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EXPLORATION OF THE MOON AND PLANETS

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One of the first things that Galileo did when he discovered that two lenses make a telescope was to look at the heavens. He described the mountains on our Moon and the moons of Jupiter. He observed the phases of the planet Venus. He began the exploration of our Moon and the planets.

Since his time, telescopes have improved in size and capability. New types of instruments have been attached to them, and new instruments, such as radio telescopes, have been used to extend our knowledge of the solar system. With the aid of this host of instruments here on the surface of the Earth, we have learned a great deal about the Moon and the planets. We know their orbits, their sizes, their temperatures. We know something about their atmospheres, and in a few cases we have some vague notions of their surface markings.

We have come a long way from the myths and legends of classical times and have put aside most of the superstitions of astrology. But now, with the development of powerful rockets, we are truly standing at the threshold of the real exploration of the Moon and planets.

The elementary physics of sending instruments, or man, to a nearby planet involves many problems. Figure 1 shows a portion of the solar system approximately to scale. Figure 2 (distances to the planets) illustrates the distances from the Earth to some of the planets as a function of time. Venus, Mars, and Mercury come within less than 100 million kilometers of the Earth; Jupiter is much further away. To travel to even the nearest planets, we must consider voyages of many tens of millions of kilometers.

The first problem is to accelerate the spacecraft sufficiently to escape from the Earth's gravitational pull. From a point near the surface of the Earth this requires a speed of about 7 miles per second. When it has climbed out of the Earth's field, the spacecraft is in the gravitational field of the Sun and perhaps the Moon. Its motion is determined by its remaining velocity (relative to the Earth), which will be quite small unless its initial speed was much greater than 7 miles per second, combined with the velocity of the Earth in its orbit around the Sun. This latter speed is about 19 miles per second, so the spacecraft speed relative to the Sun will not differ greatly from that of the Earth. Therefore, as seen from the Sun, the spacecraft will be in an orbit which is approximately an ellipse with its perihelion or aphelion on the Earth's orbit depending on whether the spacecraft velocity is greater or less than that of the Earth. If the initial conditions are correctly chosen, this ellipse may then be used to transport the spacecraft to a close encounter with another planet.

To send a spacecraft to the Moon, we can consider the situation as being approximately one in which the Moon is rotating around the Earth, and the effect

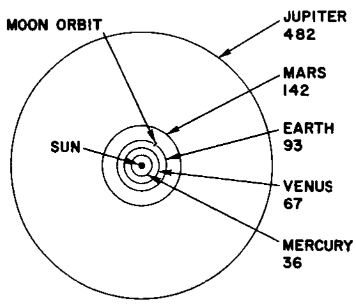

FIGURE 1.—The solar system (distances from Sun in millions of miles).

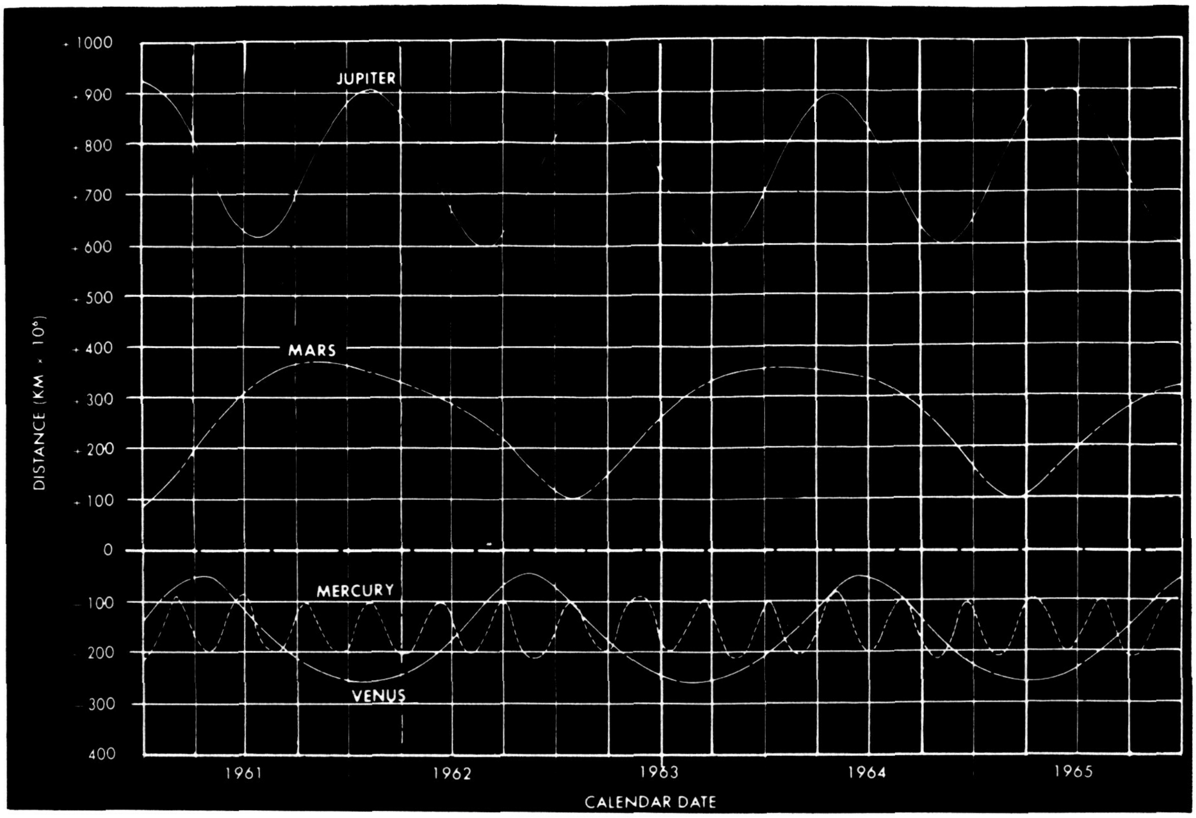

FIGURE 2.—Relative planet distances and periods.

of the motion of the combined system around the Sun can be neglected. The spacecraft must, therefore, leave the Earth on a trajectory which carries it close to the Moon. It will then come under the influence of the Moon's gravitational field and be pulled towards the Moon. The actual path must be computed as a solution to the problem of the motion of a particle in the gravitational field of the two attracting bodies, with minor perturbations from the other members of the solar system.

