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SPACECRAFT CONTROL SYSTEMS*

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INTRODUCTION

The topics covered by the technical program of this Third Congress of the International Council of the Aeronautical Sciences attest to the breadth of the aerodynamic and mechanical disciplines now involved in today's aeronautical and aerospace programs.

Possibly some of the earliest pioneers in this industry foresaw the expansion of the basic aerodynamic and mechanical disciplines into such complex areas as supersonics, hypersonics, high temperature material fatigue and boundary-layer control. Some even might have been aware that aero medicine would be added as an important discipline for the study of the effects of this new environment on man.

However, only the wildest of dreamers, I believe, could have conceived the impact of the young electronics and electromechanical industries on our efforts today. In the last half century of flight-vehicle development, on-board electrical equipment has expanded from simple ignition systems to the most complex electronics systems for controlling and managing fuel flow, flight attitude, communications, performance analysis, and numerous other tasks impossible for man to accomplish either because of hazard, or man's limited speed of response. Today it is not at all uncommon on a large transport aircraft, missile, or spacecraft to find the electronic parts count running into the hundreds of thousands.

In addition electronic and electromechanical simulation techniques have been utilized as standard design and analysis tools with increased acceptance. Because electronics and electromechanics portend to have continued growth in the aeronautical sciences it seems to me timely, as part of the general lecture series of this conference, to acquaint you with some recent developments in these areas. The embodiment of these disciplines in spacecraft control systems provides a good medium for this examination.

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* This paper describes activities at the Jet Propulsion Laboratory, California Institute of Technology, sponsored by the National Aeronautics and Space Administration.

U.S. SPACE PROBE EFFORTS

As you are aware, President Kennedy has publicly announced the intention of the United States to safely land a man on the moon and return him, within this decade. Preliminary stages of the United States "man in space" program have so far included suborbital flights by Alan Shepard and Virgil Grissom and orbital flights by John Glenn and Scott Carpenter.† Scheduled to follow are the Project Gemini two-man orbital flights and finally the three-man-crew Apollo lunar orbit and landing missions.

The decision on the part of the United States scientific and engineering community to explore in depth the lunar and interplanetary environments before subjecting man to these extreme conditions, however, has engendered the National Aeronautics and Space Administration program of unmanned maneuverable space probes.

The success of these probes is highly dependent on the extensive development of reliable automatic and remotely controlled flight systems, communications systems, and the secondary electrical power generation schemes required for their implementation.

These Aeronautic and Space Administration projects in the unmanned category, directed toward the moon, are the Ranger (which is already underway)

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† Also the 22-orbit flight of Gordon Cooper, May 15–16, 1963—Ed.

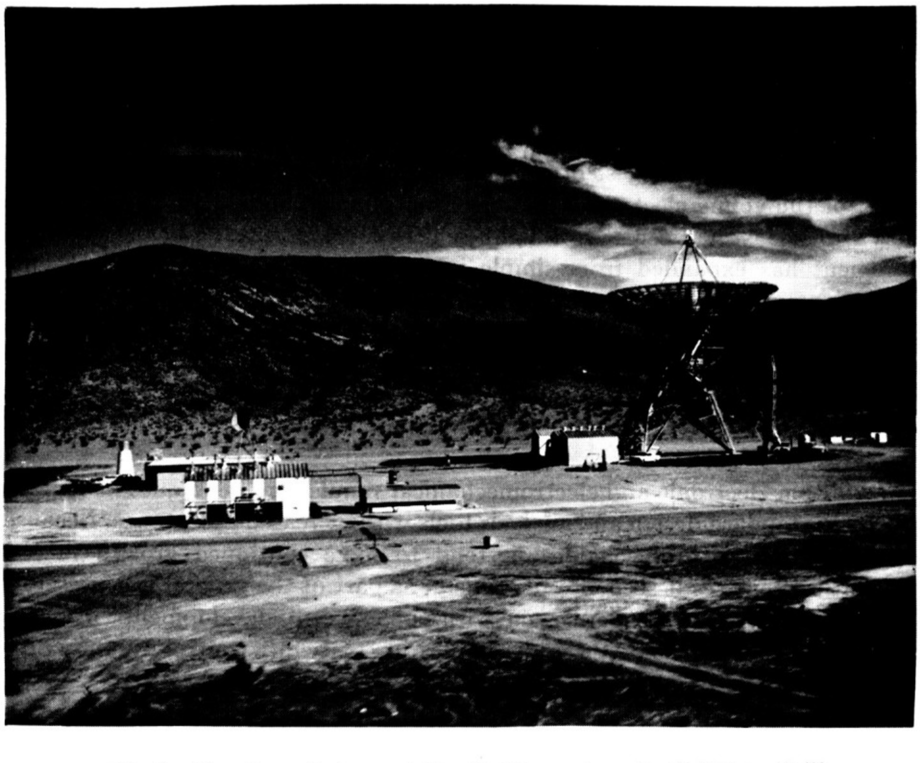

Fig. 1. Deep Space Instrumentation Facility receiver site, Goldstone, Calif.

