Chapter 2
The Early Years

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It would be difficult to portray an accurate portrait of the Jet Propulsion Laboratory (JPL) spaceborne antennas without giving a brief introduction of how JPL got into the spacecraft business in the first place [1]. JPL started in 1936 as the Guggenheim Aeronautical Laboratory, California Institute of Technology (GALCIT) rocket project, a collection of six amateurs working for the eminent Hungarian-born professor, Theodore von Karman. During World War II they made fundamental breakthroughs in the theoretical and applied aspects of both solid- and liquid-propellant rocketry. The project developed into a full-fledged, permanent installation operated by the California Institute of Technology for the Army Ordnance Corps and was renamed the Jet Propulsion Laboratory in 1944. The laboratory's major responsibility was basic research in missile technology and the development of the country's first tactical nuclear missiles, Corporal and Sergeant.

It was this rocketry background that eventually lured JPL into space exploration. JPL teamed with the German V-2 group at White Sands, New Mexico in 1949 to launch the Bumper-WAC, the "first recorded man-made object to reach extraterrestrial space." JPL engineers speculated that it was possible to cluster some Loki rockets (a solid-propellant antiaircraft missile based on the Germans World War II Taifun) on a Corporal missile and land an empty beer can on the moon. (What? No antenna!)

Scientists won approval for a satellite as a United States' contribution to the 1957–58 International Geophysical Year. JPL became involved in Project Orbiter, a joint effort between the Army Ballistic Missile Agency (ABMA) and the Office of Naval Research (ONR). Orbiter's first stage would be an updated

Redstone missile, and the upper stages would be a scaled down version of the Sergeant rocket motors. Based upon proven technology, it almost certainly would have made possible a launch by August 1957. However, based primarily on the desire by then President Eisenhower for the space program to be nonmilitary, Project Orbiter was cancelled, and the go-ahead was given to the Naval Research Laboratory's Vanguard, a smaller rocket that was still under development.

However, JPL and ABMA found an institutional outlet for their Orbiter studies in the reentry test vehicle (RTV) that was claimed to test the nose cone for the Army's Jupiter intermediate-range ballistic missile. The nose-cone test missile would be launched above the atmosphere then point straight down and aim at the Earth. To counteract the intense heat encountered reentering the atmosphere at high velocity, ABMA planned to use a blunt ablation-type nose cone, in which the various layers burned away during reentry. The RTV was extraordinarily similar to Orbiter, only needing a forth stage rocket and payload to create a satellite. JPL's Orbiter electronics were readily adaptable to the RTV program. The laboratory's telemetry could send data back to the ground on the heating effects of the missile during flight, and its tracking mechanism made it possible to recover the nose cone at the end of the flight. The main JPL electronic contribution was Microlock, a phased lock loop tracking system that could lock to a very low-level signal. There were three launches of the system, with the third firing, on August 8, 1957 succeeding brilliantly. All major systems worked satisfactorily, and the nose cone was recovered at a range of 1,160 miles (1,870 km). After validating the design, the RTV project was terminated, and the several sets of flight hardware left over were put in controlled storage, from which it could be made flight ready in less than four months.

With the launch of Sputnik on October 4, 1957 President Eisenhower cautiously accepted the suggestion to use the army as a backup to Vanguard. Then, on December 6, 1957 under the hot glare of international television, Vanguard exploded and burned up on the launch pad. The go-ahead was then given to JPL and the ABMA to launch the first U.S. satellite. This culminated in the launch of Explorer I at 10:48 p.m. on January 31, 1958 using the Jupiter-C, which had already been flight-tested as part of the RTV program.

2.1 Explorer I

Explorer-I (see Fig. 2-1 and [2]) was placed in an orbit with a perigee of 224 miles (360 km) and an apogee of 1575 miles (2535 km) having a period of 114.9 minutes. Its total weight was 30.66 pounds (13.91 kg), of which 18.35 pounds (8.32 kg) were instrumentation. The instrument section at the front end of the satellite and the empty scaled-down Sergeant fourth-stage rocket casing

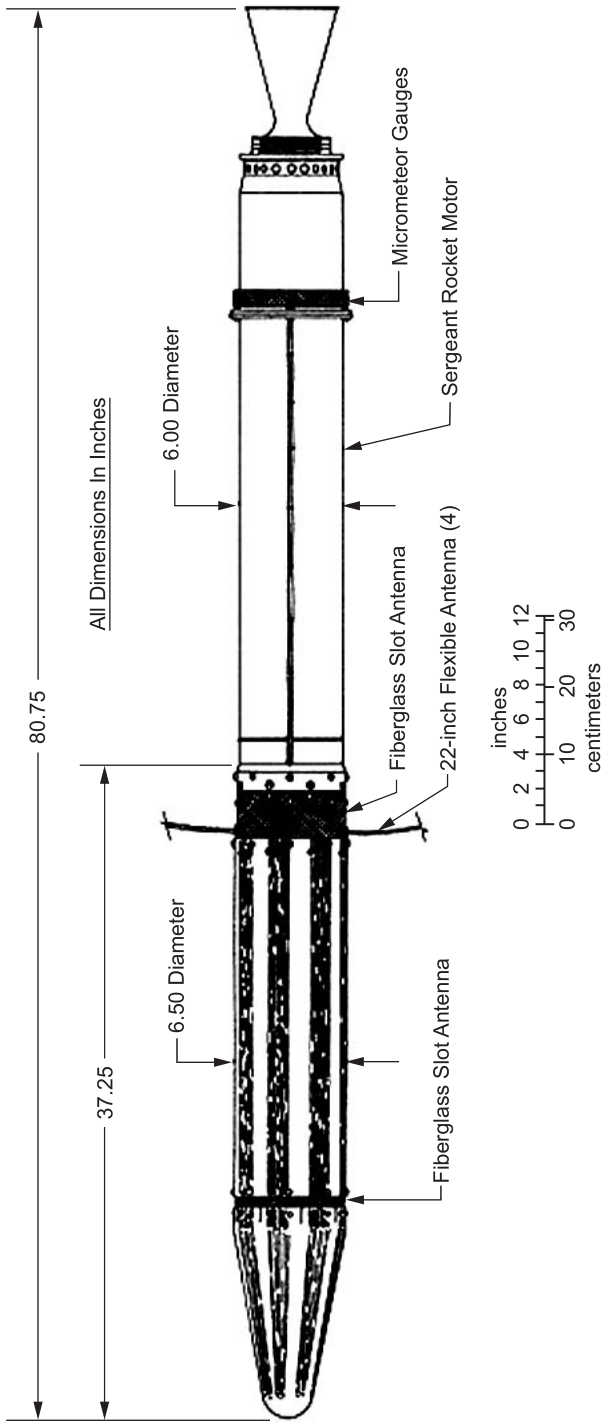


Fig. 2-1. Explorer I satellite schematic.

orbited as a single unit, spinning around its long axis at 750 revolutions per minute.

Instrumentation consisted of a cosmic-ray sensor, an internal temperature sensor, three external temperature sensors, a nose-cone temperature sensor, a micrometeorite impact microphone, and a ring of micrometeorite erosion gauges. The cosmic-ray sensor detects the penetration of high-energy atomic particles through the stainless-steel wall of the Geiger-Mueller tube.

A 60-mW transmitter operating on 108.03 MHz and a 10-mW transmitter operating on 108.00 MHz transmitted data from these instruments to the ground. Transmitting antennas consisted of two fiberglass slot antennas in the body of the satellite itself and four flexible whips forming a turnstile antenna. The rotation of the satellite about its long axis kept the flexible whips extended. The flexible whips caused instability in the attitude of the satellite and were deleted for subsequent flights.

The external skin of the instrument section was painted in alternate strips of white and dark green to provide passive temperature control of the satellite. The proportions of the light and dark strips were determined by studies of shadow-sun-light intervals based on firing time, trajectory, orbit, and inclination.

Nickel-cadmium chemical batteries, which made up approximately 40 percent of the payload weight, provided electrical power. These provided power that operated the high power transmitter for 31 days and the low-power transmitter for 105 days.

Because of the limited space available and the requirements for low weight, the Explorer-I instrumentation was designed and built with simplicity and high reliability in mind. It was completely successful.

Once in orbit, the cosmic ray equipment of Explorer-I registered at least a thousand times what had been expected; counts exceeded 35,000 per second at the highest altitudes, over South America, and saturated the Geiger-Muller counter. Dr. James Van Allen theorized that the equipment might have been saturated by very strong radiation caused by the existence of a belt of charged particles trapped in space by the Earth’s magnetic field. The existence of these Van Allen Belts, discovered by Explorer-I, was confirmed by Explorer-III, which was launched by a Jupiter-C on March 26, 1958. There were five Explorer launches in all, of which three were successful.

The discovery of the Van Allen Belts by the Explorer satellites was considered to be one of the outstanding discoveries of the International Geophysical Year.