The speed of a lunar spacecraft when near the surface of Earth may be somewhat less than escape speed. In fact, the orbits used by both the United States and Soviet Moon probes have been elliptical orbits around the Earth with the apogee at a point lying beyond the Moon's orbit.

As a measure of our present capability to send spacecraft into deep space, Table I shows the performance of several U.S. rockets as measured by the payloads which can be accelerated to escape velocity.

For comparison, the Soviet payloads sent to the Moon or beyond include Lunik I in 1959 (800 pounds), the Venus attempt of February 1961 (1,400 pounds), the Mars attempt of Nevember 1962 (1,980 pounds), and Lunik IV attempt in April 1963 (3,100 pounds).

TABLE I.—*Payload performance*

	Pounds that can be sent to—		
	300 nautical miles	Escape velocity	Mars/Venus
Delta	800	105	90
Atlas/Agena–B	5,000	750	400
Centaur	8,500	2,300	1,300

With this capability of sending relatively small payloads far out into the solar system, several types of experiments can be considered. (This discussion is based on the assumption that we have the capability of guiding the vehicle close to the target object, and of communicating with it while it is at the target.)

We can visualize three types of missions. The simplest is a "fly-by." The spacecraft passes close to the target and makes observations as it goes by. These observations may be stored for later transmission to the Earth, or sent back in real time over the radio circuit. The Soviet pictures of the back side of the Moon were taken as the spacecraft flew past, and then developed and transmitted to the Earth at a later time. The U.S. Mariner spacecraft to Venus transmitted its data in real time as it flew past the planet.

The next type of mission is an orbital mission. In order to be captured into an orbit around the Moon or a planet, the spacecraft must lose kinetic energy. Hence, either a retrorocket must be carried, or it must skip through the atmosphere of the planet and lose sufficient energy by friction. Practically speaking, the retrorocket solution is the only one considered at this time. An orbiting spacecraft can, of course, make a

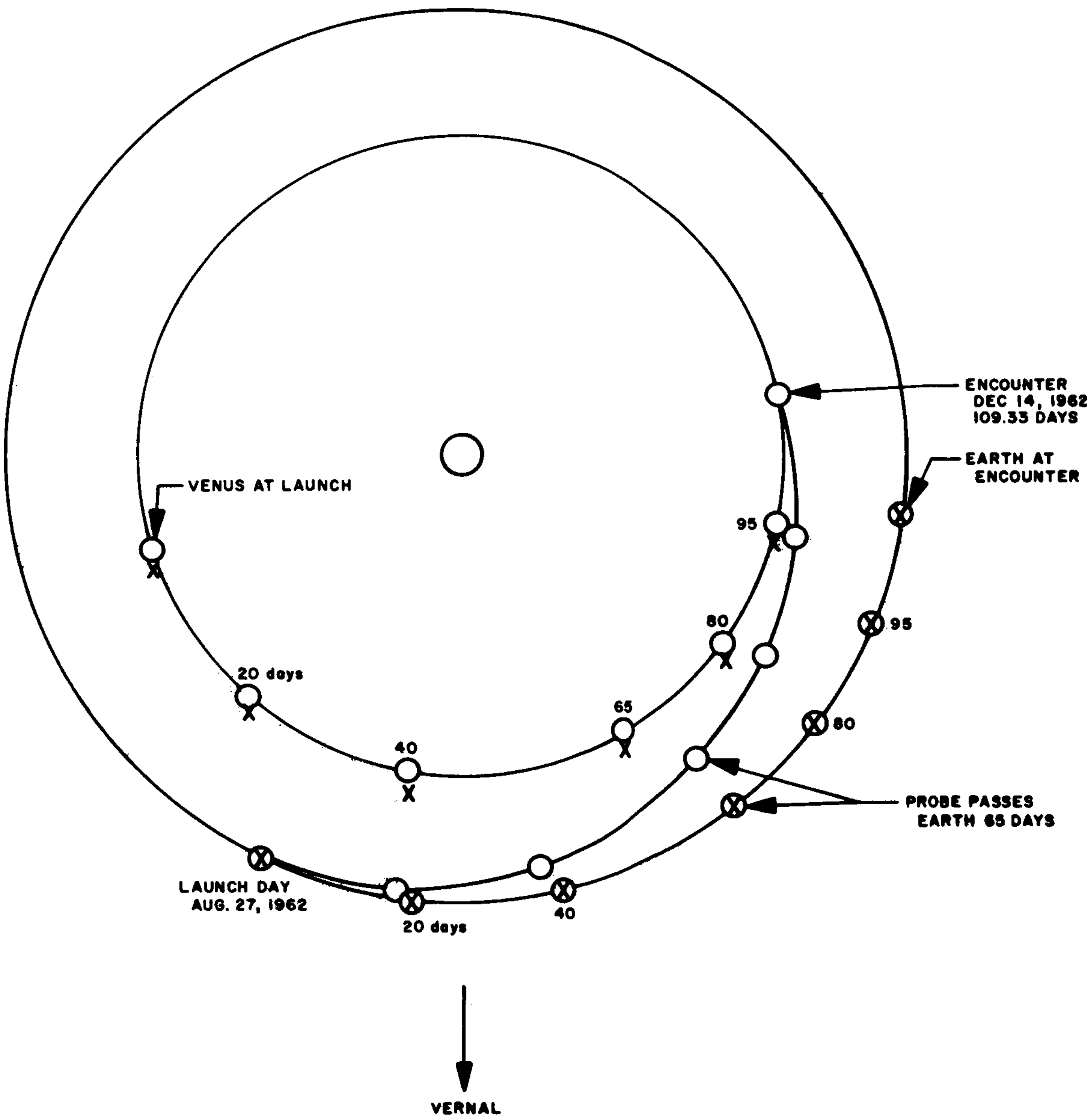

FIGURE 3.—Heliocentric plan view of trajectory of Mariner II Venus probe.

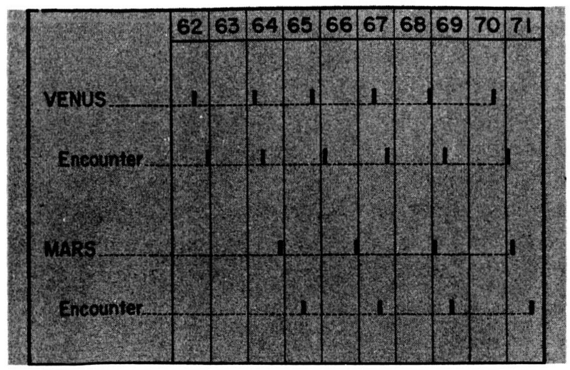

FIGURE 4.—Planet availability.

