is read out over a wide-band telemetry system. The readout is non-destructive and we plan to transmit the data at least twice to avoid loss of data due to transmission errors. We also expect to have the capability of transmitting television pictures (slow scan) in real time. Together these requirements have led to the necessity of a 50 km bandwidth for the wide-band transmission system. It became apparent rather early that it was impossible to use minitrack receivers for the large data rates from the satellite. Therefore, 85-foot parabolic receivers have been located in Rosman, North Carolina, about 200 miles southwest of Washington, and 40-foot receivers in Quito, Ecuador, and Santiago, Chile. While other stations in the minitrack network will track the satellite to determine its orbit, only these stations will be used to read data from the satellite or to transmit commands. The stations are distributed in latitude so that each satellite orbit will pass over at least one of them. No attempt has been made to provide full-time tracking of the satellite.

A central control station will be maintained at the Goddard Space Flight Center near Washington. This station will have an IBM 7090 computer which can be used full time for the operation of the satellite if necessary. As mentioned earlier, this computer will generate the command tapes which will redirect the satellite from one position to another. It will also, of course, generate command tapes for all other activities connected with the experiment. The computer will also be used to predict the status of various spacecraft systems, such as battery voltage, temperatures and other indications used to be sure that the satellite is performing correctly. A tape is generated for each satellite pass and is transmitted to the appropriate remote station. As the satellite comes into view of the ground station a command will be sent to turn on the narrow-band transmitter. This transmitter will send the status data, which is then compared with the expected status data. If they compare within pre-computed limits, the wide-band transmitter is turned on and stored data is transmitted. The reception from the wide-band transmitter is stored on tape and eventually mailed back to the Goddard Space Flight Center, where it is processed. If, however, the status data does not check with the expected values the observer requests a repeat transmission to be sure that the error was not in the data. If the second transmission again indicates a problem, he sends a command to put the satellite into a mode which we call the "hold" mode. This is a mode of operation which prevents the satellite from doing anything which might endanger it permanently. The defective status data is sent immediately to Goddard by teletype. At Goddard, experts on the various satellite subsystems will be available. They will also have the use of spacecraft simulators and the large computer to analyze the situation which may have led to the unexpected status data. A command tape will be generated which, hopefully, will remedy the problem. This tape is then sent by teletype to the next station which will be able to observe the satellite. The process can be repeated until the satellite is again operating successfully. The only communication links between Quito, Santiago and Goddard are the relatively narrow-band teletype links. However, there may be times when the astronomer needs to analyze some of his experiment data quickly to determine if the instrumentation is working properly, or there may be other occasions when it is necessary to analyze the wide-band data rapidly. Therefore, a microwave link has been established between Rosman and Goddard over which an essentially real-time operation of the system can be conducted if necessary.

Another aspect of spacecraft design which may interest you is that of thermal design. The main problem thermally has been to avoid gradients which would distort the structure and therefore mis-align the optical axis of the experiment with that of the star tracker system. Two methods have been used to avoid thermal gradients. We have made the thermal inputs to the structure as few as possible. The electronic equipment is almost all thermally insulated from the structure and thermally connected with the outside skin of the spacecraft. This skin is of aluminium specially coated with Alzac to have the proper temperature characteristics. The structure is also thermally isolated by means of super-insulation from the experimenter's tube. The super-insulation is actually a mylar plastic coated with aluminium and used in many layers. The central tube used for the optical equipment is maintained at a temperature between 0° C and -30° C. The temperature setting is different for different experimenters and will not have a wide range for any one experiment. Photomultipliers tend to work more quietly at cold temperatures, hence the -30° possibly. However, at these temperatures some electronic equipment runs into trouble and therefore for experiments in which this can be a severe problem, such as the Smithsonian experiment, the higher temperature can be used. The mirror, of course, sees outer space and hence will be very cold, but most of the tube structure cannot be kept at such a cold level. The satellite temperature control system is primarily a passive one. In order to maintain the structure at a proper temperature a small amount of heat is allowed to leak into the structure. There are also some parts of the equipment, particularly electronic equipment that must be mounted in the experimenter's tube, which require small heaters to keep the operating temperature sufficiently high but these heat sources will be very small relatively speaking and most of the temperature control will depend on the properties of the Alzac skin. Because it is easier to control the temperature if it is not necessary to mount solar cells on the spacecraft itself. the solar cells are mounted separately on paddles. The resolution of the mirror is, of course, dependent on temperature. To test the mirror we have built an optical bench which can operate at -60° C. This probably will not be as cold as the temperature mirror will attain in orbit but it is as cold as we have been able to produce in the laboratory.

Several test facilities have been designed for the OAO. The first is a large air-bearing table operating in a crude vacuum. The vacuum is used only to prevent aerodynamic torques, not for environmental tests. This chamber contains simulated stars on which the OAO can lock and track and also a simulated sun. Using this chamber and its air-bearing table, the control system of the OAO has been checked out. It is possible to add disturbance torques comparable in size and nature to the various torques which the satellite will experience in orbit. I have already mentioned the optical bench in which the alignment and performance of the optical equipment in the satellite can be tested at various temperatures down to -60° C. This is a horizontal optical bench in which the entire telescope system can be mounted for a checkout of the equipment. The optical bench contains a monochromator which provides a 38-inch light beam with a wavelength range of 1100 Å to 4000 Å, although the shorter wavelengths cannot be used because the facility is not evacuated. The optical equipment can be rotated in this optical bench to check that gravity disturbances are not distorting the alignment. To allow testing and alignment of the system at shorter wavelengths, a vertical optical bench has been constructed which will operate at a pressure of about 5×10^{5} millimeters. It will, however, operate at room temperature. An attempt is being made to improve the vacuum in this optical bench. However, at present a hydrogen lamp is being used and it is impossible to evacuate the gas from this lamp fast enough to maintain a better vacuum. The vertical optical bench is arranged so that the experiment can be hung on the same mounting hinge that will be used to mount it on the OAO spacecraft. A beam of light is sent in from the top to check the collimation accurately. The experiment can then be turned over with the light beam entering from the bottom to see if the collimation has been changed due to gravity. We have been unable to devise a system to check the optics in a gravity-free environment and hence have compromised by checking the alignment in various orientations in a gravity field.