2.2 Pioneers 3 and 4

With the President’s approval, on March 27, 1958, Secretary of Defense Neil McElroy announced that the Advanced Research Projects Agency (ARPA) space program would advance space flight technology and “determine our capability of exploring space in the vicinity of the moon, to obtain useful data concerning the moon, and to provide a close look at the moon" [3]. Conducted as part of the United States' contribution to the International Geophysical Year, the lunar project would consist of three Air Force launches using modified Thor ballistic missiles with liquid-propellant Vanguard upper stages, followed by two Army launches using modified Jupiter-C missiles and JPL solid-propellant upper stages. JPL was to design the Army's lunar probe and arrange for the necessary instrumentation and tracking. ARPA directed the Air Force to launch its lunar probes "as soon as possible consistent with the requirement that a minimal amount of useful data concerning the moon be obtained."

The ARPA lunar program approved in March 1958, generally known as the "Pioneer program," offered five flight opportunities, three for the Air Force and two for the Army. The three Air Force probes were called Pioneer 0, 1, and 2. Only Pioneer 1 was partially successful. The Pioneer 3–4 payload (Fig. 2-2) antenna is basically an unsymmetrically fed dipole built in the shape of a cone [4]. The antenna cone is 12 in. (30.5 cm) high and 9 3/8 in. (23.8 cm) in diameter with a 2 ¾-inch (7.0-cm) aluminum probe at its apex. The cone was fabricated of a cloth epoxy laminate 0.016 in. (0.04 cm) thick. Weight of the cone was 4.6 lb (2.1 kg). Metallization of the cone was accomplished by depositing a 0.0006-in. (0.0015-cm) coating of silver and then plating with gold on the outside of the cone. Electrically, the antenna had a characteristic impedance of 50 ohms and a gain of 3 ±0.5 decibels (dB). Vibration tests on the

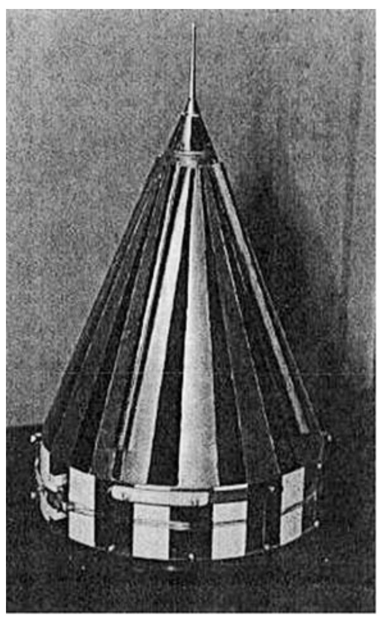


Fig. 2-2. Pioneer 4 antenna.

fiberglass cone at 20 g root mean square (rms) revealed several mechanical resonances. In order to provide the necessary mechanical rigidity, four longitudinal half-round external stiffeners and one internal bulkhead were added. Pioneer 3 was launched December 6, 1958 and transmitted 180 mW at 960.5 MHz. Because of a slight error in the satellite's velocity and angle after burnout of the Juno II rocket, it did not reach the Moon; instead it achieved a peak altitude of 102,320 km (63,580 miles). The satellite did, however, discover a second radiation belt around Earth during its flight. Pioneer 3 reentered Earth's atmosphere over equatorial Africa a day after launch. Pioneer 4 was launched March 3, 1959, and successfully passed within 60,000 km (37,300 miles) of the Moon the following day. The satellite was tracked for 82 hours to a distance of 655,000 km (407,000 miles) from Earth, a record at that time. Pioneer 4 is now orbiting the Sun, the first U.S. spacecraft placed in solar orbit and the first to escape the Earth’s gravitational field. Pioneer 3 was the original object tracked by the first Deep Space Network (DSN) antenna, which was appropriately named the Pioneer antenna [5].

2.3 Project Ranger

Pioneer 4 was the last of the ARPA-initiated lunar probes. By mid-1958 responsibility for a coherent program of civilian space research had been vested in the new National Aeronautics and Space Administration, familiarly known as NASA. JPL was mandated by NASA to conduct unmanned “deep space” exploration—research at lunar distances and beyond. By the end of 1959, NASA specifically directed JPL to undertake a series of unmanned lunar missions. Actually, many JPL engineers and scientists tended to favor investigating the planets and space medium ahead of the Moon. However in 1959 and 1960, NASA did not have a reliable launch vehicle capable of planetary missions. The decision was to adopt the Atlas-Agena B as NASA’s interim launch vehicle until the larger Atlas-Centaur rocket, capable of an interplanetary launch, became available in 1962. It was deemed mandatory that NASA acquire early experience with the next generation of American spacecraft for deep-space missions—vehicles attitude stabilized on three axes and guided by means of midcourse and terminal (lunar or planetary approach) maneuvers—before trying to develop still larger spacecraft. The Ranger project was to launch probes directly toward the Moon. The craft were designed to relay pictures and other data as they approached the Moon and finally crash-landed into its surface. Although the first attempts failed, the later Rangers were a complete success [6].

JPL had been working on a Martian spacecraft, but the Juno IV program was cancelled in October 1958. However, the fundamental design elements of a planetary spacecraft were formulated. To communicate adequately from planetary distances, the spacecraft would require a high-gain antenna (HGA, a reflector antenna or "dish") mounted and hinged so as to point continuously at the Earth. On the ground, sensitive receivers, powerful transmitters, and very-high-gain ground antennas would complete the circuit. All the while, the spacecraft antenna would have to be kept pointing in the right direction through an appropriate method of stabilizing the attitude of the spacecraft itself. Spinning the vehicle along its roll axis had stabilized both the Explorers and Pioneers. For flights to the planets, it was deemed necessary to have complete control of the spacecraft in all three axes, roll, yaw, and pitch. This would ensure precise pointing of the experiments and the antenna, and it would maximize solar power collection and thermal control. With full attitude control, igniting a rocket engine on board in a "midcourse maneuver" could also refine the flight trajectory of a planetary spacecraft. A small rocket would be able to compensate for minor guidance errors introduced by the launch vehicle, thus permitting the spacecraft to approach more closely or even hit a celestial target. In addition to the features of an HGA and full attitude stabilization, the spacecraft would be designed so that its longitudinal axis would point continuously toward the Sun (except during midcourse or terminal maneuvers), since it was uncertain whether the Earth could be "seen" by onboard sensors at planetary distances. This decision simplified the problem of maintaining thermal equilibrium on the spacecraft and permitted the use of solar cells on fixed panels as a primary source of electrical power.

When NASA decided to emphasize the lunar objective in July 1959, JPL did not abandon the Martian spacecraft. They preferred to stick with it even though on a 66-hour flight to the Moon batteries could suffice in place of solar panels, and an HGA was unnecessary for communicating to a distance of 400,000 km (a quarter million miles). Adapted to lunar missions, the HGA, instead of being used for long-range, narrowband communication would now be used for relatively wideband transmission such as television at lunar distances. The bus and passenger concept, three-axis attitude stabilization, and solar power, its designers reasoned, could be used to develop the technology required for the planetary flights postponed to 1962.

Ranger was originally designed in three distinct phases, called "blocks." Each block had different mission objectives and progressively more advanced system design. The JPL mission designers planned multiple launches in each block, to maximize the engineering experience and scientific value of the mission and to assure at least one successful flight [7].

Block 1, consisting of two spacecraft launched into Earth orbit in 1961, was intended to test the Atlas/Agena launch vehicle and spacecraft equipment without attempting to reach the Moon.

Block 2 of the Ranger project launched three spacecraft to the Moon in 1962, carrying a television camera, a radiation detector, and a seismometer in a separate capsule slowed by a rocket motor and packaged to survive its low-speed impact on the Moon's surface. The three missions together demonstrated good performance of the Atlas/Agena B launch vehicle and the adequacy of the spacecraft design, but unfortunately not all on the same attempt.

Ranger's Block 3 embodied four launches in 1964–65. These spacecraft boasted a television instrument designed to observe the lunar surface during the approach; as the spacecraft neared the Moon, they would reveal detail smaller than the best Earth telescopes could show, and finally details down to dishpan size.

The first of the Block 3 series, Ranger 6, had a flawless flight, except that the television system was disabled by an in-flight accident and could take no pictures. The next three Rangers, with a redesigned television, were completely successful. Ranger 7 photographed its way down to target in a lunar plain, soon named Mare Cognitum, south of the crater Copernicus. It sent more than 4,300 pictures from six cameras to waiting scientists and engineers.

The problem of providing antennas for the Ranger spacecraft involved two general requirements [8]. The first requirement was to provide a high-efficiency communication link for telemetry, to be utilized for the later portions of the Ranger flight. This function demanded a high-gain, vehicle-mounted antenna that could be directed toward the Earth. However, there are times when an HGA is incapable of being-oriented toward the Earth: (1) before the spacecraft is stabilized in space; (2) during the period when the spacecraft is undergoing its midcourse maneuver; and (3) any time when the spacecraft is in a failure mode such that the HGA cannot be pointed toward Earth.