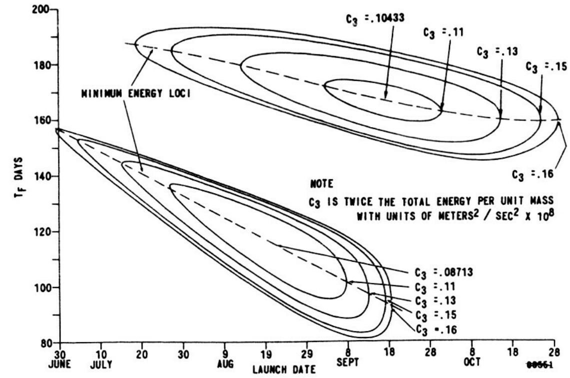

FIGURE 5.—Increase in energy as launch day departs from optimum (availability of Venus in 1962).

more extensive series of observations than a simple fly-by; however, the observations will be basically of the same type. When the orbit can be closely controlled, the distance may be made quite small or the spacecraft may be made to travel through some interesting region such as radiation belts or an ionosphere.

The third type of mission is the entry or landing mission. Again, the spacecraft must lose kinetic energy if it is going to reach the surface at zero speed. If the target has no atmosphere, retrorockets must be used; if there is an atmosphere, aerodynamic braking probably will be a better answer. The entry vehicle can perform two classes of missions, atmospheric measurements during descent and surface observations after landing. Detailed exploration of a lunar or planetary target will certainly have to wait for entry and landing missions.

Instead of a discussion of the scientific details or objectives of lunar and planetary exploration, this is a review of some of the engineering problems which must be solved if an unmanned spacecraft is to be sent to another planet. We can visualize the elements of an exploration program of a whole new world, but there are many engineering problems which must be solved first. Actually, our rocket and spacecraft technology is still in the stage where engineering developments far exceed in cost and complexity the purely scientific developments necessary to carry out the missions.

As noted earlier, the spacecraft is required to move on a trajectory that is a section of an ellipse passing through both the Earth's orbit and the orbit of the target planet. The motions of Earth and planet are known from astronomical data. Therefore, the trajectory must be calculated so that the spacecraft will leave the Earth with the correct velocity and direction to arrive at the orbit of the target coincident with the target planet. A typical example of such a trajectory is shown in figure 3, which is the trajectory of the Mariner Venus probe. Since the motions of Earth and planet are determined, it is clear that launchings can take place only at limited times. Figure 4 shows these times for launchings to Mars and Venus; the exact length of the launch period at a permissible time depends upon the energy available with the launching rocket. Figure 5 illustrates the increase in energy as the launch day departs from the optimum; travel time is plotted against launch date for two types of trajectory and parameter C_3 is a measure of the spacecraft energy required.

Thus, we have one engineering constraint imposed on a planetary mission, namely a nonslippable launch schedule. On any one day in the launch opportunity there will be a short period of about 1 hour during which a launch may be conducted from Cape Kennedy. This constraint is determined by the permissible launch azimuths from the cape and the limitations of range instrumentation. The maximum flexibility is obtained by using a so-called "parking orbit" where the spacecraft is placed in a low Earth satellite orbit until it has traveled to an appropriate point on the Earth's surface, at which time it is accelerated up to its escape speed.

In order to attain the desired orbit, it is obvious that the spacecraft must be guided with a very high degree of accuracy. The launching rocket must be capable of being fired on a path which varies with the exact moment of launch and which places the spacecraft, together with the final stage rocket, on a predetermined satellite orbit. During the coasting phase of this orbit, the final stage rocket must be correctly oriented so that its thrust will be in the correct direction to achieve the desired final velocity. The exact instant of initiation of this final burning and the final velocity will likewise be determined by the moment of launching.

Theoretically, the launch-rocket guidance system could be made sufficiently accurate to attain the desired trajectory. However, in practice it is much more reasonable to place a somewhat relaxed requirement on the initial guidance and to carry aboard the spacecraft a small rocket which can be used to make a correction to the path.

This *midcourse* guidance requires a precise knowledge of the actual trajectory, which can be obtained by radio tracking stations on Earth and a calculation of the desired vector velocity change to bring the spacecraft on course. The spacecraft must then be maneuvered into a calculated attitude, and the rocket motor turned on to give the desired velocity change. Figure 6 illustrates such a maneuver, as used with the Mariner spacecraft. The requirement for accurate guidance, therefore, places additional constraints on the spacecraft. Its attitude must be controllable, it must carry a controllable rocket motor, and it must be able to accept radio commands.

A third class of constraints associated with a planetary mission is that associated with the vast distances to be traversed. A voyage to Venus requires about 3½ months and the spacecraft is 36 million miles distant from the Earth when it reaches the planet. To travel to Mars requires about 8 months, and the distance to the planet is more than 100 million miles. Hence, the spacecraft equipment must be designed to operate properly in the space environment for these long periods. Furthermore, it must be able to communicate over these distances of tens of millions of miles.

Because of obvious limitations of available power and antenna size, communication systems for planetary spacecraft must be designed to perform very close to ultimate theoretical capability. Even so, the information from a spacecraft near another planet is very low. Near Venus, Mariner provided only 8⅓ bits per second. Therefore, the scientific or engineer-