The three test facilities which I have described have been designed specifically for the OAO. There are also numerous other test facilities at the Goddard Space Flight Center which are used for the checkout of the OAO and its subsystems. Perhaps the most impressive of these is a large vacuum chamber 28 feet in diameter and 40 feet, high which is supposed to operate in a temperature range between -54° and +100° C at a vacuum of 10^{9} millimeters of mercury. This chamber also has a solar simulator for testing solar cells. It is large enough to enable the OAO to be operated with its solar paddles open and such satellites as the Orbiting Geophysical Observatories (OGO) to be operated with their booms extended.

As I have implied earlier, there were many technological developments required for the development of the OAO spacecraft system, and a number of technological firsts have been achieved: the same is true for the experiments.[†] The first spacecraft contains two experiments: one by the Smithsonian Astrophysical Observatory, an attempt to map the sky in the ultraviolet by means of a television-type camera; and the other by the University of Wisconsin, an attempt to do photoelectric photometry in the ultraviolet. The Wisconsin experiment (Figure 5) has been a straightforward extension of ground-based techniques. In this case the astronomer performed beautifully by having his experiment ready, tested and operating almost a year before the spacecraft is able to accept it. The project manager, after hounding people to get things done on time, now finds himself in an embarrassing position of being presented with this experiment on the date he requested it and having no place in which to mount it. I am sure he wishes all of his problems were of this type.

On the other hand, the Smithsonian experiment has had real problems. Five years ago it did not appear too difficult to build a television camera that would work in the ultraviolet. There were good television cameras for the visible and photographic regions and it would be necessary only to change the photocathode to produce a television camera for the ultraviolet. Experience has proved this assumption to be naive. A television tube operating in the ultraviolet must transmit ultraviolet light to the cathode, which means the tube cannot have a glass window. However, it was impossible to make the tube completely from other material so that the first problem to be solved was how to seal a quartz or a lithium fluoride window to the metal structure of the tube. When this problem was finally solved we found that the tube showed a number of defects when operated at the designed target voltage. For most applications a few small defects on a television screen would not be serious, but these defects look exactly like stars and hence would degrade the experiment seriously. These defects could be removed by decreasing the voltage on the target, but unfortunately, this voltage decrease also decreases the intensity of the images and by the time the defects disappeared the stars being observed disappeared also. This problem was solved by the development of a conducting target in place of the original emitting target. The image falls on one side of the target and is transmitted to the other side which in turn emits a bundle of electrons which can be focused onto a screen.

[†] A discussion of these experiments has been given by Dr. John Rogerson in Space Science Reviews, Vol. 2, pp. 621-652, 1963.

This screen is then scanned in the same way as that in any other television tube. Although the conducting targets may be slightly more sensitive than the earlier targets, the primary advantage is that they can be operated at lower voltages and the false stars have now been removed. Then we had a problem of the target flaking during vibration; however, this appears to be solved.

Tubes were built and continued to operate satisfactorily after environmental testing. Then we ran into a problem which might have been amusing had it not been so costly in both time and money. The next tubes produced did not work. Investigation showed that the targets were being destroyed due to moisture in the tubes. A thorough study uncovered the fact that there had been a change in the technician assigned to this program. The earlier technician was a careful soul who, seeing a rough edge where the new window was butted onto the tube, thought "that's no way to do things. I'll just take a flame and smooth that off before I put the window on." The new technician realized that he would heat the tube when he put on the new window and thought that he could make a perfectly good seal without smoothing the rough edges ahead of time. Therefore, he made the seal without heating it first. Of course, neither technician mentioned his method to anyone else. The second technician was correct; the new seal was as good as the old one. It was some time before we discovered that the first technician unwittingly removed moisture from the rest of the tube when he heated the rim, thus preventing the moisture problem later.

Another problem which has since been solved was that the star field image tended to remain on the tube after it was supposed to have been erased. A serious problem remains, that of quality control. Every tube is made essentially by hand and there has been a tug of war between the research department and the production department as to who should make these tubes. The research department has the capability to hand-produce tubes and moreover is needed to handle the various problems which arise in the development of a new tube, but they are not set up to exercise strict quality control. The production department can control the quality but probably does not have the capability to solve the problems which arise. At present we are trying to determine how the research department can exercise adequate quality control.[†]

[†] Added March 1966. The problem of producing satisfactory television tubes is now apparently solved. However, the delays were sufficiently extensive that this experiment had to be removed from the first OAO spacecraft. The experiment was replaced by a package of three X-ray and gamma-ray experiments.