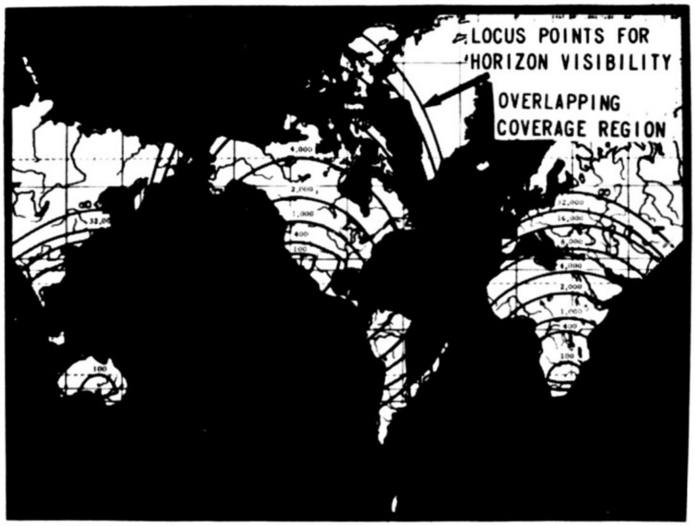

Fig. 2. Deep Space Instrumentation Facility coverage.

and the Surveyor (which will commence in 1964). Also adding to the technical development will be the unmanned planetary program which will fly from earth to Venus and from earth to Mars as the planetary opportunities present themselves in the next few years. Favorable Venus conjunctions occur only every 19½ months and favorable Mars conjunctions occur only every 25 months.

These unmanned projects are being carried out by the Jet Propulsion Laboratory of the California Institute of Technology, a space research center under contract to the National Aeronautic and Space Administration.

In addition, an important part of the lunar and planetary programs is the establishment of a precision earth-based tracking and communications system capable of providing command, telemetry, and position tracking of space vehicles. The Deep Space Instrumentation Facilities (DSIF) has been established to satisfy this requirement in lunar and planetary programs for which the Jet Propulsion Laboratory has been assigned either direction or supporting responsibility by the National Aeronautics and Space Administration. The earliest DSIF station, at Goldstone, Calif., is shown in Fig. 1. The DSIF is primarily intended for spacecraft tracking and communication at cislunar distances and beyond. Its deep-space function precludes its use as an earth satellite tracking network. The DSIF is comprised of three deep-space stations and a mobile station. The latter is presently used as an acquisition aid in the short-range, high-angular-velocity phase around spacecraft injection, and its utilization is expected to diminish after 1963.

The deep-space stations located as shown in Fig. 2 in Goldstone, Calif., Woomera, Australia and Johannesburg, South Africa are presently equipped with 85-ft diameter reflectors and can track at angular rates to 1°/sec with a 1° beam width. The mobile station (Fig. 3) is equipped with a 10-ft diameter reflector and can track at angular rates of 10 to 20° per sec, depending on