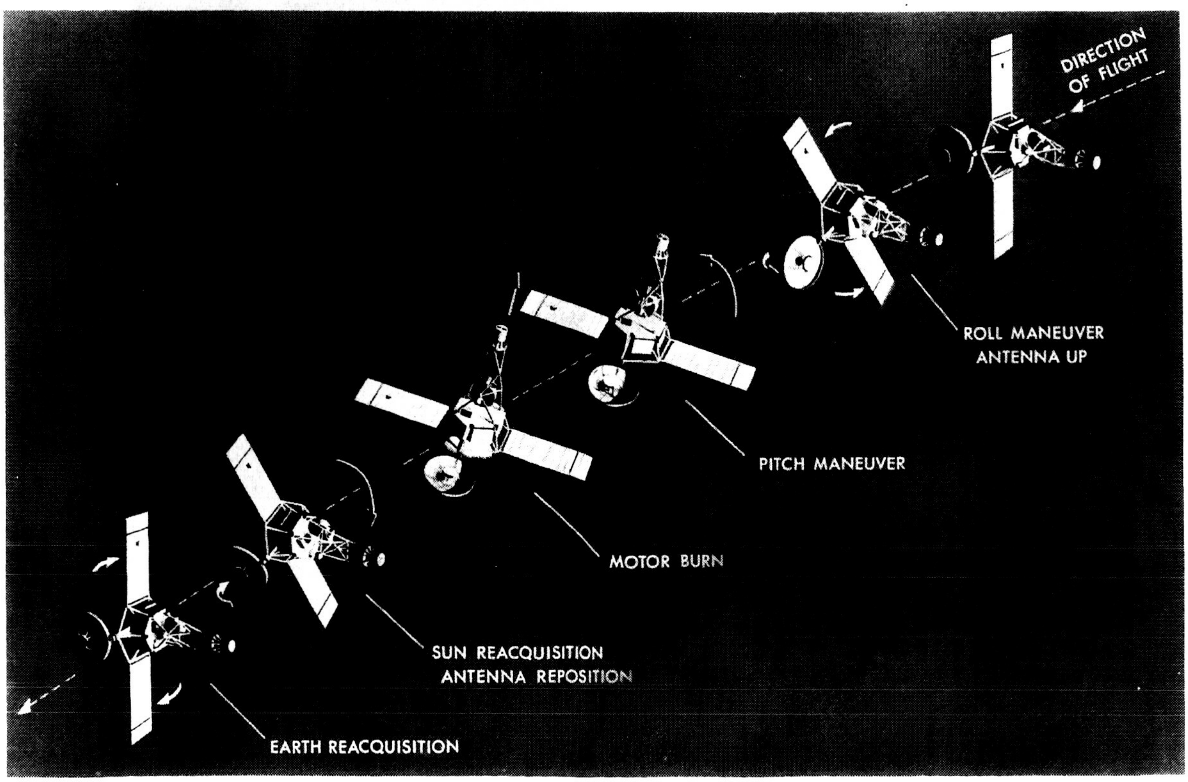

FIGURE 6.—Mariner midcourse maneuver.

ing data which is to be sent back to Earth must be carefully processed before transmission, and the rate at which a measurement is sampled must be kept as low as possible. In the Mariner shot to Mars at the end of this year, it is hoped to include a television system to take some closeup pictures of the planet. However, the low data rate (in this case, also, 8$\frac{1}{3}$ bits per second) requires that the pictures be stored and transmitted over a period of about 1 day for each picture.

The actual implementation of a planetary mission can be illustrated by the Mariner flight to Venus. The boost-rocket performance permitted a total spacecraft weight of 450 pounds. It was determined that guidance capability to fly by the planet within about 20,000 miles with communication capability to send a reasonable amount of scientific data back to earth was within the state of the art. A group of scientific experiments to provide both cruise data en route to the planet and planetary data while passing the planet were selected. The Jet Propulsion Laboratory was assigned the task. Figure 7 shows the result, Mariner II, which successfully carried out its mission.

It was obvious almost from the beginning of the Mariner project that the permissible weight would require very careful design of the structure and careful integration of all elements of the spacecraft into an optimum configuration. The structure selected was a hexagon with the spacecraft electronics distributed in boxes around the hexagon. One instrument, the magnetometer, had to be placed as far as possible from the electrical circuits, hence a lightweight tower structure above the hexagon carried this instrument.

A parabolic directional antenna was needed to communicate back to Earth. Since this had to be contained within the internal dimensions of the nose shroud of the launching rocket, it was conveniently nested at the base of the hexagon. A midcourse motor was needed to correct the course to the desired close encounter with Venus. This was placed along the axis of the spacecraft inside the hexagon.

Finally, solar cells were selected to generate electrical power during the flight. These cells covered two solar panels which could be folded up alongside the spacecraft during the launch phase. Hence, the