The second OAO spacecraft will carry a Goddard experiment package consisting of a spectrometer fed by a 36-inch mirror. This telescope and the star tracker telescopes on the spacecraft use beryllium mirrors rather than quartz. As far as I know, this is the first attempt to use a metal mirror in a situation in which good optical quality is required. The mirror is machined from beryllium and overcoated with canogen, a ceramic coating. After polishing, the mirror is coated with aluminium and then with magnesium fluoride to give good ultraviolet reflectivity (Figure 6). The making and figuring of the mirror has actually proved easier than we had expected. Tests under standard laboratory conditions have indicated good performance but the mirror has not yet been tested at low temperature or in the ultraviolet. The grating for this experiment is unusual. To keep the optical system compact the light path from the collimator to the photocells goes through the grating. Therefore, there have had to be five holes cut in the grating after it has been made and figured to a slightly aspheric surface. Since a discontinuous grating cannot be ruled, these holes must be cut after the grating has been finished. To protect the grating while the holes are being cut it is covered with an epoxy coating. After cutting the holes, the epoxy is dissolved. This process worked beautifully for the prototype grating. However, for the flight grating, the process did not work at all. Apparently something had gotten under the aluminium coating on which the grating was ruled or had reacted with something under the aluminium coating. This situation proved to be somewhat similar to that of the moisture in the Uvicon. Bausch and Lomb, the company which ruled the grating, changed the oil that they were using in their grating ruling engines between ruling the prototype and the flight grating from a carbon-based oil to a silicon-based oil. It happens that silicon oil is not as easy to remove as the carbon oil and apparently, in spite of thorough cleaning, some silicon-based oil remained on the grating and reacted with the epoxy. As the prototype grating can probably be used in the flight experiment package, this difficulty should not delay completion of the experiment package. However, it has been a costly lesson in chemistry.

The third OAO spacecraft will also carry a spectrometer, designed by Princeton University. In contrast with the second instrument, the third experiment (Figure 7) is designed to give very high spectral resolution in the far ultraviolet. A resolution of 0.05 and 0.1 Å is desired for the short and long wave portions of the experiment respectively. To obtain this high resolution requires a narrow slit and to avoid losing most of the light it is necessary to center the image accurately on the slit for a long period of time. This in turn requires accurate guiding and minimum thermal distortions in the optical system. Goddard is also worried about thermal distortions in their optical system, but they believe that they can solve this problem within their lower tolerance by using a structural shell between the primary and secondary mirrors made partly of titanium and partly of aluminium to compensate for thermal variations. Because of the much higher compensation required for the Princeton experiment the use of a metal structure appeared difficult. Therefore, Princeton, which uses quartz elements in its optical system, is using quartz rods to separate primary and secondary mirrors. If this system expands or contracts due to thermal changes, the image will remain in focus. To set the focus originally and to be sure that it is being maintained, Princeton is developing a system to scan the star image across the slit. From the shape of the received signal they can determine if the image is indeed focused and if not, correct the positioning accordingly. They also plan to use this image scanning device to detect any misalignment in the optical system.

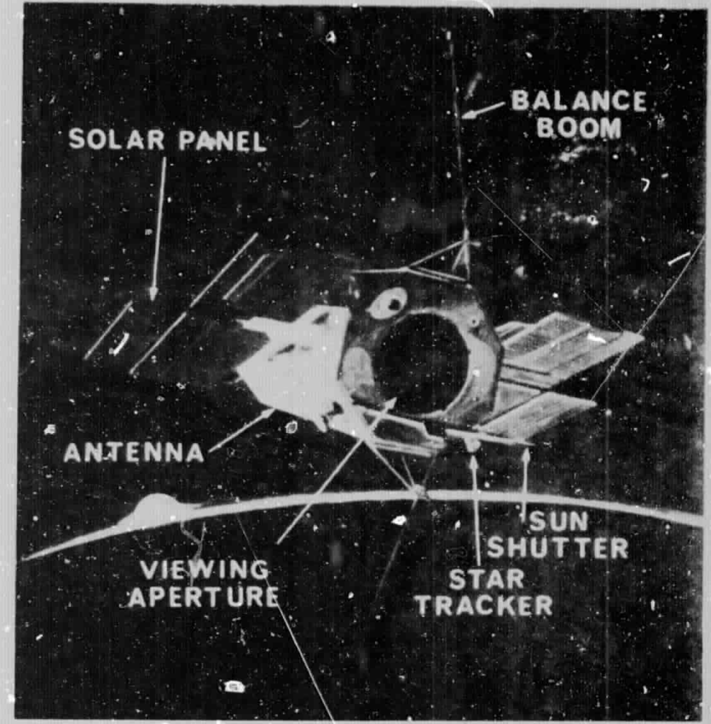
Figure 8 illustrates the Princeton guidance system. An off-centered image is reflected from a side of the slit. By tilting the sides of the slit slightly, the beams from the two sides are separated and can be handled individually. After passing through a field lens and a few other components the beams fall on a prism, which separates each of the incident beams into two beams. The four beams then fall on a rotating shutter which transmits one beam at a time to a photocell. Thus if the image is off center, the amount of light falling on the photocell will vary as the shutter rotates, sending a signal to the guidance system. The basic system is fairly simple and a natural extension of that used on the ground, but many problems arose. On the ground astronomers would use two photocells, one for each of the beams. This was undesirable in orbit because the gain of the two photocells might change differently with time. In order to be able to guide on stars of different brightnesses an automatic gain control system was added to the amplifier. Redundancy was added so that if one photo-multiplier fails to work a second system would take over. To provide an indication to the servo system as to how far the star is from its proper position, the slit has been coated with a reflective coating which grades in reflectivity from the center to the edge. Another problem which arose was how to avoid overloading the AGC system while the satellite was oscillating slightly, trying to settle down on the star. To avoid this, a capacity circuit was added to help the AGC system remember for about five seconds the brightness of the star for which it is searching. The same AGC system is also used to tell the spacecraft that the fine guidance system has acquired a star. The spacecraft guidance system is used to point the telescope sufficiently accurately to ensure that the fine guidance system should indeed acquire a star. Then the spacecraft guidance system is switched to operate on the error signal produced by the Princeton experiment. The interface problem between these two guidance systems has been far from trivial but now appears to be solved. Incidentally, this guidance system operates with light in the normal photographic region, where the image will be larger, rather than with ultraviolet light