A second type of antenna is required to accommodate such situations, incorporating "quasi" omnidirectional pattern characteristics. With such a radiation pattern, communications can be provided almost independently of the spacecraft orientation. However, this increased pattern coverage is obtained at the penalty of reduced antenna performance. This antenna can be used for telemetry purposes during the early portion of the spacecraft flight, when the spacecraft is undergoing attitude stabilization and during the period of midcourse maneuvers. When this antenna is used for long-distance communication, it provides low information bandwidth.

Therefore, there are basically two antennas systems required. An omnidirectional system providing telemetry coverage during the early portions of the flight, and an HGA system, giving required science communication-system performance during the long-distance phases of the flight.

A third requirement is the capability of receiving commands sent to the spacecraft. Since one of the purposes of the ground command system is to override various spacecraft-generated commands or maneuvers when the spacecraft malfunctions, it is necessary to get commands through to the spacecraft no matter what the spacecraft orientation happens to be. This means that an omnidirectional antenna is required for command purposes. Since there is already an omni antenna aboard for telemetry, it is logical to use it to satisfy the omnidirectional command requirement. A diplexer is needed to allow both the transmitter and receiver of the spacecraft transponder to operate on the same omni antenna.

The antenna system must have a rotary joint to point the HGA back at the Earth through two degrees of rotational freedom. One degree of freedom is obtained by rolling the spacecraft on its axis. The second degree of freedom results from moving the antenna relative to the spacecraft. This means the transmission line, which connects between the antenna and the spacecraft communication pan, must have bending capability. The best way to meet this requirement is to use a rotary joint.

2.3.1 High-Gain Antenna System

The original constraints imposed on the HGA system were that its maximum size would be 4 ft (1.2 m) in diameter, and the weight of the reflector and feed structure should be less than 10 lb (4.5 kg). The HGA was a 4-ft (1.2-m) paraboloidal reflector, with a focal length-to-diameter ratio of 0.35 (Fig. 2-3). The reflective surface of the dish consisted of ¼-in. (0.63-cm) square

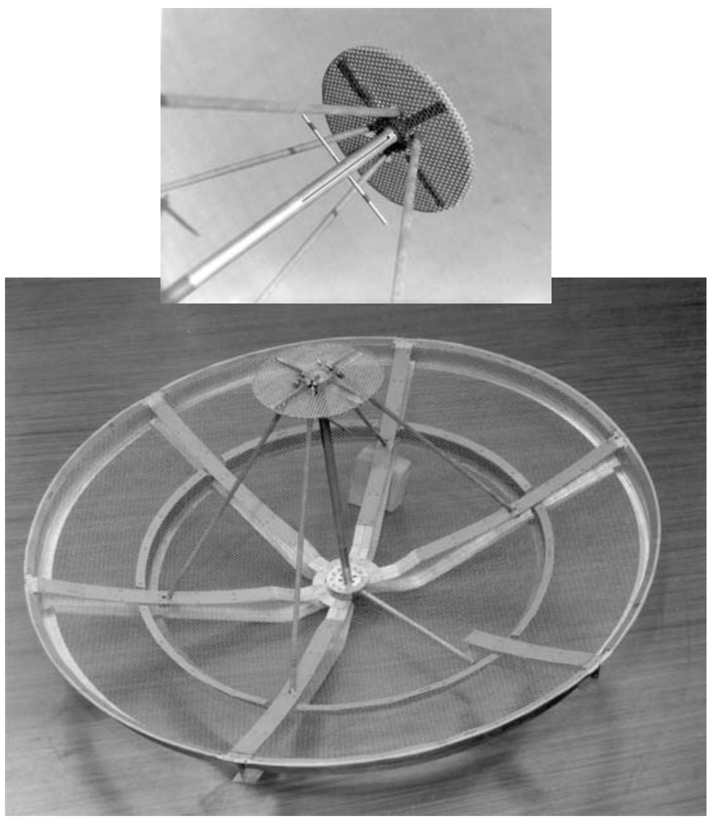


Fig. 2-3. Rangers 1 through 5 high-gain antenna.

mesh. This mesh was supported by a structural system consisting of six radial arms and three concentric hoops. The feed for this antenna consisted of a dipole mounted 1/4 wavelength in front of a 9-in. (23-cm) diameter ground plane. For the first five Ranger spacecraft, a linear polarized radiator was chosen for simplicity; it matched the polarization of the omni antenna. For this particular configuration, the antenna was slightly defocused. Displacing the feed from the nominal focus has certain advantages. With the feed at the focus of the reflector, very sharp nulls were produced at either side of the maximum lobe whenever there was no phase variation in the illumination of the antenna aperture. By slightly moving the antenna and causing a variation in the phase of illumination, these nulls fill in, and therefore provide additional reliable angular coverage when the antenna is not closely directed toward the Earth. This advantage, however, can be utilized only during the early portions of the spacecraft flight when there is a sufficient signal margin. The performance parameters for the antenna were as follows, all measurements being made at 960 MHz: The voltage standing wave ratio was 1.1 to 1. The half-power beamwidth in the E plane was 17½ deg and in the H plane it was 15½ deg. The 1-dB beamwidth in the E plane was 10.5 deg and in the H plane was 9.5 deg. The highest side lobe level in the E plane was down by 22.5 dB, whereas in the H plane it was down by 16 dB. The gain of the antenna was 19.5 dB. The Ranger E-plane and H-plane antenna patterns are shown in Fig. 2-4.

The matching section of the antenna system consisted of a quarter-wave coaxial transformer located approximately 1 in. (2.54 cm) below the balun slot (toward the base of the reflector). The balun slot itself was resonant at 0.454 wavelength or 5.587 in. (14.19 cm). The final length of the dipole element was 6.25 in. (15.9 cm) over-all, and it was spaced 3.13 in. (8.0 cm) from the 9-in. (23-cm) diameter ground plane.

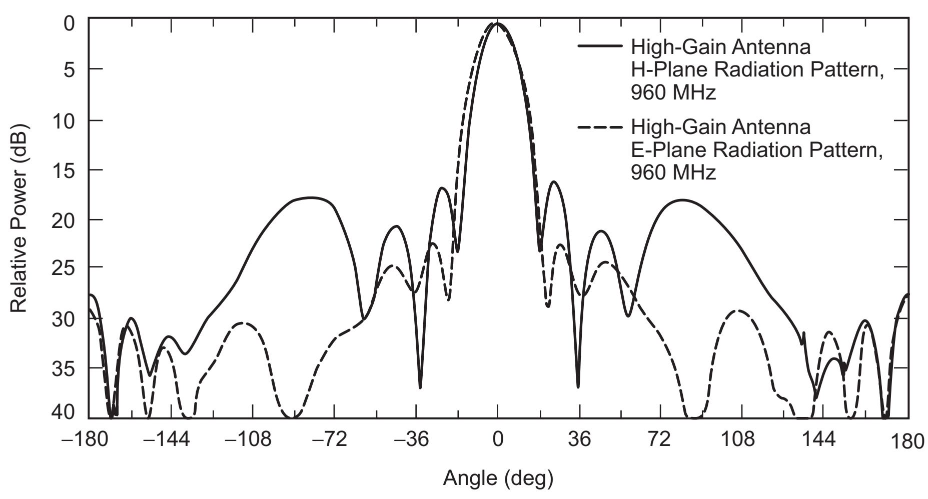


Fig. 2-4. Rangers 1 through 5 high-gain antenna patterns.

Since this feed was driven from an unbalanced coaxial transmission line, and the feed was a balanced type of antenna, some type of balun was required. The balun type selected consisted of a one-half wavelength axial slot cut into either side of the outer conductor of the coaxial transmission line, thus splitting the outer conductor into two halves. Half of the way along the slot, one side of the outer conductor was shorted to the center conductor of the coaxial transmission line; the dipole feed was driven at this point. The 9-in. (23-cm) ground plane was mounted onto the outer end of the balun slot. The other end of the balun slot became the coaxial transmission line, which ran from the feed area down to the base of the reflector. The feed structure position was stabilized by a fiberglass quadripod.

For Rangers 6 and 7 it was decided to use a circular polarized HGA. In order to circularly polarize the antenna, the ½-wave dipole on the feed of the antenna used for Rangers 1 through 5 was replaced by a turnstile (two crossed dipoles). The dipoles were of unequal length to get the 90-deg shift required for circular polarization. Since the turnstile changed the impedance of the HGA, the ¼-wave matching transformer required redesign. This involved changing the diameter and location of a ¼-wavelength enlarged section of the center conductor of the coaxial transmission line. Some mirror modifications were made to the reflector structure to enhance the reliability of the reflector surface and the focus was adjusted. With the HGA right-hand circularly polarized, its performance was essentially the same as the antenna used for Rangers 1 through 5.