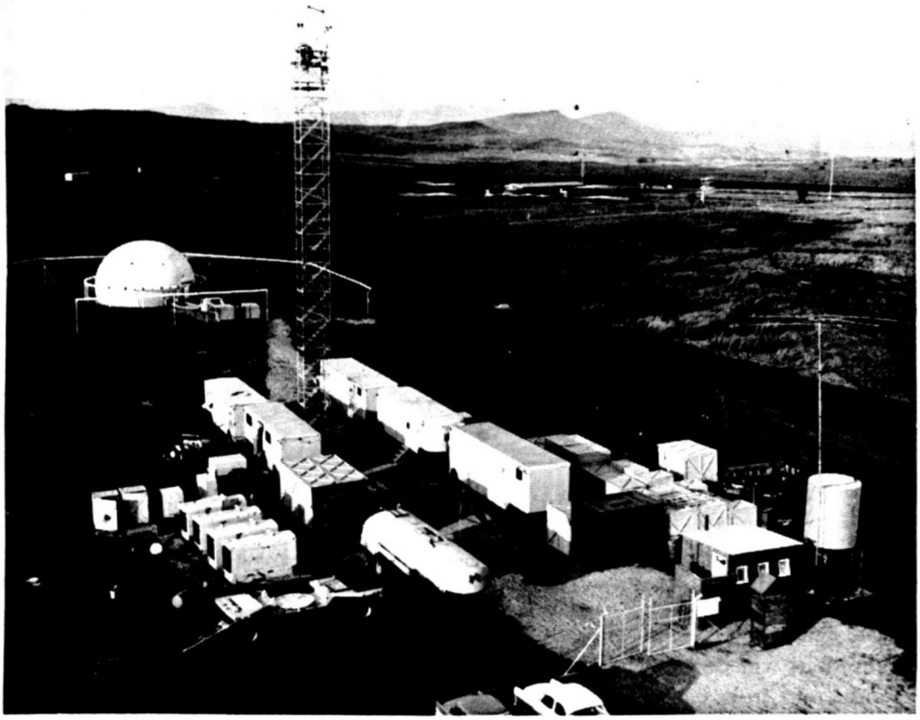

Fig. 3. Mobile tracking station deployed in South Africa.

tracking accuracy. The mobile station as an acquisition aid tracks and communicates with space vehicles from injection to about 10,000 miles altitude.

The design philosophy of the DSIF is to provide a precision radio tracking system which measures two angles, radial velocity, and range, and to utilize this system in two-way communication efficiently and reliably. The Jet Propulsion Laboratory carries out the research, development, and fabrication of the deep-space stations and is responsible for the technical coordination and liaison necessary to establish and operate the DSIF throughout the world. The overseas deep-space stations, at Woomera, Australia (Fig. 4) and Johannesburg, South Africa (Fig. 5) are operated by personnel provided by cooperating agencies in the respective countries. Velocity-measurement accuracy of 0.2 meter per second using a two-way doppler system is attainable. Data from the complete DSIF network is sent to a computer center at the Jet Propulsion Laboratory where the spacecraft trajectory can be computed and the required decisions made for in-flight corrections. Presently the DSIF is operating in the L band megacycle spectrum but future plans call for a shift to S band.

RANGER PROJECT

The Ranger Project represents attempts by the United States to take close-up pictures of the moon and to make measurements on the lunar surface. Two types of Ranger payloads are being utilized and will be launched at intervals during this year, 1963 and 1964. To provide information on the composition of the lunar surface and learn more about its history and structure, an instrument capsule model and a high-resolution-TV model will provide design criteria for future manned vehicles, survey suitable landing sites, and provide lunar surface information with particular regard to landing gear design.

The proof test model of a capsule Ranger is shown under test in Fig. 6. The Ranger is a 750-lb gold-and-silver-plated machine which makes a 66-hr flight to the moon and is called on to perform for the first time a most complicated series of events.

It is asked to:

1. Leave the earth, achieve a parking orbit and reach escape velocity of approximately 25,000 mph.
2. Perform a three-axis maneuver in space to lock on to the sun and earth. The on-board power system as described later depends on sunlight for its

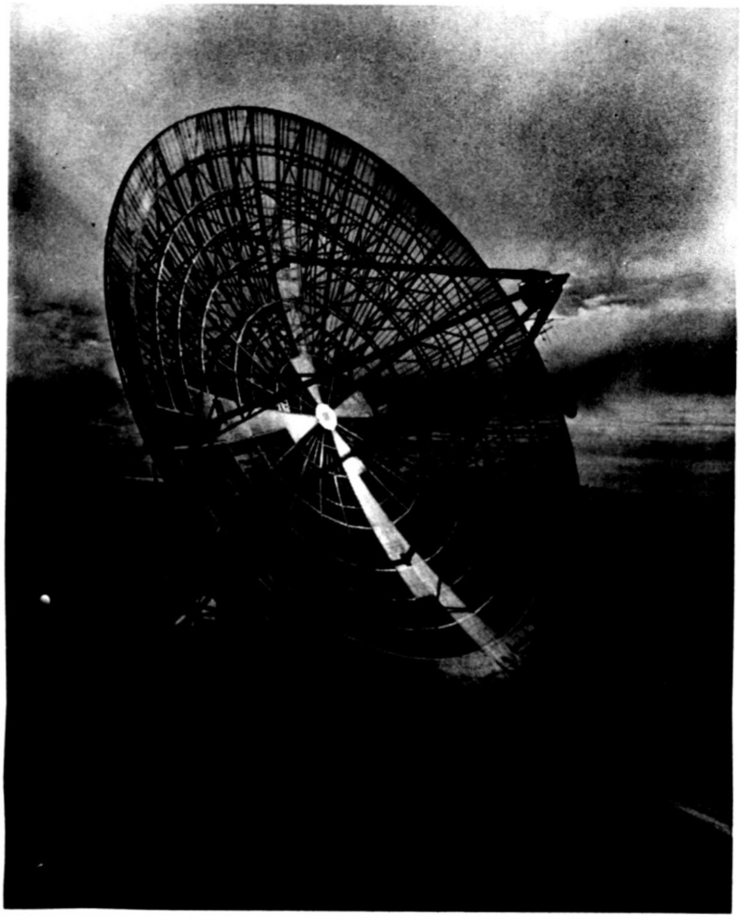

Fig. 4. Woomera, Australia, DSIF Antenna.