The Goddard experiment also has a means of checking the focus. Although their tolerance is much greater than that of the Princeton experiment, because of the use of metal structure, their temperature effects also will be larger. On the side of the large mirror, a small mirror approximately one inch square has been set at a slight angle. Two additional small mirrors rotate into the beam from this auxiliary mirror in front of and behind the expected focus. Each mirror sends its light successively through a slit to a photomultiplier. If the telescope is in focus the beams from the two rotating mirrors should be of the same diameter. If the telescope is not in focus the focal setting is shifted toward the position of the mirror with the smaller image.

I have mentioned that the mirrors on the Goddard experiment and in the star trackers are made of beryllium. The mirrors in the Princeton and in the Wisconsin and Smithsonian experiments have been made of quartz. We are not yet sure which is the better material for use in space. The metal mirrors come to thermal equilibrium much more rapidly than do the quartz mirrors. On the other hand, thermal distortions are larger. The beryllium is lighter and probably stronger, but we are not sure of the stability of beryllium over long periods of time in the space environment. The mirrors in the Smithsonian Astrophysical Observatory and University of Wisconsin experiments are small enough and the images crude enough for the thermal problems not to be serious. In order to save weight, the Princeton mirror is made in an egg crate structure, that is, it is composed of two thin layers of quartz separated by a quartz honeycomb. None of the optical systems used on these satellites are standard systems. The Smithsonian experiment uses a Schwarzschild system which uses a parabolic mirror and an aspheric correcting plate with the image tube at the prime focus. The other instruments are modified Cassegrain systems. Because Goddard wishes to keep the major weight that of the primary mirror near the center of the spacecraft, they have designed a system in which the primary mirror is approximately an equal distance from the secondary mirror and the spectrometer mirror. The same mirror is used as a collimator and camera mirror. The Princeton experiment uses an almost standard Cassegrain system, although it is used somewhat off-axis.

Currently we have selected experiments for three OAO spacecraft. We have tentative experiments in mind for two additional flights and hope to be able to fly one spacecraft each year, possibly in a slightly modified form into the mid-1970's. Then we would like to use a somewhat larger system, perhaps with a primary mirror 50 to 55 inches in diameter and also to begin to make use of man in the maintenance of our satellites. We doubt if we will ever want a man actually hanging onto the telescope while we are taking observations. But, hopefully, some day we will be able to put up a very large satellite which will probably be larger than can be kept in adjustment during launch. Hence, man will be needed to make the adjustments between launch and observation and to make repairs so that a very expensive instrument will not have to be discarded when a particular battery or a transistor fails. We may also wish to use man for collecting film, which is still the most efficient data storage system available to astronomers. Finally, because of the versatility of a large telescope we will want to use man to change auxiliary instrumentation in much the same way as the versatility of ground-based instruments is increased by such changes. At present, therefore, we think that near the mid-70's we may wish to have a limited amount of manned activity in our astronomical systems; then perhaps in the 1980's we can think in terms of a large telescope in which man will play a major role. I wish to emphasize that this is nothing more than tentative planning at present. The picture could change significantly according to our experience with the OAO and budgetary situation. However, we feel that it is important to start on the major instrumentation, at least to the extent of determining in what areas technological developments must take place soon, so that we can plan on the major instrumentations a decade from now.

ORBITING ASTRONOMICAL OBSERVATORY



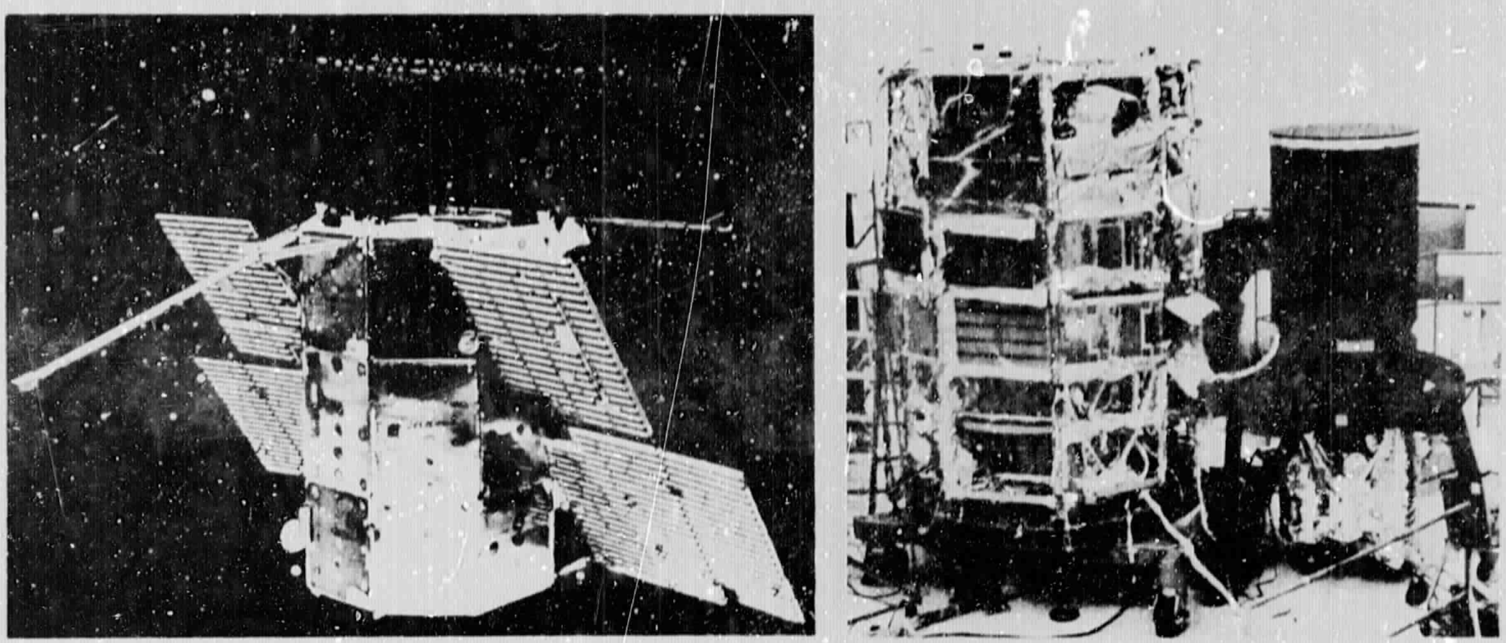
GROSS WEIGHT	3,900 LBS
INSTRUMENT WEIGHT	1,000 LBS.
STABILIZATION	ACTIVE 3 AXIS
LAUNCH VEHICLE	ATLAS-AGENA
ORBIT	CIRCULAR, 500 MILES 35° INCLINATION