2.3.1.1 High-Gain Antenna Development for Rangers 8 and 9. The performance required of the HGA for Rangers 8 and 9 was the same as that for Rangers 6 and 7 at 960 MHz. However, Rangers 8 and 9 carried an S-band communication and tracking experiment, and it was required that an HGA be used with the S-band experiment. Because it was not feasible to put a second HGA on the spacecraft, the decision was made to broadband the existing antenna to cover the S-band frequencies, as well as the 960-MHz frequency. A design was borrowed from the Mariner program (Fig. 2-5). The reflector was the same as that used for Rangers 6 and 7. The major difference was in the feed design and the feed support structure. To meet the bandwidth requirement for the feed, a conical spiral periodic antenna structure was used. Since this type of antenna has to be fed at the small end of the cone, by a balanced line with an impedance of over 100 ohms, a broadband balun transformer was required to connect the antenna to the 50-ohm unbalanced coaxial line. The design used consisted of a coaxial line, which had been peeled open so the end was transformed into a twin line. Since the impedance on the twin line end was higher than that of a closed coaxial line, and also was a function of the width of the twin line, this type of balun could be used to give the required impedance transformation.

Fig. 2-5. Rangers 8 and 9 high-gain antenna.

During the development of this broadband feed, it became apparent that conducting material in close proximity to the feed was highly undesirable. Therefore, the final configuration incorporated a dielectric feed-support structure. Gain measurements versus focal distance (Fig. 2-6) of the original Mariner (a high-gain broadband antenna) indicated that the minimum distance for good operation at all three frequencies required (960, 2113, and 2295 MHz) was about 22 in. (56 cm). This focal distance was also the maximum allowable feed protrusion into the Rangers 1 through 7 sterilization diaphragm without requiring a change to that structure.

2.3.1.2 Rotary Joint. Two different types of rotary joints were required for the *Ranger* program. The rotary joint for Rangers 1 through 7 was required to operate at 960 MHz only; and, therefore, it was a single-frequency design. The rotary joint used for Rangers 8 and 9 had to pass 960 MHz and S-band, since the HGA would be operating both at 960 MHz and at S-band. Since there were no commercially available rotary joints adequate for a space environment, JPL developed a suitable rotary joint. The basic configuration chosen was a rotary joint with radio frequency (RF) chokes since this technique eliminates any metal-to-metal relative motion joints at low impedance levels, which could cause seizing of the rotary joint or could cause noise because of corrosion or dirt in the joint. The conventional joint, where the relative motion was taken through fingerstock, was eliminated at the start since it was believed that the fingers could conceivably weld to the mating portion of the joint. The choke for the center conductor of the rotary joint consisted of an open-circuit ¼-wavelength choke. It reflected the high impedance at the open end of the choke into very low impedance at the point where the ¼-wavelength choke entered the transmission line. The choke in the outer conductor was a shorted

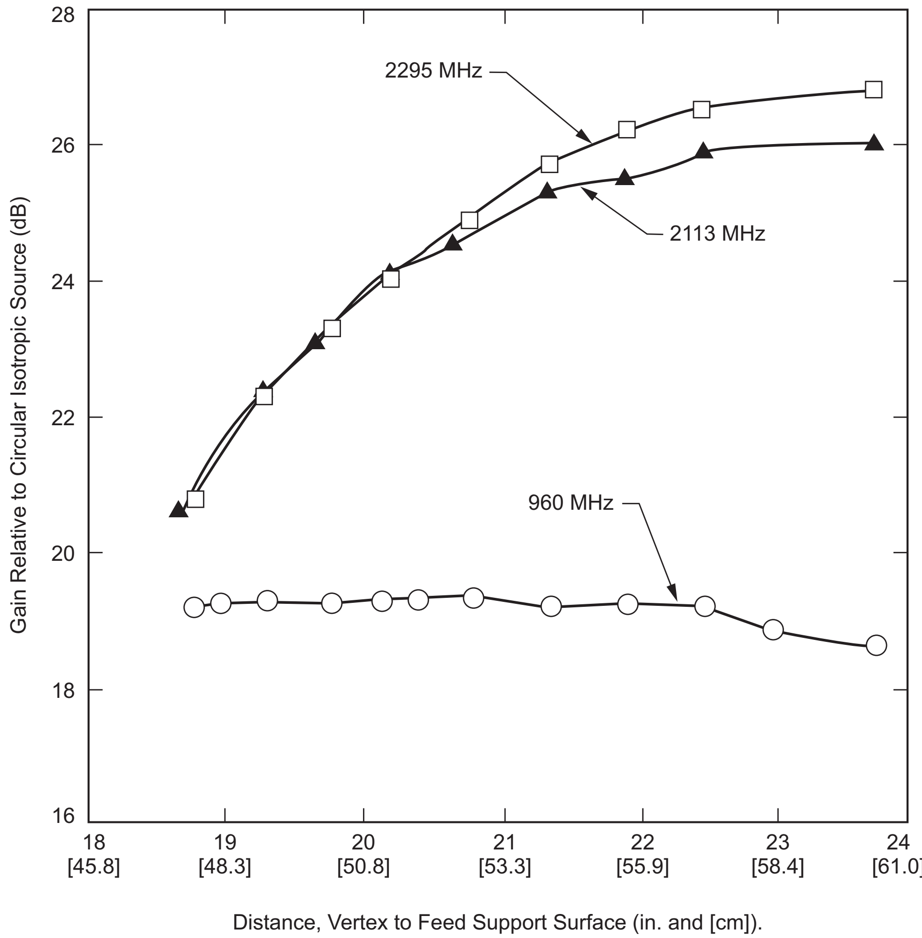


Fig. 2-6. Rangers 8 and 9 high-gain antenna gain versus feed position, fiberglass struts.

½-wavelength choke; the short was reflected through ½ wavelength into a short at the point where the choke entered the transmission line at the outer conductor. The only metal-to-metal contact in the rotary joint occurred in the center of this ½-wavelength choke. However, this was not critical since at this point the choke was at a very high impedance level, and noisy or erratic performance would be greatly attenuated by transformation through ¼ wavelength down to the point where the choke intercepted the outer conductor.

It was desired to optimize the performance of the rotary joint at the spacecraft transmitting frequency. However, sufficient broadbanding was included so the rotary joint could be used at the receiving frequency in case a two-way system ultimately was needed. Considerable effort was expended designing the bearing system of the rotary joint. Due to the low expected angular rates of the antenna, the rotary joint was designed with dry bearings. This eliminated the problem of lubricants and the probability that the lubricants would evaporate in a vacuum environment. The selection of the bearings for the rotary joint was complicated for several reasons:

1) Due to the size of the rotary joint, conventional ball bearings would not fit.
2) Lubrication of conventional bearings would be difficult because of the basic requirement that the rotary joint could not be pressurized.
3) The bearings within the coaxial section of the rotary joint itself could not be allowed to degrade the electrical performance of the joint.

In the final design, one main bearing was used at the rotating end of the joint and was located in the center of the ½-wavelength outer choke (Fig. 2-7). This arrangement consisted of a sleeve bearing with silicon copper running on

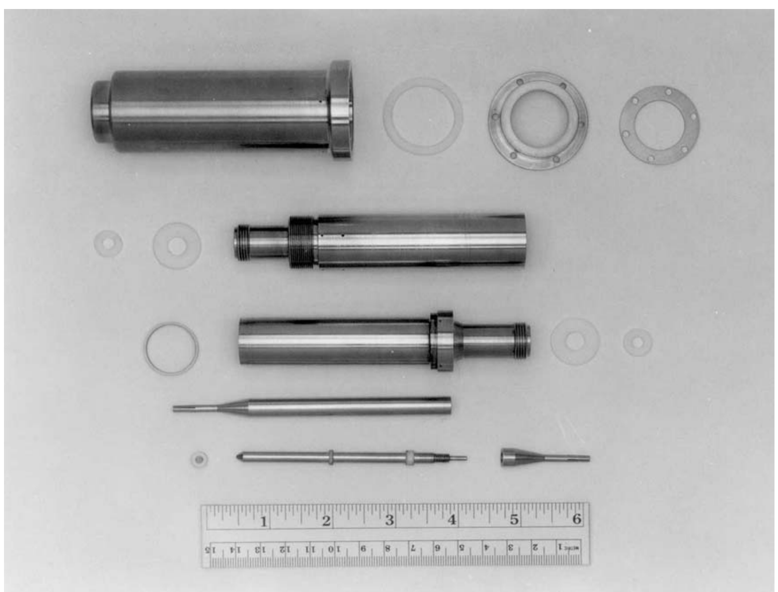


Fig. 2-7. Prototype rotary joint, disassembled.