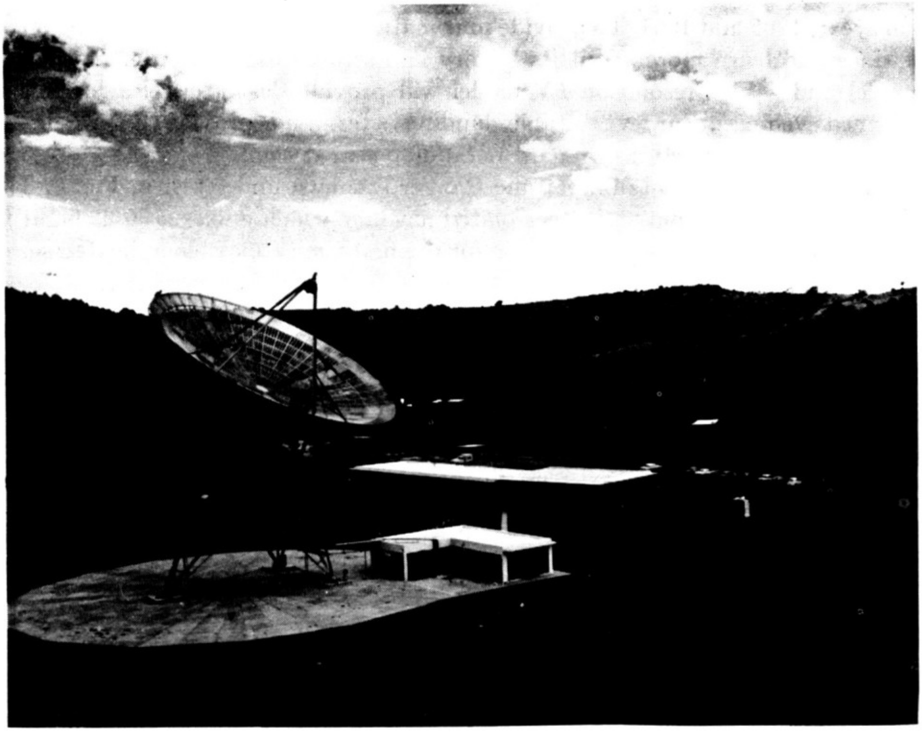

Fig. 5. Johannesburg, South Africa, DSIF Station.

energy and except for short periods on battery power the craft must continually look at the sun to obtain its life-giving power. It must point its high-gain directional antenna continuously at the earth in order to obtain suitable bandwidth for transmitting its data.

3. Accept correction commands from the earth, change its orientation in flight and fire a midcourse motor to put itself on a collision course with the moon. This midcourse maneuver is necessary to overcome the injection errors which might accumulate in the complicated three-stage launch vehicle system required to lift the Ranger payload.
4. Reestablish its lock on the sun and the earth.
5. Perform a terminal maneuver when it gets within 5,000 miles of the moon.
6. Take television pictures of the lunar surface as it approaches the moon.

The foregoing description applies to both payload missions.

In the high-resolution-television mission (Fig. 7) pictures of the lunar surface can be relayed back to the earth right up to the moment the spacecraft impacts the moon.

In the capsule mission the spacecraft must perform the following additional operations:

1. Make studies of the composition of the lunar surface and its radar-reflection characteristics.
2. Separate a retro-rocket and capsule system from the spacecraft when it is 10,000 ft above the lunar surface.
3. Fire the retro-rocket to slow the capsule system from 6,000 mph to zero velocity 1,100 ft above the surface of the moon.
4. Detach an instrumented capsule containing a seismometer from the retro-rocket so that it rough lands after a free fall from 1,100 ft, survives the landing, positions itself and then for the next four weeks telemeters back to earth information on moon quakes and meteoric impact. All of this will be accomplished by a spacecraft control system receiving its intelligence through the DSIF link and by on-board measurements 240,000 miles from the earth.