POINTING CHARACTERISTICS

- ANYWHERE IN CELESTIAL SPHERE
  ONE ARC-MINUTE ACCURACY
- STAR TARGET
  0.1 ARC-SECONDS ACCURACY
- LONG DURATION POINTING

Figure 1 --- Artist's conception of the Orbiting Astronomical Observatory (OAO) showing key portions of the spacecraft. (Photograph reproduced by permission of NASA)

ORBITING ASTRONOMICAL OBSERVATORY
FLIGHT UNIT A 1



ASSEMBLED OAO·A1

OAO·A1

SPACECRAFT EXPERIMENT PACKAGE

Figure 2 --- The first OAO under construction. (Photograph reproduced by permission of NASA)

Figure 3 ---- The OAO star tracker, showing the sun shield and gimbal system. (Photograph reproduced by permission of NASA).

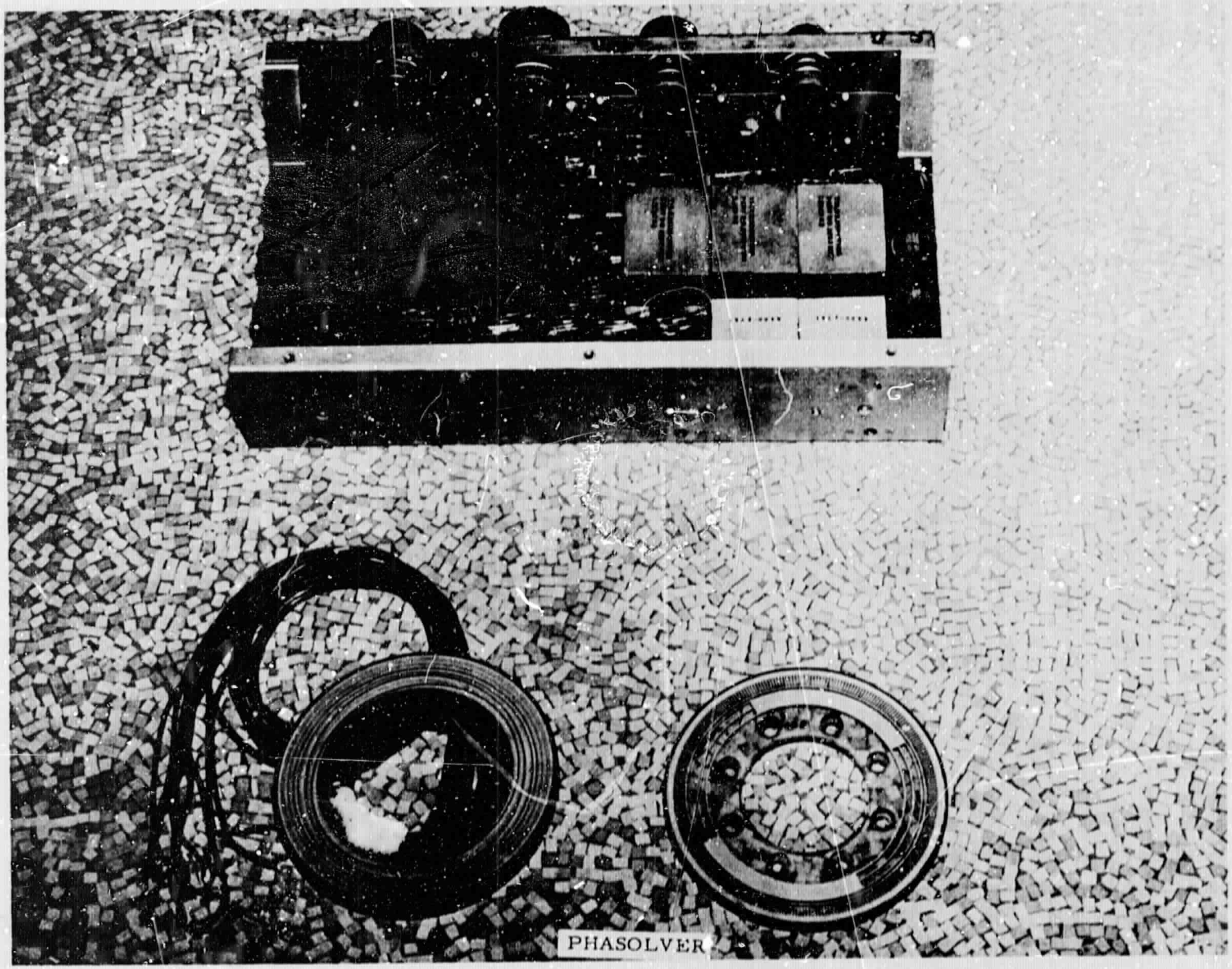


Figure 4 ---- The electronic and phasolver discs used with the OAO star tracker. (Photograph reproduced by permission of NASA)