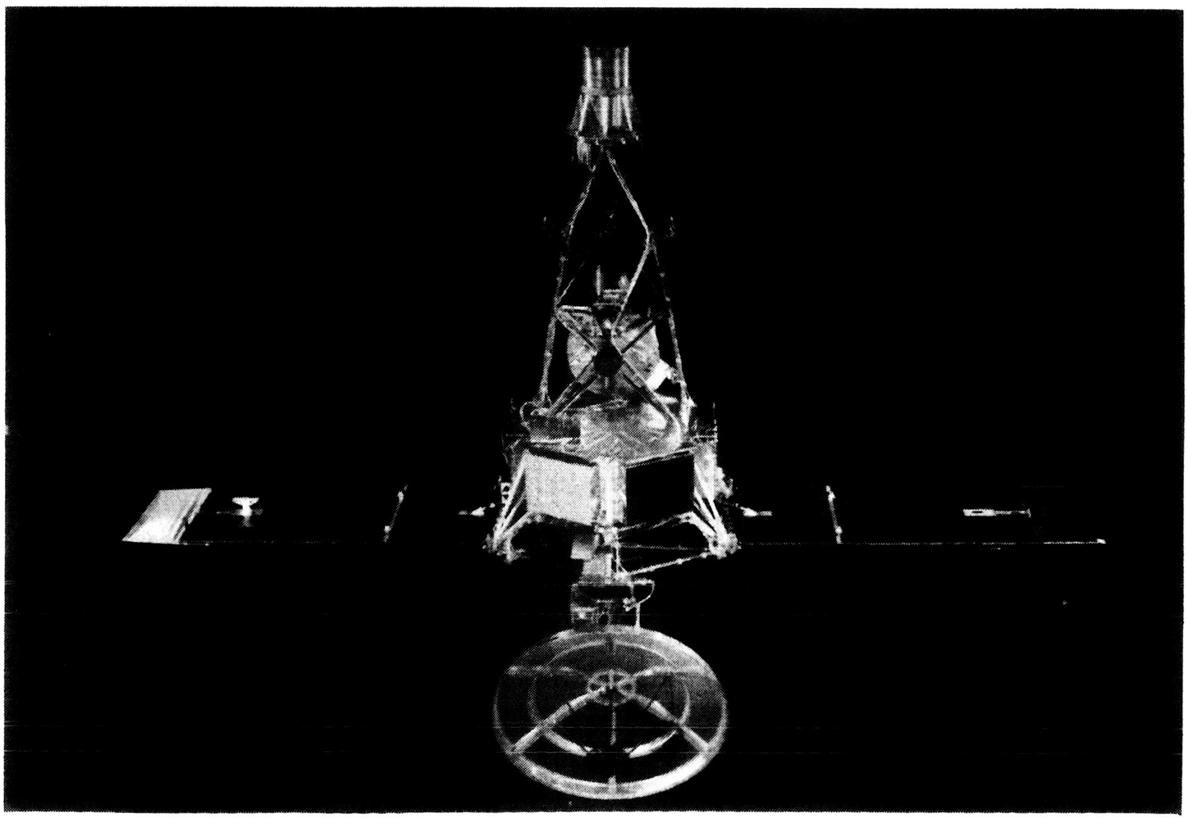

FIGURE 7.—Mariner II.

basic elements of the structure were defined. The scale of the device was adjusted to fit the Agena launching rocket, and the weight was constrained to be within the 450 pounds permitted.

Of the various subsystems making up the spacecraft, the science instruments can be divided into the cruise science and the encounter science. Cruise science included measurements of the interplanetary environment, radiations, magnetic fields, and micrometeorites. Encounter science added two infrared and 2-millimeter wave radiometers to scan the planet as Mariner flew past. These last instruments were mounted on a platform which was designed to scan about one axis so that the radiometers would sweep across the planet. Clearly the guidance accuracy had to be such that Mariner would pass the planet in a limited region where the instruments could collect data. Furthermore, the attitude stabilization had to be precise to ensure that the instruments would actually see the planet. A means had to be provided to switch on the encounter science experiments at the correct time. Actually, two switches were used, one turned on by an internal clock and the other by a radio command from Earth.

Data from the various science instruments had to be collected and processed for transmission to Earth. The various scientific and engineering measurements, about 100 in all, were, therefore, divided in a time-sharing scheme that sampled some measurements as frequently as once every 20 seconds and others as infrequently as once every 4 hours.

The communications subsystem consisted of a transmitter to send telemetry information back to Earth, a receiver to receive signals from Earth, and a decoder to

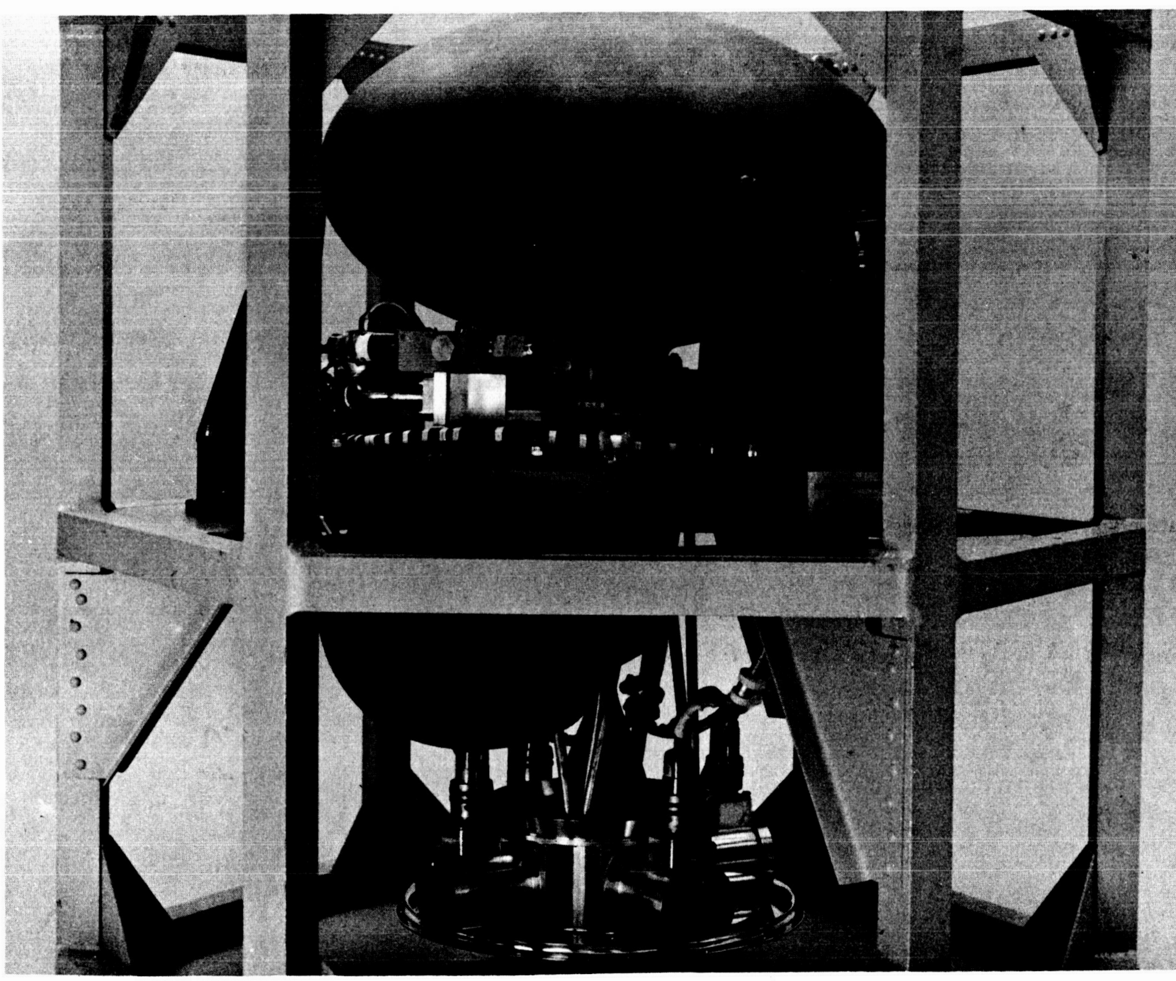

FIGURE 8.—Midcourse motor of Mariner II.

separate out command information from Earth. The transmitted signal was locked in frequency to an integral fraction of the received frequency, so that doppler information could be received on the earth. Three antennas were used: a command-receiver antenna, an omnidirectional-transmitter antenna, and a parabolic antenna which was kept pointed at the Earth except during spacecraft maneuvers.