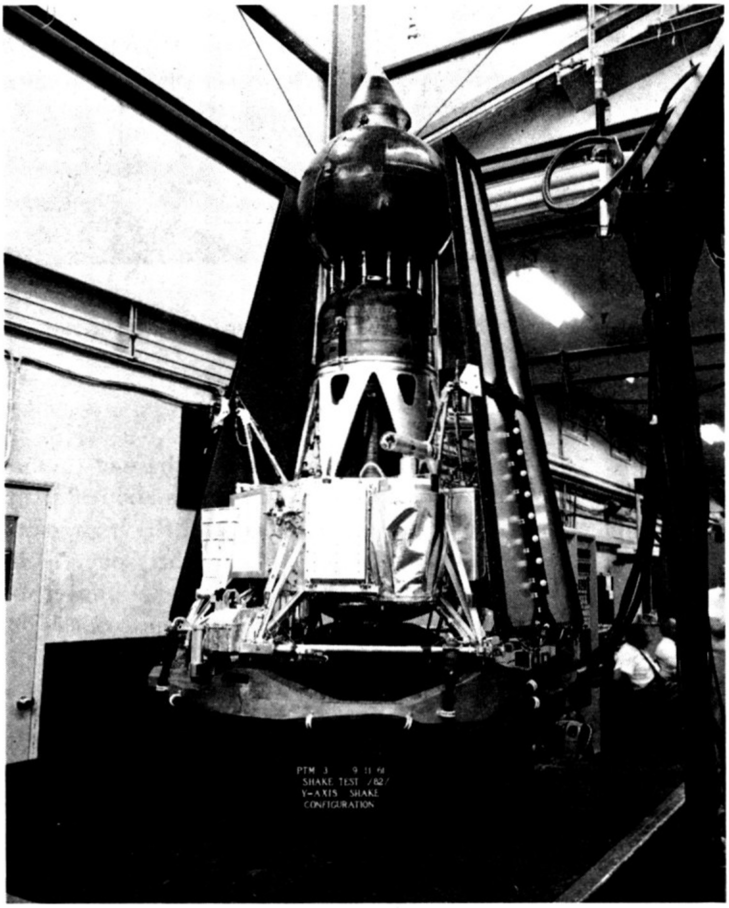

Fig. 6. Ranger (Capsule Mission) spacecraft under test.

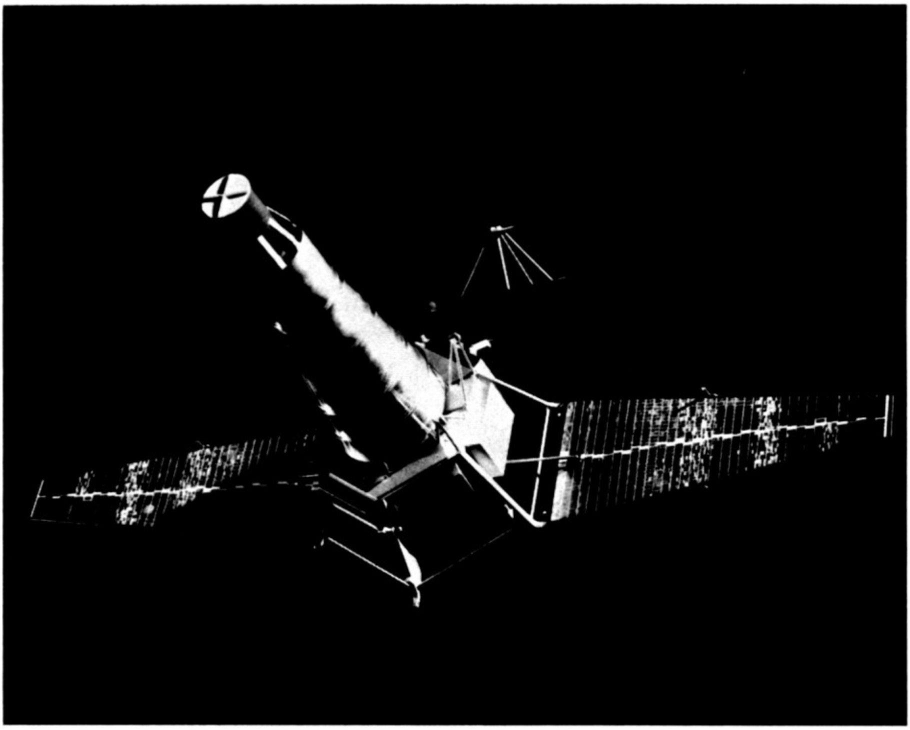

Fig. 7. Ranger (high-resolution TV mission) spacecraft configuration.