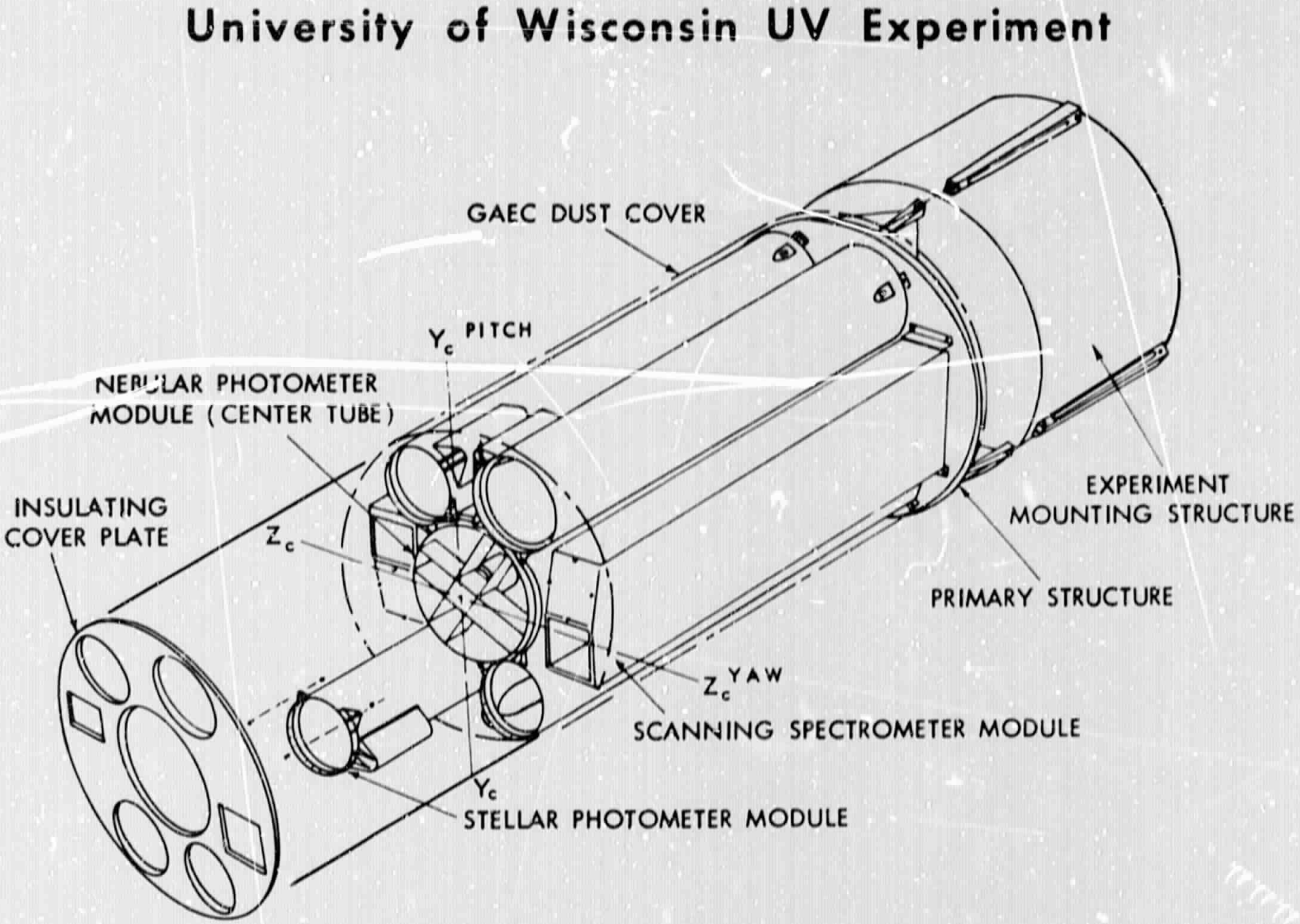


Figure 5---- Schematic layout of the University of Wisconsin Experiment Package. (Figure reproduced by permission of NASA)