303 stainless steel, with a molybdenum disulfide dry lubricant. A tungsten carbide needle bearing, running dry in an aluminum oxide ceramic jewel, carried the axial loads of the rotary joint in a compressive direction. This bearing was located within the ¼-wavelength open-circuit choke, which was within the center conductor of the rotary joint. A 303 stainless-steel collar on the sleeve bearing kept the rotary joint from separating in the axial direction. To maintain the concentric tubes of the joint in line, aluminum oxide spacers were used. Aluminum oxide was ideal in this application because it has low RF losses and is a very hard material. The design approach on the bearings was conservative due to the lack of information on bearing performance at extremely low pressures.

The final version of the rotary joint was 5-1/2 in. (14 cm) long and 1-3/8 in. (3.5 cm) in diameter and weighed 0.99 lb (0.45 kg) (Fig. 2-8). The chokes in the rotary joint were determined to be quite broad, providing a voltage standing wave ratio (VSWR) of less than 1.1 over a frequency range of 770 to 1000 MHz. The insertion loss turned out to be 0.05 dB at 960 MHz, and the wow was within 0.01 dB (the measuring accuracy of the insertion loss measurement).

2.3.1.3 Rotary Joint for Rangers 8 and 9. Since on Rangers 8 and 9 an S-band experiment was to be flown that would use the HGA, the rotary joint had to be redesigned to handle not only the 960 MHz, but also 2295 MHz (which was the S-band transmitter frequency) and 2113 MHz (which was the S-band transponder receiver frequency). See [8] for further details on the rotary joint redesign.

Fig. 2-8. Flight RF coaxial rotary joint.

2.3.2 Omni Antennas

The basic requirement of an omni antenna is to provide coverage over as large an angular region of space as possible. This provides for communication if the spacecraft is not properly oriented, or it allows the spacecraft to assume different attitudes in flight. The Ranger spacecraft required omni communications within 40 deg to 140 deg of the spacecraft roll axis and for any angle about the roll axis.

Constraints were imposed on the spacecraft to help meet this communication requirement. One such constraint was that no spacecraft hardware could lie within the specified communication angle. A second was that the bulk of the spacecraft below the antenna should appear symmetrical. A number of antenna configurations were considered and evaluated (Fig. 2-9), and these configurations included a sleeve dipole, a ¼ wavelength stubbed cone, and a disc-cone antenna.

To meet the requirement that the spacecraft should not interfere with the antenna field of view, the only location acceptable for the antenna was above the spacecraft, on its roll axis. It was in this location that the above configurations were tested. To maintain the requirement that the spacecraft appear symmetrical and to control the points where reflections could originate, a diffraction structure or ground plane was used to isolate the antenna from the spacecraft.

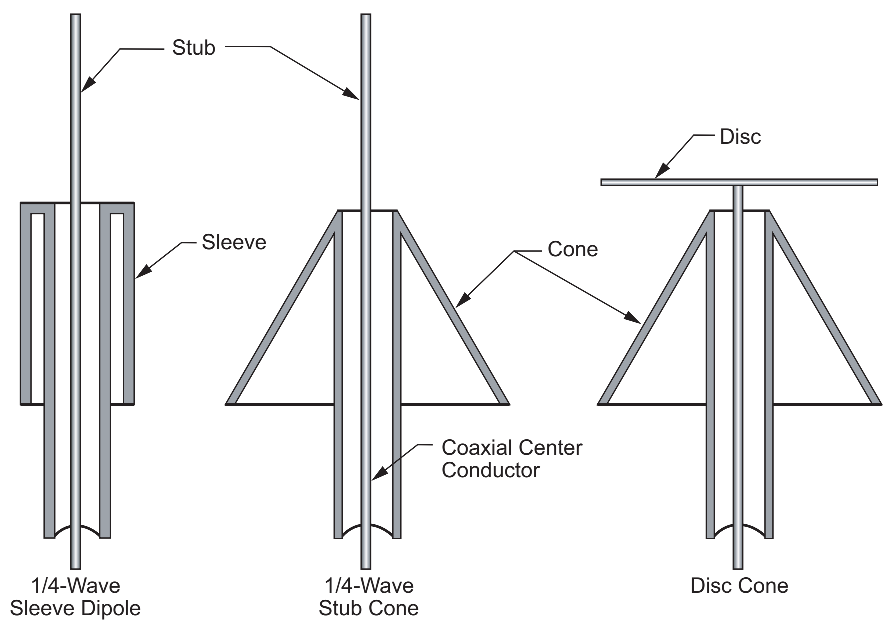


Fig. 2-9. Omnidirectional antenna types.

The disc-cone antenna was selected because it was sufficiently broadband to handle both the 890 and 960 MHz, and it had a lower silhouette, thus allowing it to be mounted higher while still providing a shorter all-around spacecraft system. This antenna was found to be versatile, since there are many parameters (the length and the angle of the cone and the diameter of the disc) that can be used to vary the pattern shape. The pattern shape of a disc-cone antenna with a ¼-wavelength diameter disc and a ¼-wavelength cone is similar to that of a dipole. Tests made with the Ranger disc-cone antenna indicated that the radiation could be directed toward the aft end of the antenna when either the cone angle was made smaller (i.e., going from an 80-deg to a 60-deg cone), or if the length of the cone was increased. Increasing the diameter of the disc to more than ¼ wavelength shifted the pattern toward the forward end of the antenna. It was found that a combination of increasing the length of the cone and increasing the diameter of the disc provided the required pattern coverage. The final configuration used a disc approximately ¾ wavelength in diameter and a cone approximately ½ wavelength long with an angle of 80 deg. The pattern of a full-scale disc-cone without the spacecraft is shown in Fig. 2-10.

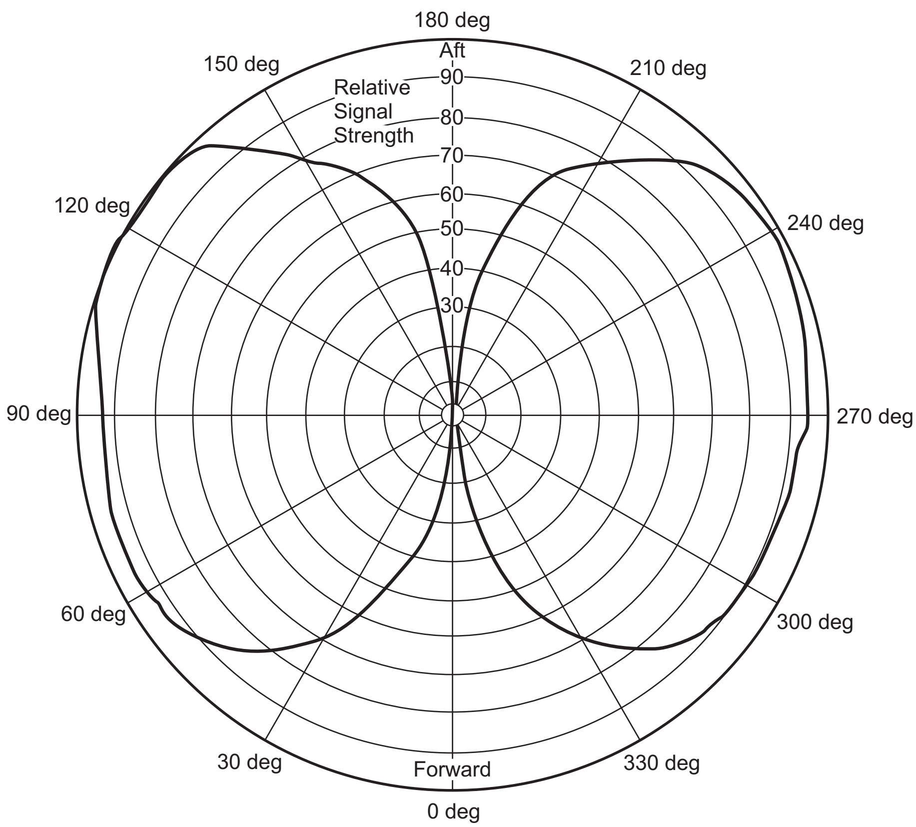


Fig. 2-10. Full-scale disc-cone antenna pattern.

Next, measurements were made to determine the effect of a diffraction disc on the disc-cone antenna pattern. It was found that the diffraction disc had an appreciable effect on the resultant pattern of the disc-cone antenna. Depending upon the position of this disc, a pattern could be produced which was predominately forward-directed or aft-directed. It was found that a 16-in. (41-cm) diameter diffraction disc placed 16 in. (41 cm) from the forward end (i.e., the disc) of the antenna gave the best results (Fig. 2-11). By comparing with the previous pattern (Fig. 2-10), it can be seen that the disc caused approximately a 1-dB dip at the equatorial plane of the pattern, and somewhat reduced the energy radiated toward the aft end of the antenna. In order to determine whether the effect of the diffraction disc could be minimized, absorbers were mounted on the side of the diffraction disc facing the antenna. It was found that the absorber only had a small effect on the diffraction disc. Since the absorber would add considerable weight to the antenna and would provide mechanical problems, the small increase in antenna performance was not sufficient to warrant its use. The prototype antenna is shown in Fig. 2-12.