RANGER SPACECRAFT

The basic Ranger (Fig. 8) is 5 ft in diameter at the base of the hexagon, and in its launch position, with the solar panels folded, it is about 8 ft in height. In the cruise position with its solar panels extended and the high gain directional antenna deployed it has a span of 17 ft and it is slightly over 10 ft in height. The instrument capsule weighs about 60 lb and the impact limiter weighs about 40 lb. The lunar capsule rests atop a retromotor which in turn sits on top of the spacecraft hexagon. The retromotor, with a thrust of approximately 5,000 lb, weighs 200 lb including the small spin motor that rotates the assembly for stability just before the retromotor is fired.

The on-board electrical system (Fig. 9) consists of the two solar panels covered with almost 9,000 individual photovoltaic cells. These cells connected in series parallel arrangement provide the electrical requirements for the on-board experiments, the communication system, and the attitude control system. The power is boosted from its low voltage level and through a series of inverters and converters supplies the required a-c and d-c system voltages. A typical converter in its flight package is shown in Fig. 10.

The Ranger has three antennas in its first configuration—two in its spacecraft bus and one on top of the instrumented sphere that lands on the moon. The

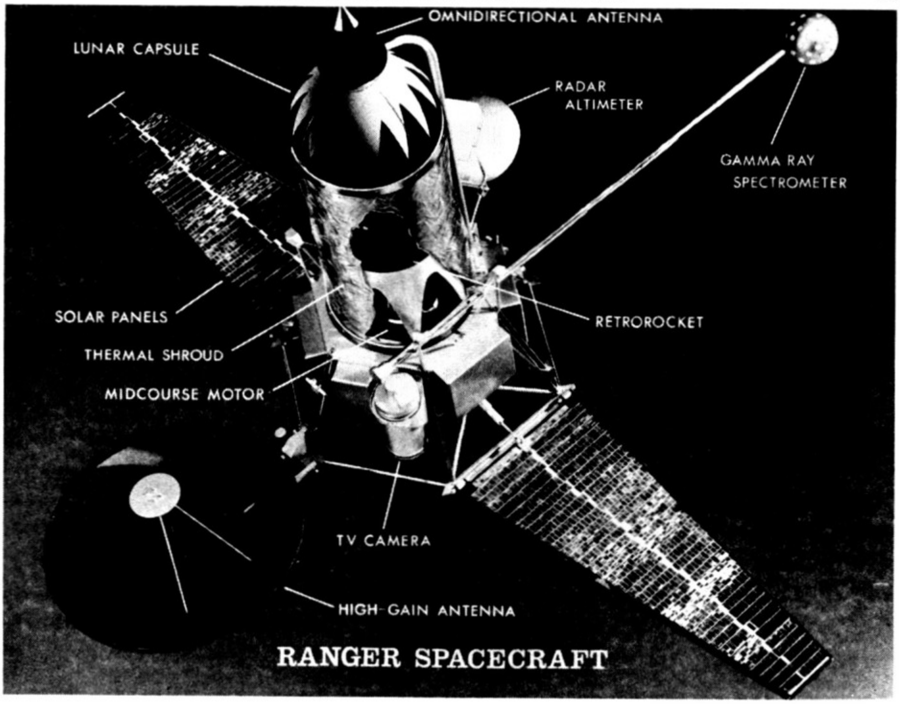

Fig. 8. Ranger spacecraft elements.

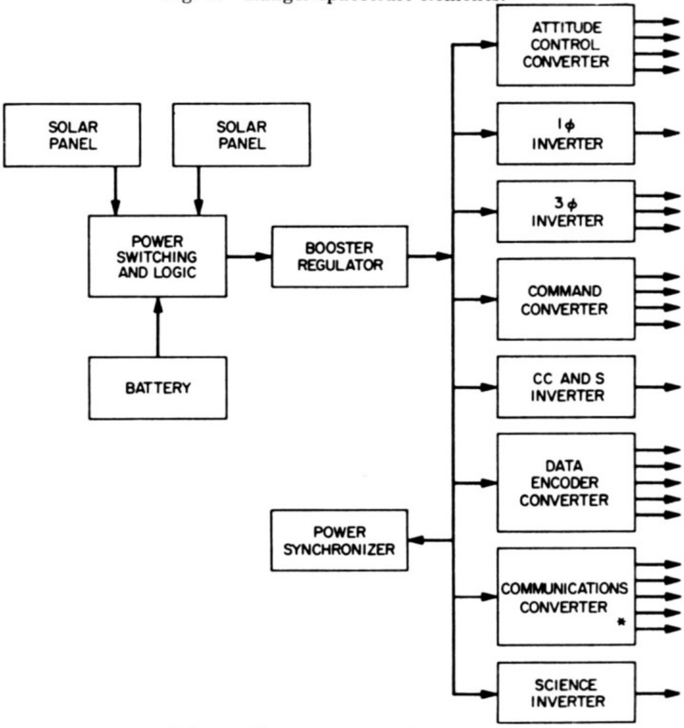

Fig. 9. Ranger power subsystem.