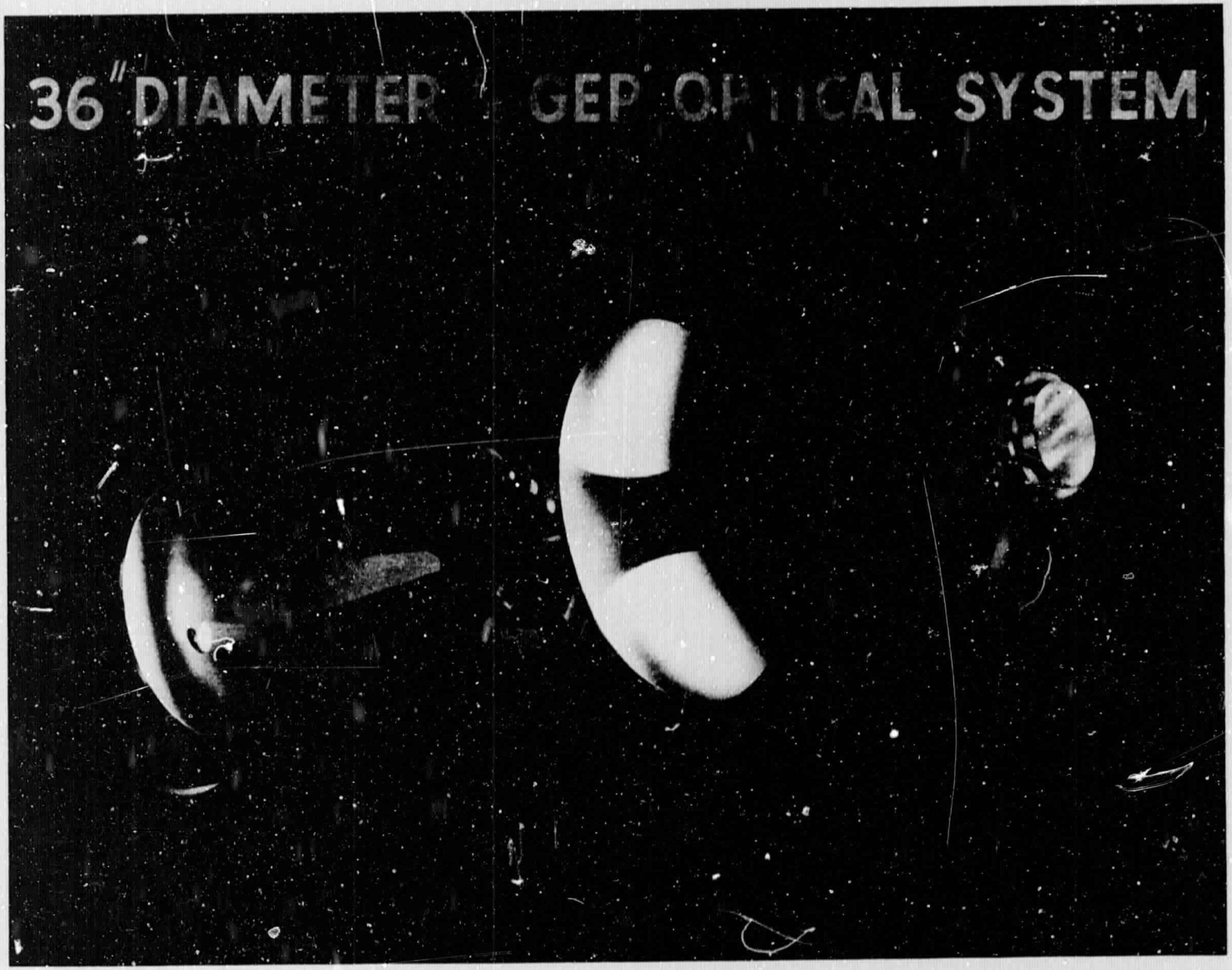


Figure 6 ---- Artist's drawing of the Goddard Experiment Package.
(Photograph reproduced by permission of NASA)