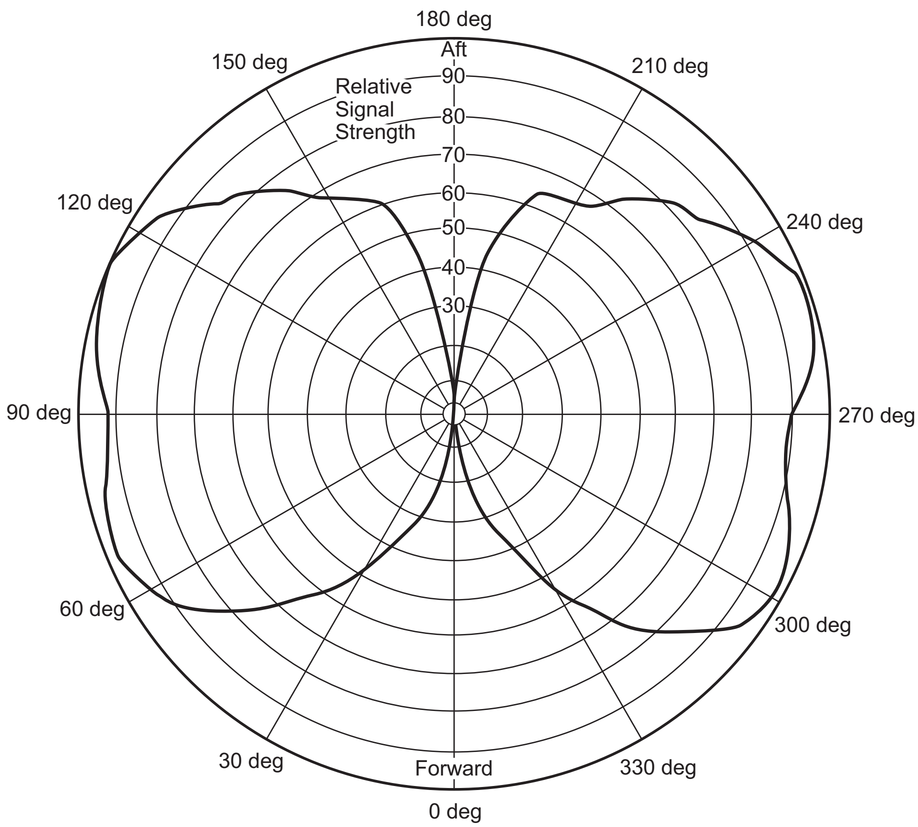


Fig. 2-11. Full-scale disc-cone antenna pattern with diffraction disc.

Fig. 2-12. Disc-cone antenna with diffraction disc.

Figure 2-13 shows the final flight configuration of the omni antenna. A fiberglass cylinder was used to support both the disc at the top of the antenna and the rim of the cone. The fiberglass cylinder mated with the ground plane. Because the outer rim of the ground plane supported the antenna, buttresses were used to carry the loads up from the edge of the ground plane to the fiberglass cylinder. A coaxial transmission line that traveled up the center of the fiberglass cylinder fed the disc-cone antenna. Within this transmission line was a ¼-wavelength matching transformer located where the phase of both the 890- and the 960-MHz impedance was the same. The original design of the antenna had a lip at the top of the antenna where the disc and the fiberglass cylinder were laced together. It was feared that this lip might hang up on the shroud, as it was ejected. To eliminate this possibility, a modification was made to the antenna by adding a small fairing. The fairing began approximately 2 in. (5 cm) below the top of the antenna and ran up to the edge of the disc. This

Fig. 2-13. Rangers 1 and 2 omnidirectional antenna.

modification did not appreciably affect the electrical characteristics of the antenna.

The VSWR of the antenna at both 890 MHz and 960 MHz was below 1.2. The gain was approximately 1.6 dB above isotropic at 960 MHz, and 1.7 dB at 890 MHz. Its weight was approximately 3.3 lb (1.5 kg).

The Pioneer 3 and 4 antenna was adapted for the omni antenna design for Rangers 3, 4, and 5 since the spacecraft was designed to carry a lunar landing capsule. However, since none of these rangers had a successful mission, its design is not included here.

Diplexer. A diplexer (Fig. 2-14) was required on the Ranger series so that the command receiver and the telemetry system could operate over the same omni antenna. A diplexer serves two basic functions. It isolates the power of the transmitter from the receiver, since the high power level could disturb the operation of the receiver. Second, the diplexer matches the transmitter to the antenna so that no power is lost into the receiver, which would cut down the efficiency of the transmitter communications link. The Ranger diplexers were designed and built by Rantec Corporation. The diplexer had four coaxial

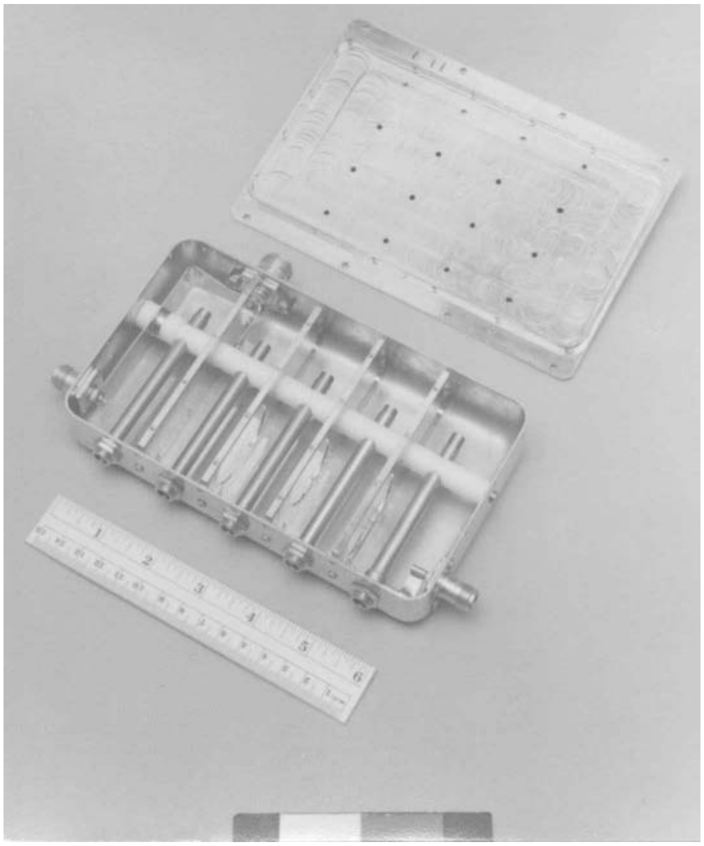


Fig. 2-14. Ranger diplexer.

cavities in the receive arm and one in the transmitter arm. Further details on the design and performance of the diplexer can be found in [8].

2.4 Surveyor

Following up on the Rangers, the Surveyor series (Fig. 2-15) was the first United States' effort to make a soft landing on the Moon. The Surveyor missions tested a new high-energy Atlas/Centaur rocket, a new spacecraft design, two-way communications to control spacecraft activities from the ground, and a new and elegant landing method (with three steerable rocket engines controlled by onboard radar). The Surveyor project began its development in 1961 with the selection of Hughes Aircraft Company as spacecraft system contractor to JPL, which managed the project.

Delayed repeatedly by the extended development of the launch vehicle's Centaur booster and the difficulties of its own development, Surveyor underwent many evolutions of management, engineering, and science before

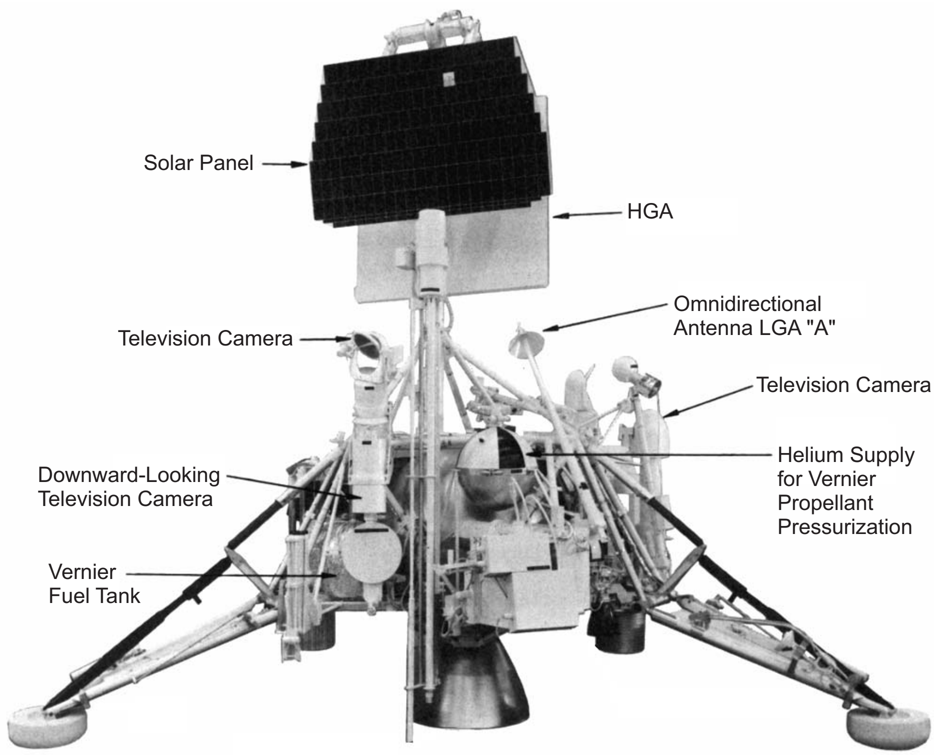


Fig. 2-15. Surveyor Spacecraft.

successfully landing with a remote-controlled TV camera at *Flamsteed* in *Oceanus Procellarum* in June 1966.