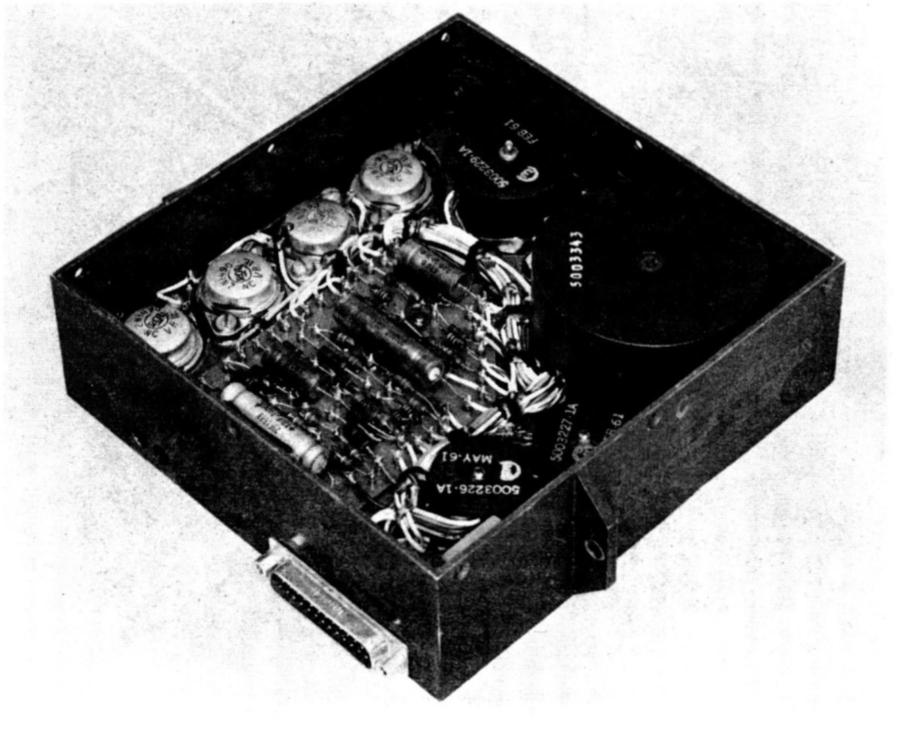

Fig. 10. Ranger power converter package.

omnidirectional antenna positioned at the forward end of the spacecraft provides communication until the 4-ft-diameter high-gain directional antenna is positioned by the attitude control system.

The midcourse motor which as previously mentioned corrects for injection inaccuracies is a liquid monopropellant engine that weighs, with the fuel and the helium pressurizing system, about 35 lb. When the midcourse motor receives the command to fire, helium under 3,000 lb/in.^{2} pressure injects the hydrazine fuel into the combustion chamber. This monopropellant needs a starting fluid to initiate combustion and a catalyst to maintain combustion. The starting fluid (nitrogen tetroxide) is admitted into the combustion chamber by means of a pressurized cartridge. Burning is maintained in the combustion chamber by a catalyst of aluminum oxide pellets. The midcourse motor is so precise that it can burn in bursts as small as 50 millisec and can increase velocity by as little as 1/10 ft per sec or as much as 144 ft per sec. The duration of its burn is determined by data received from the DSIF and is controlled by a solid state digital computer called the Central Computer and Sequencer.

This CC&S is a system which allows commands to be stored for later subsystem operations on board the spacecraft, and it allows specific ground commands to be stored in the CC&S for later routing to perform specific functions.

FLIGHT SEQUENCE

The Ranger uses the parking orbit technique which is a means by which the geometry imposed on moon impact shoots by the location of the Atlantic Missile Range at Cape Canaveral, Florida is corrected by using the second stage rocket for a mobile launching platform in space.

The Atlas booster of the Atlas-Agena vehicle carries the Agena and the Ranger to an altitude of 115 miles above the earth. At this point the spacecraft is still considerably below orbital speed. During launch phase the Ranger is protected against aerodynamic heating by a shroud. After Atlas cutoff the shroud is jettisoned by a spring-loaded mechanism and it moves on ahead of the vehicle. At this time the second stage Agena and spacecraft combination separates from the Atlas booster. The Agena is then commanded to pitch down to be almost level with the local horizon. In this horizontal attitude the Agena fires the first time and burns to reach an orbital speed of 18,000 mph. After this burning time the Agena shuts down and coasts in a parking orbit for more than 13 min until it reaches the optimum point in time and space to fire for the second time to attain its escape ellipse to the moon.