The attitude stabilization system was used in two different ways. During the cruise period a Sun seeker kept the long axis of the spacecraft pointed at the Sun; an Earth seeker kept the axis of the parabolic antenna pointed at the Earth. In order to do this, the spacecraft rolled around the Sun axis, and the antenna hinge angle was adjusted to the correct value. Motion of the spacecraft was accomplished by small cold gas jets operated through a relay servosystem. During the midcourse maneuver, the attitude was measured and controlled by gyroscopes which were run up to speed shortly before the maneuver. When the rocket engine fired, jet vanes in the exhaust were used to develop appropriate correction torques.

Power for the spacecraft came from the solar panels. A battery was used during the launch phase and during the maneuver phase when the solar panels were not alined normal to the Sun. Because of the doubling of solar intensity between the Earth and Venus, the power system had to be designed with appropriate regulation and stability. The power consumption during cruise was about 150 watts.

The midcourse motor (fig. 8) was a monopropellant hydrazine motor with 50 pounds thrust, which could be run for periods as short as 2/10 second or as long as 57 seconds. The duration of motor burn during flight was determined by an integrating accelerometer which measured and compared the actual velocity change against the commanded velocity change.

One of the interesting engineering problems in a spacecraft is that of temperature control. In the vacuum of space, heat energy enters or leaves the spacecraft only through radiation. Hence, the radiating properties of the surfaces of the craft are vitally important. Mariner controlled the temperature throughout the vehicle by means of appropriate surface treatments. Paint patterns, aluminum sheet, gold plating, and polished surfaces were all used. Thermally controlled louvers were also used on one electronic box.

During the actual flight, the temperature control was not quite as good as expected. Temperatures were higher than anticipated, and towards the end many electronic components had exceeded their design temperatures. However, no serious difficulties occurred until about 3 weeks beyond the planet.

This brief description suggests some of the engineering problems which must be solved for a spacecraft of this type to fulfill its mission. It is clear that electronic devices are of tremendous importance. These devices fall into two broad classes: First, the various elements of the communication system, including the modulation circuitry required to convert instrument signals into an appropriate form for transmission and, second, the computing and other circuitry associated with the guidance problems.

Mariner demonstrated what can be done with modern electronic engineering. Much of the electronic design for the spacecraft grew directly from fundamental research done at the Jet Propulsion Laboratory during the past 10 to 15 years. As an example of the efficiency of modern communication systems, the transmitter on the Mariner spacecraft radiated only 3 watts of power, yet it successfully sent back data when it was more than 50 million miles from Earth.

On the Earth's surface, three receiving stations were

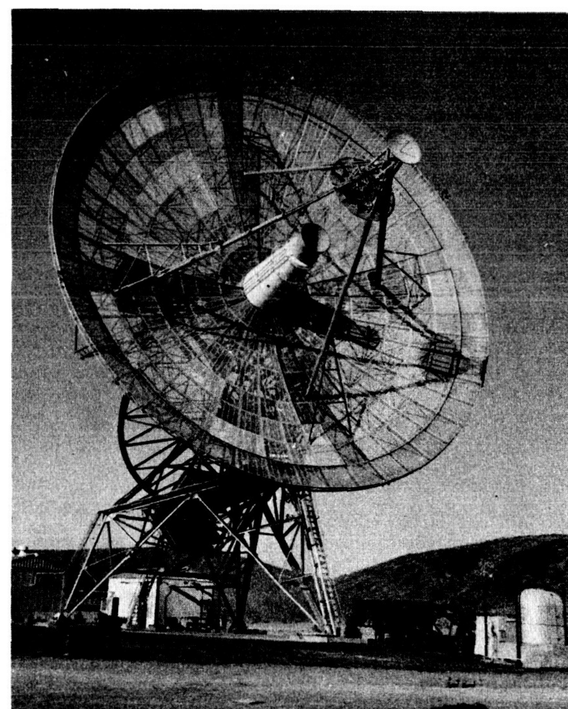

FIGURE 9.—Parabolic 85-foot antenna at Goldstone, Calif.

TABLE II.—*Illustrative communication systems*

	Earth satellite	Lunar orbiter	Lunar lander	Mars orbiter	Space probe
Range, km	4×10^3	4×10^5	4×10^5	4×10^8	4×10^{10}
Earth antenna gain, db	10^3	4×10^4	10^6	10^6	10^6
Vehicle antenna area, m^2	0.05	7	2.5	100	100
System temperature, °K	400	220	400	100	100
Vehicle radiated power, watts	200	50	10	150	150
Bandwidth (for S/N = 10^3 watts/watt), cps	4×10^6	10^6	10^6	2.5×10^3	2.5×10^{-2}

used. These employed 85-foot-diameter parabolic antennas located in California, South Africa, and Australia so that at least one station was always observing the spacecraft. Figure 9 is a photograph of one of the 85-foot antennas at Goldstone, Calif. Data from each station in the system are recorded on magnetic tape at the station and also sent to the central control point in Pasadena where they are decoded and presented in analog and digital form as necessary.

Table II illustrates the performance of typical space communication systems built with such equipment. The last line in the table gives the band-widths which