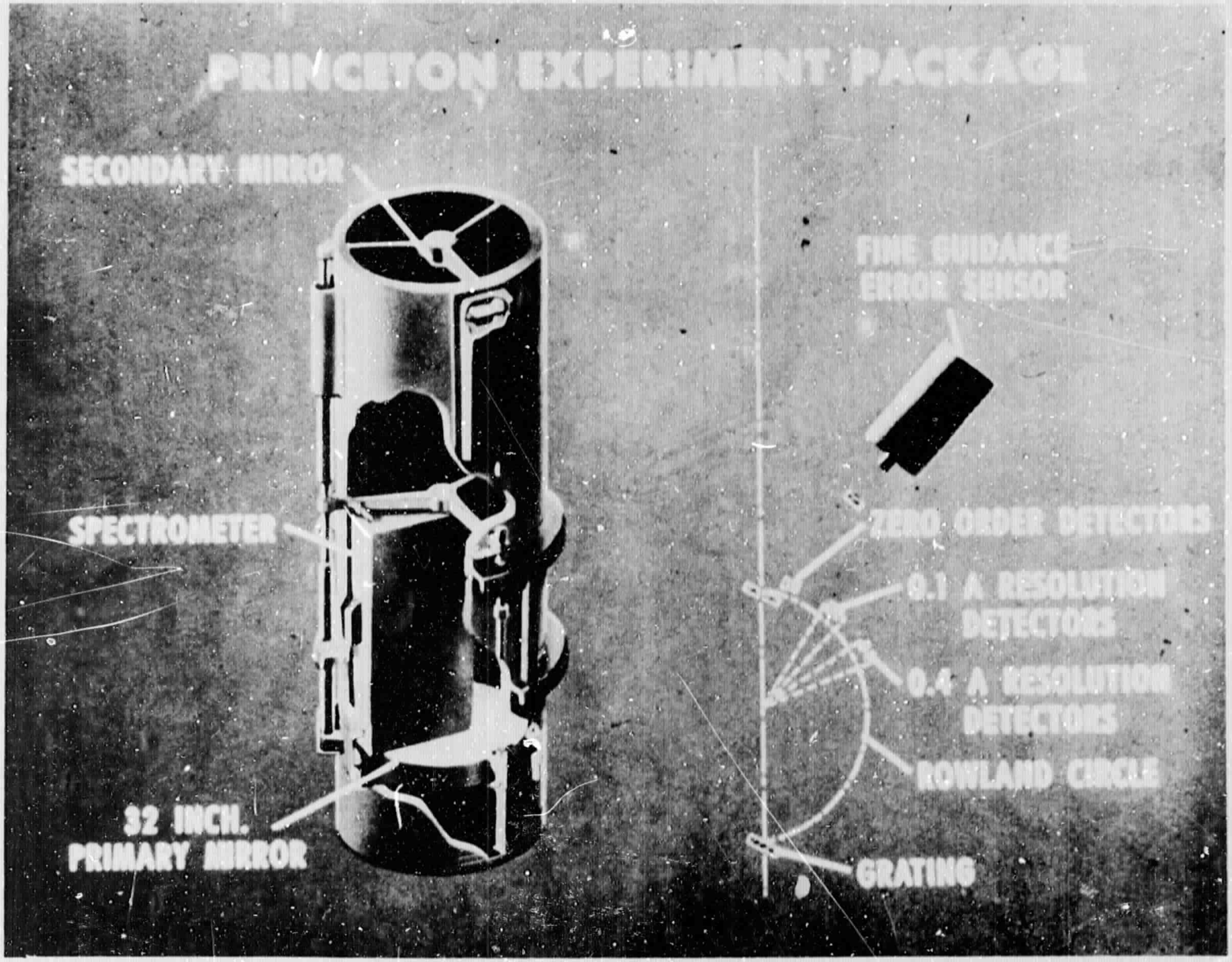


Figure 7 ---- Artist's drawing of the Princeton Experiment Package. (Photograph reproduced by permission of NASA)

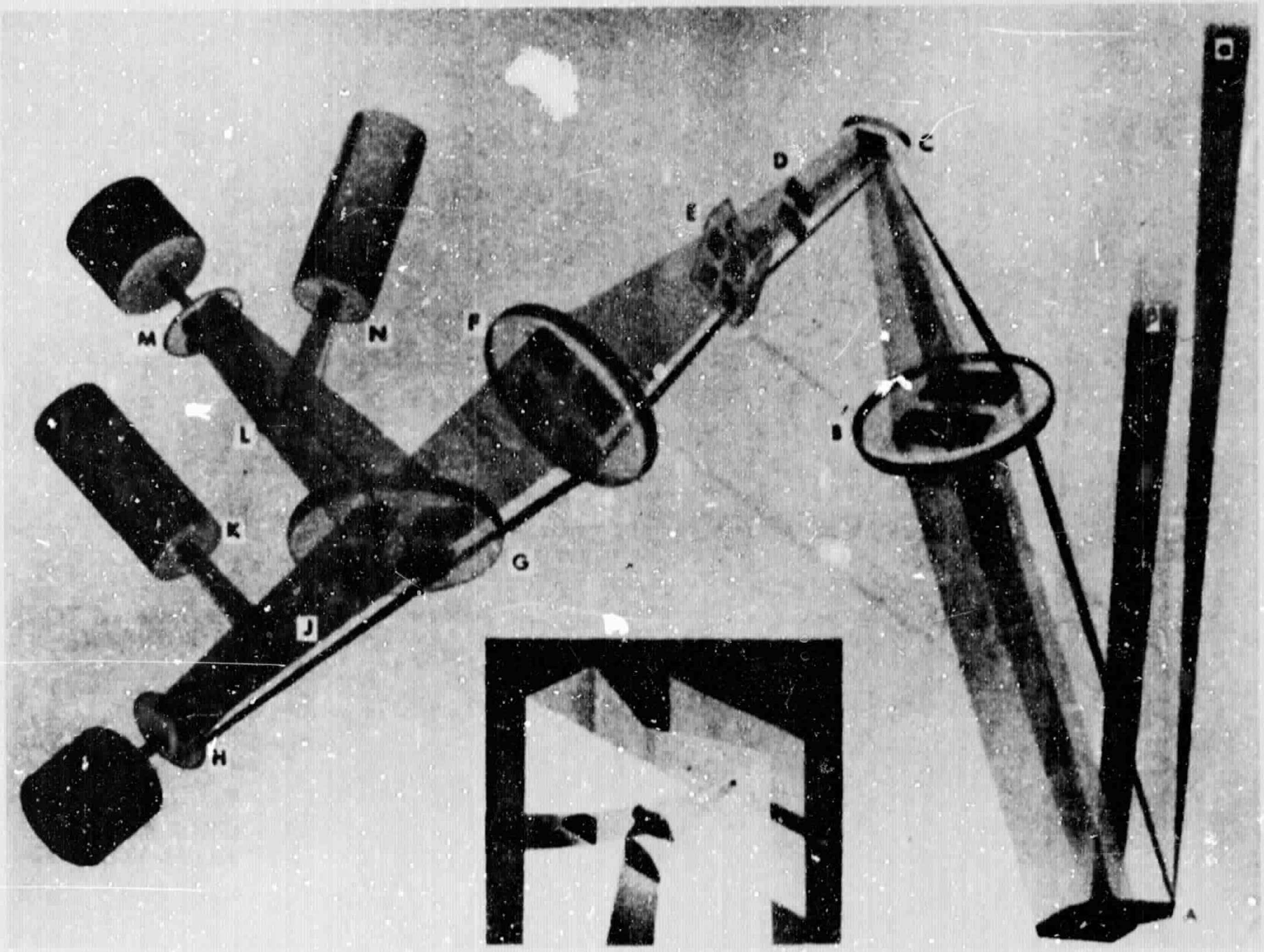


Figure 8 ---- Schematic drawing of the optical path and operation of the Princeton fine error sensor. (Photograph reproduced by permission of NASA)