2.4.1 Surveyor Radio Switching and Antenna System

The Surveyor radio switching and antenna system contained [9,10]:

1) Two omni antennas (A and B).
2) Planar array directional antenna.
3) Two diplexers (A and B).
4) Two RF power monitors.
5) Antenna transfer switch.
6) Omni antenna selector switch.

The purpose of this system was to connect the output of the operating transmitter to the appropriate antenna and to radiate and receive RF energy.

The two low-gain, omnidirectional turnstile antennas, which were circularly polarized, were used for simultaneous reception of command information and transmission of TV and engineering data. They were positioned on the spacecraft so that their composite antenna pattern ensured reception of command information for all spacecraft attitudes. The omni antennas had patterns that may be visualized as cardioids of revolution with the null centered back along the antenna support in the direction of the spacecraft. Thus, together both antennas provided the required full 4π steradian coverage at near 0-db gain.

Each omni antenna was permanently connected to a receiver through a diplexer. Located at the ends of fiberglass booms, the antennas were extended away from the main body of the spacecraft during flight and lunar operations.

The high-gain planar-array antenna was a slotted waveguide array, had a gain of 27 dB, and had a beamwidth of approximately 6 deg. It was used for transmitting only, so it operated at 2295 MHz. In normal mission operations, the planar array antenna was used only on the lunar surface, and to take full advantage of the directional gain properties of the antenna, the unit was positioned by command from the controlling ground station.

Each diplexer was permanently connected to one of the omni antennas, and it provided for simultaneous reception and transmission via that single antenna. Each unit was a double-tuned cavity device that had one arm tuned to pass 2.113 GHz and the other to pass 2.295 GHz. A minimum of 60 dB of isolation was provided between the two arms.

The transmitter RF output from the diplexer was applied to the stripline power monitor. A small portion of the transmitter RF, during both high- and low-power transmission, was rectified and filtered by the power monitor and fed to the spacecraft signal processing system for transmission to ground control as an indication of transmitter output power.

Both the antenna transfer switch and the omni antenna selector switch were relay-operated coaxial switches commanded from ground control. The antenna transfer switch was a double-pole, double-throw unit connected to provide, as desired, the output of either of the transmitters to the input of the omni antenna selector switch or the planar array antenna. The omni antenna selector switch was a single-pole, double-throw device that directed the power to either of the two omni antennas.

2.4.2 The High-Gain Planar Antenna Array

The Surveyor spacecraft was designed to soft-land a package of scientific instruments on the lunar surface. One of its requirements was that it be capable of transmitting television pictures of the surrounding terrain back to Earth. The relatively high data rate required for this television signal necessitated the use of an HGA on the spacecraft. It was additionally required that this antenna be circularly polarized to preclude the necessity of polarization tracking. Restricted stowage space and stringent weight limitations demanded the highest possible efficiency from the antenna in a lightweight configuration. A planar-array antenna designed to satisfy these requirements was 38.5 in. (98 cm) square and weighed only 8.5 lb (3.86 kg). The overall aperture efficiency of 70 percent gave a gain of 27.0 dB. The measured ellipticity of the polarization was 1.0 dB. The Surveyor antenna based on this design is shown in Fig. 2-16. The material which follows was abstracted from reference [11].

2.4.2.1 Design Concept. Circularly polarized arrays can be constructed by using crossed slots on the broad wall of a waveguide at the point of circular polarization of the magnetic fields within the guide [12]. However, efficient aperture illumination is difficult to obtain using these slots alone since they must be spaced a full guide wavelength apart in order to keep the radiated fields in phase. This results in a free-space distance between elements of approximately $1.4\lambda_0$ for typical air-filled waveguides, thereby causing generation of secondary maxima (also known as second-order beams or grating lobes). It has been shown that adequate suppression of these lobes is required in order to obtain high aperture efficiencies. This can be accomplished by using interelement spacing between 0.5 and $0.9\lambda_0$, depending on the array length [13].

One approach considered for obtaining the proper spacing with the crossed slots was to reduce λ_g. It was rejected because none of the usual techniques of reducing λ_g satisfied both weight and gain requirements. A satisfactory solution was found in the form of additional slots in a new arrangement that together with a slow wave structure produced adequate interelement spacing.

The additional slots are of the complex type. The manner in which they solve the interelement spacing can be understood by considering a pair of them as one element. The two slots of each such pair are oriented 90 deg with respect to each other and are longitudinally separated by $\lambda_g/2$, as shown in Fig. 2-17. Each slot radiates the same power. A crossed slot and a complex slot pair located on opposite sides of the centerline radiate the same sense of circular polarization, but are 180 deg out of phase when the complex pair is centered on the same transverse plane as the crossed slot. By shifting the complex slot pair $\lambda_g/2$, in-phase radiation is obtained. Hence, this new slot element allows a commonly used technique of linearly polarized array design (i.e., staggering slot offsets to obtain in-phase radiation from $\lambda_g/2$ spacing) to be used for circularly polarized arrays.

The slow wave structure required for the slot spacing consisted of a series of transverse ridges located in the non-radiating broad wall of each linear array.

2.4.2.2 Array Configuration. The planar array slot configuration required two types of linear arrays, designated 1 and 2 in Fig. 2-18. The two arrays were designed as traveling-wave types with a beam tilt of 6 deg incorporated into the

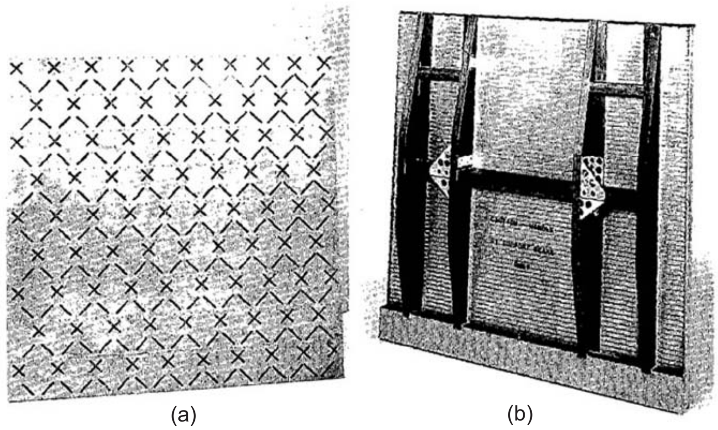


Fig. 2-16. Productized circularly polarized planar array antenna for surveyor: (a) front and (b) back.

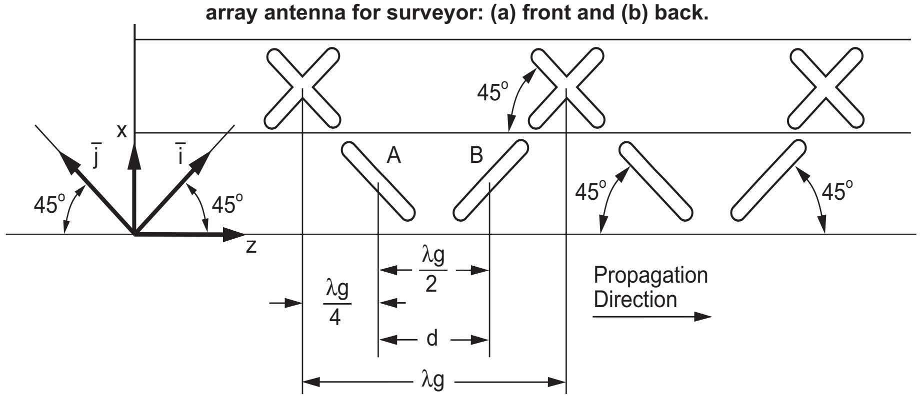


Fig. 2-17. Crossed slot-complex slot pair arrangement.

design for proper input impedance match. The design of each of these arrays was based on the assumption that a single complex slot coupled half as much power as a crossed slot. In both types of arrays, 5 percent of the input power was dissipated in the load termination. In the final design arrays 1 and 2 had 10 and 9 crossed slots, respectively, and 9 complex slot pairs each. No attempt was made to keep the complex slots in pairs since the effect of an additional slot in an array of this length is negligible.