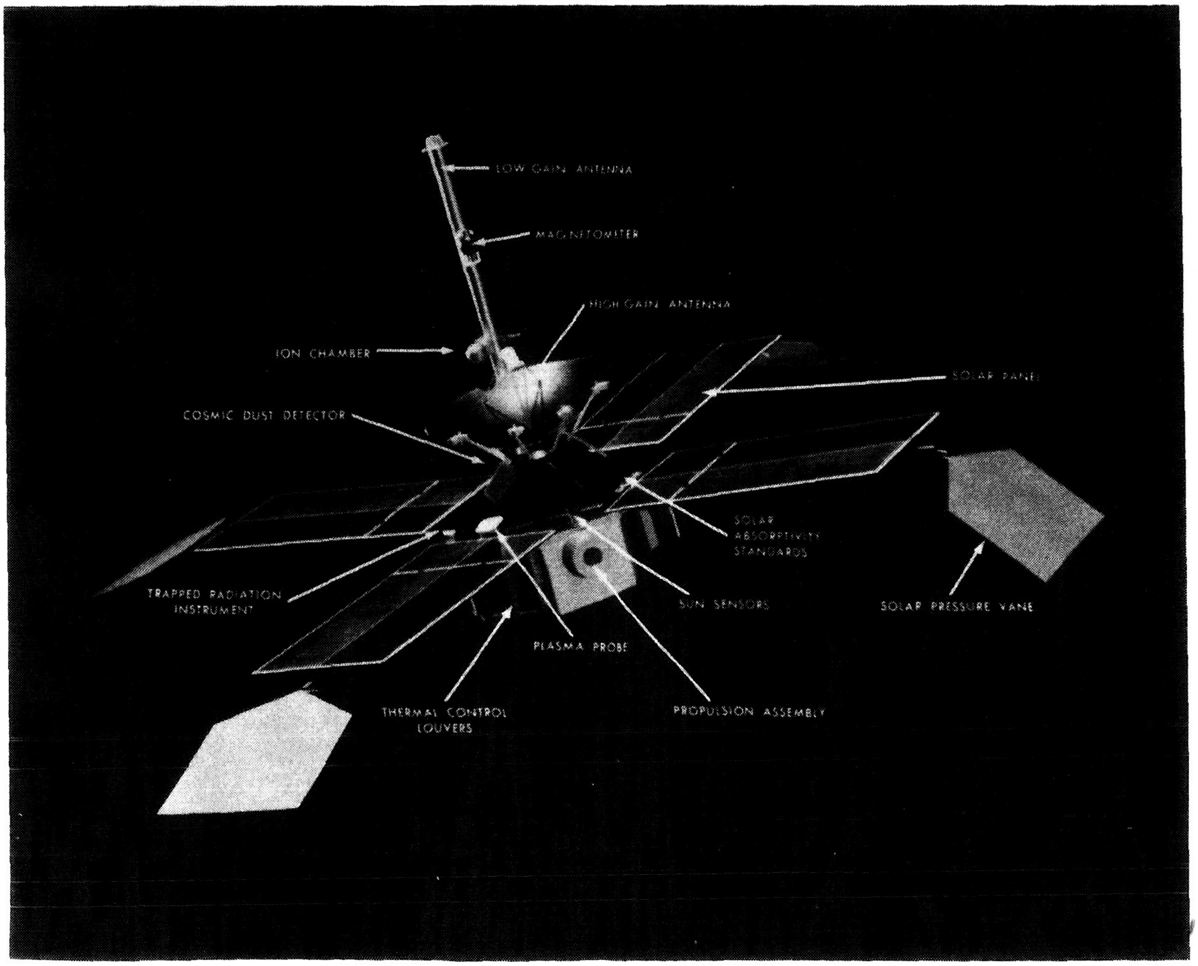

FIGURE 10.—Model of Mariner for November 1964 mission.

are attained using the parameters listed. It is obvious that television signals from the Moon can be obtained, and signals can be received out to the edge of the solar system.

As the next step in planetary exploration we intend to launch a Mariner spacecraft to the planet Mars during the opportunity in November of 1964. Figure 10 is a photograph of a model of the Mariner for this mission. It has a family resemblance to the Venus spacecraft but differs in several important details. For example, there are four solar panels, each carrying a solar vane at its outer edge. These solar vanes are designed to take advantage of solar radiation pressure to assist in stabilizing the vehicle. The vanes are connected to the attitude control system and operate in a manner similar to the trim tabs of an airplane. The high-gain antenna is fixed to the spacecraft structure. This can be done because the Sun-spacecraft-Earth angle remains nearly constant for a large part of the mission. The spacecraft is stabilized by using the Sun for one axis and the star Canopus for the other. The midcourse propulsion system is oriented at right angles to the Sun axis of the spacecraft instead of being directed along this axis as in Mariner II. The electronic components are distributed in boxes arranged on an octagonal structure. Thermal control is with light metal louvers which change the thermal radiating properties of the surface.

Figure 11 is a photograph of Ranger, our current lunar spacecraft. This particular version of Ranger, the Block III, is designed to take closeup television pictures of the Moon. Again the design is very similar to Mariner. The television cameras are con-

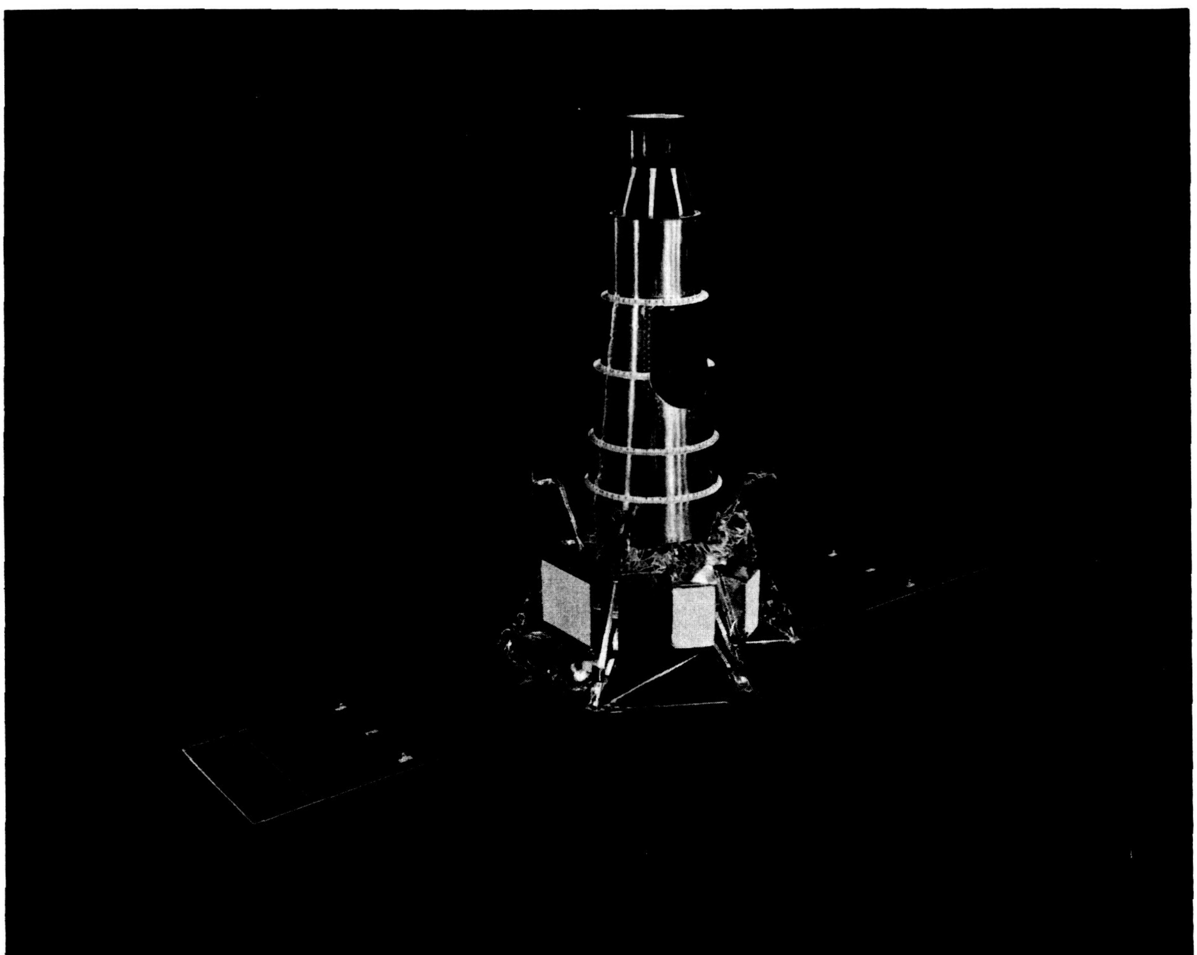

FIGURE 11.—Ranger.

tained in the conical structure above the hexagon. A set of six cameras, divided between two independent transmitters, looks out of the side of the cone. The spacecraft is oriented so that, on approaching the Moon, the cameras are looking along the velocity vector.

There are four Block III Rangers. The first, launched on January 30, 1964, succeeded in landing on the Moon very close to the specified target, as shown in figure 12. However, the television system failed, and no photographs were taken. The next in the series will be launched in the summer of 1964.

If we consider the broad problems associated with this unmanned exploration of the solar system, it is clear that the engineering design of systems which will meet the constraints of weight, volume, power consumption, and life in the space environment is most important. The next problem is that of manufacturing components and assemblies to meet the standards of performance and reliability required for these expensive missions. As we are able to solve these problems, so will we extend our knowledge far out beyond our Earth. This is the challenge which we face.

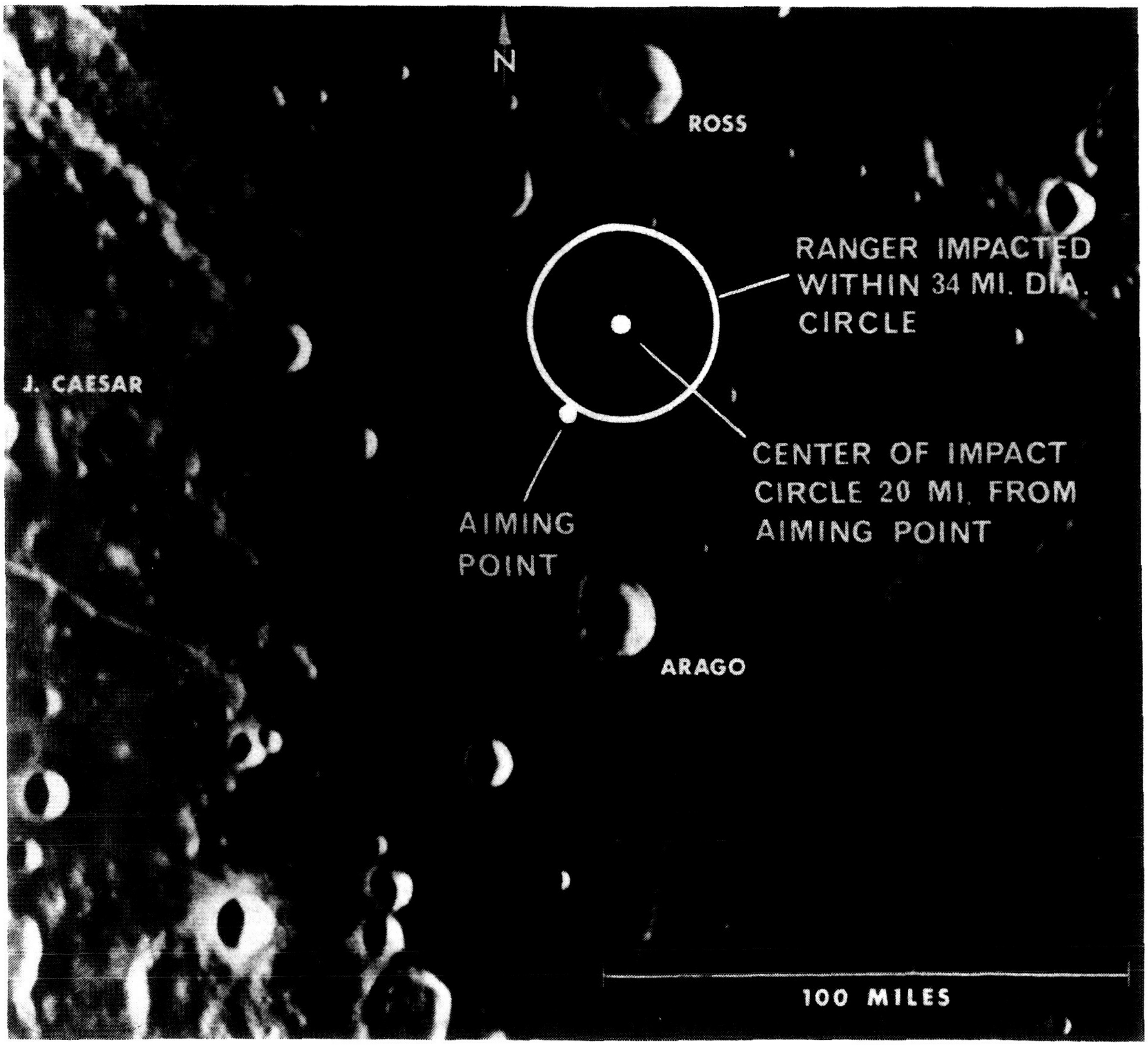

FIGURE 12.—Lunar landing area of Ranger, January 30, 1964.