The out-of-phase feeding of adjacent linear arrays was suggestive of a multimode waveguide. However, the slot arrangement resulted in a non-mirror image symmetry about the virtual walls and multimode operation was therefore not possible without heavy mode suppression. Mode suppression was used, and took the form of partial walls between the top of the corrugations and the top plate.

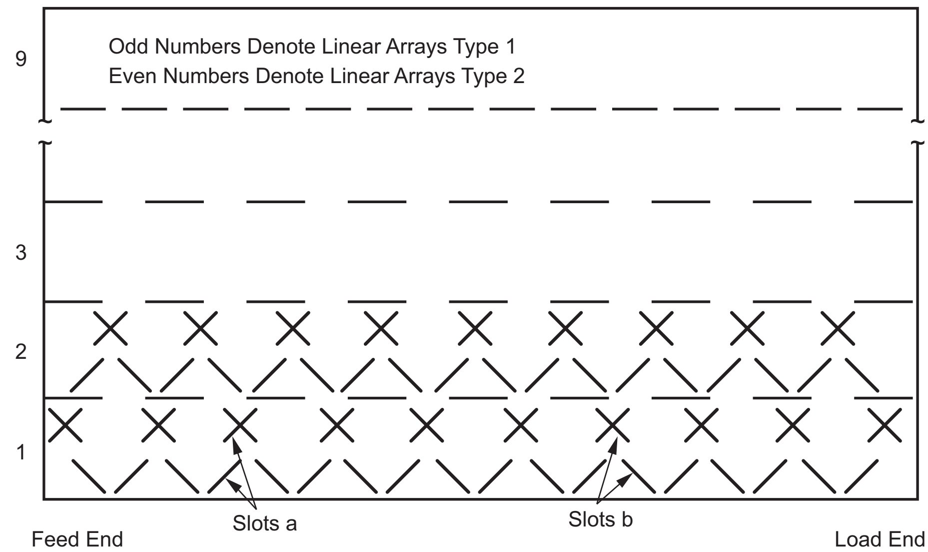


Fig. 2-18. Slot arrangement of circularized polarized planar array for maximum aperture efficiency.

The feedline was a standing-wave array with shunt-type slots coupling from the feedline into the bottom of the first corrugation gap of each linear array. The feedline was in turn centerfed by means of a magnetic loop coax-to-waveguide transition.

2.4.2.3 Performance. The coordinate system for the planar array patterns is shown in Fig. 2-19. The plane of the cut is given by the angle ϕ. The z-axis goes through the main lobe peak (thus, it is not perpendicular to the planar array surface), and the y-axis is parallel to the feedline. The polar axis, for all cuts except $\phi = 0$ deg, is the z-axis. For $\phi = 0$ deg, the polar axis is the dash line z', which is in the $\phi = 0$ deg plane and broadside to the array; accordingly, the pattern angle is θ'. The reason for showing angle θ' in the $\phi = 0$ deg plane is to bring out the existing beamtilt.

Measured patterns of the developmental model antenna showing both linear polarization components for the principal planes ($\phi = 0$ and $\phi = 90$) are shown in Fig. 2-20. The measured axial ratio of the full array is 1.5 dB. The two components are within 0.2 deg of being coincident, and the measured beamwidths are in good agreement with the 6.8-deg beamwidths computed for this aperture size. The large 1st sidelobes in the E_θ component, $\phi = 0$ deg plane, are due to the radiation from the end of the guides. In this particular array the guides are open ended.

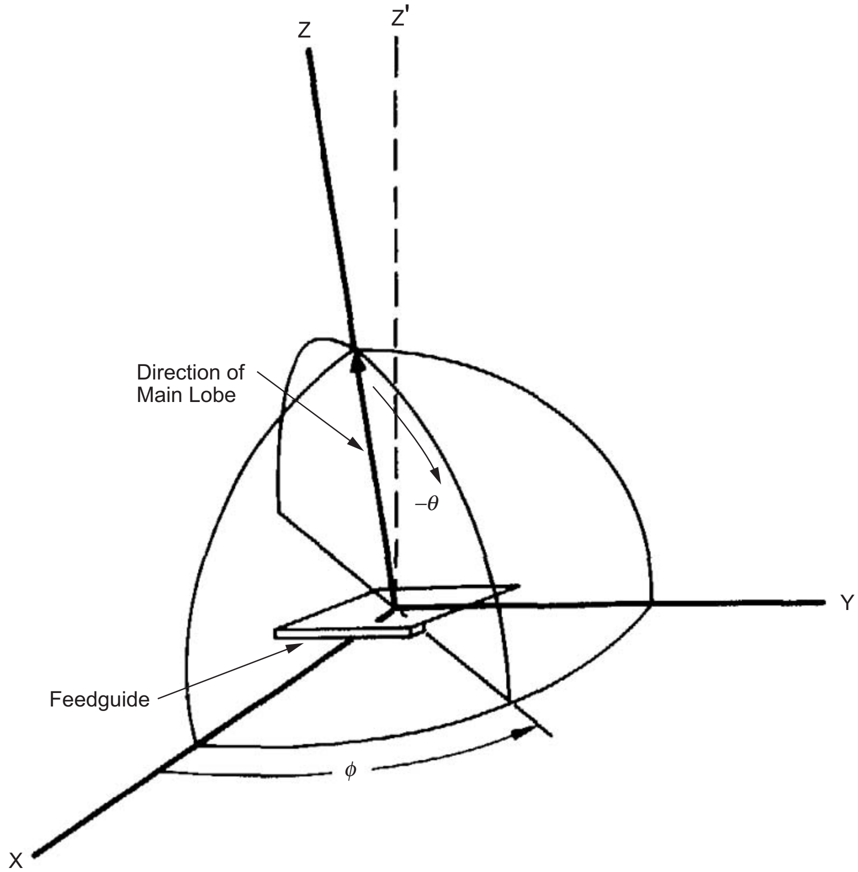
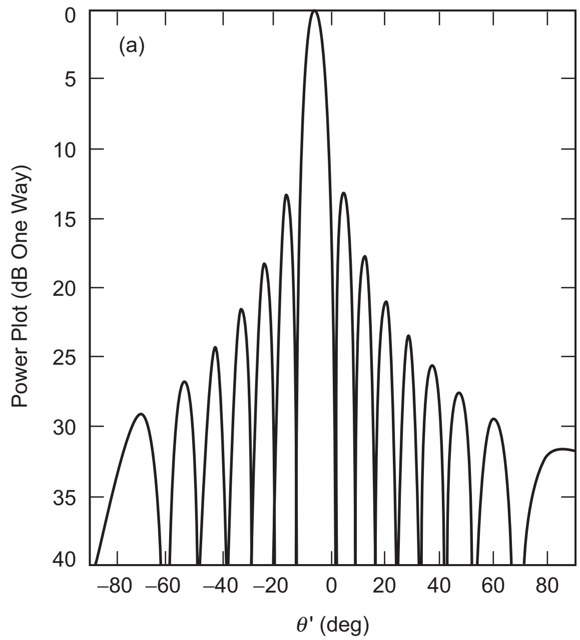


Fig. 2-19. Coordinate system for planar array patterns.

The antenna gain with a waveguide input was 27.2 dB, corresponding to an overall efficiency of 73 percent. However, with the coax input the best gain achieved was 27.0 dB.



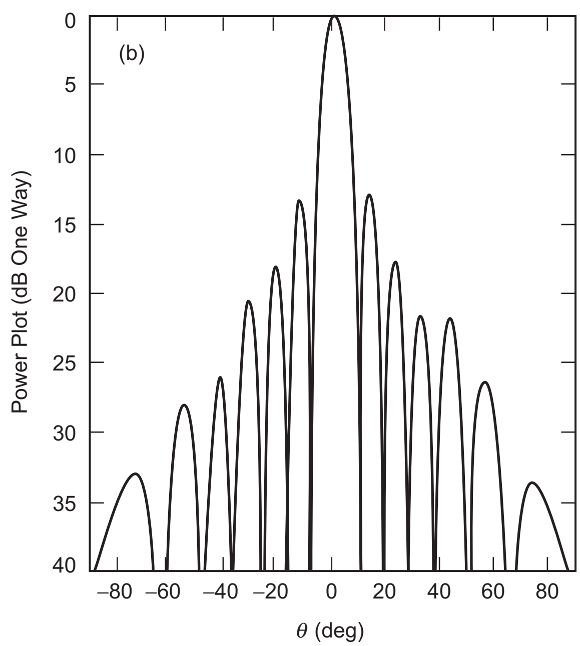


Fig. 2-20. Measured antenna patterns: (a) ϕ = 0 deg plane and (b) ϕ = 90 deg plane.

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