After the second Agena burn the Agena-Ranger combination (still as one unit) is injected in an escape velocity of approximately 25,000 mph. This takes place approximately 25 min after launch. Little more than 2 min after second burn cutoff, or injection, the Ranger is separated from the Agena, again by spring-loaded mechanisms. To prevent the unsterilized Agena from impacting the moon—and also in case the Agena follows the Ranger too closely so that the

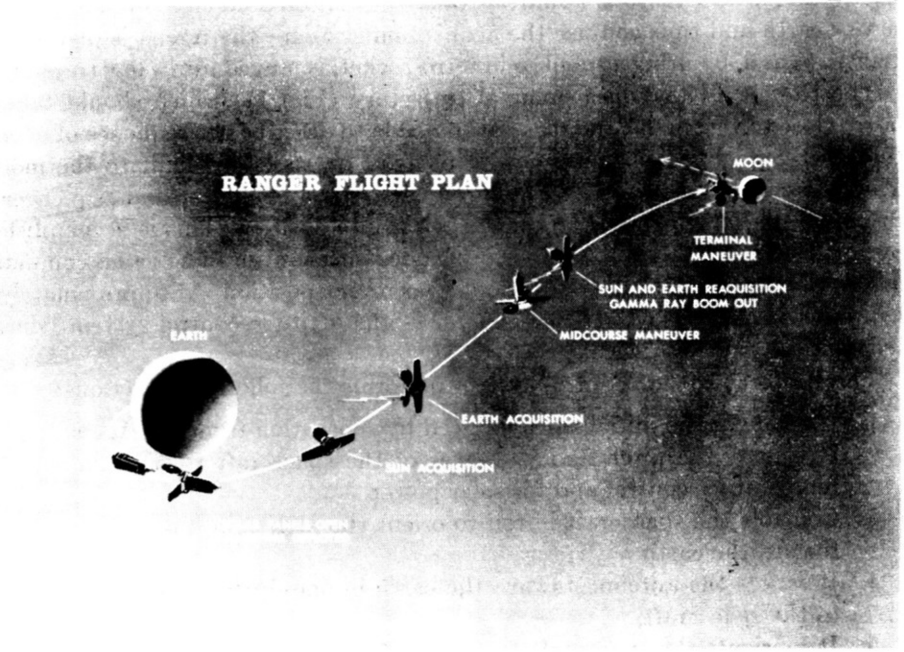

Fig. 11. Ranger flight plan.

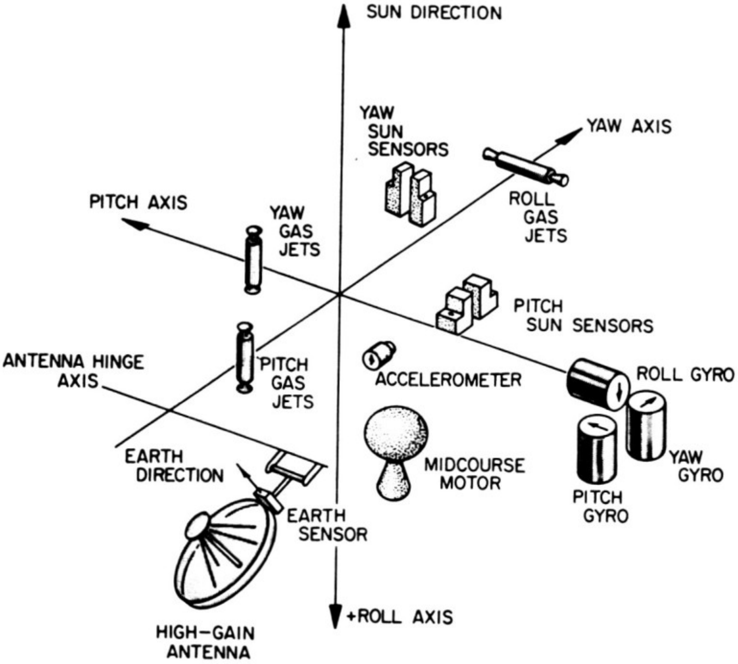

Fig. 12. Ranger control subsystem.

spacecraft optical sensors would mistake the reflected Agena sunlight for the sun or earth and thus confuse the acquisition system—the Agena is placed in a 180° yaw, and, by firing a small solid retro-rocket, is moved into a low trajectory.

The Ranger is now on a nominal trajectory (Fig. 11) which should take it fairly close to the moon, and it is now possible to describe the sequence of events that the control system must now implement on its 66-hr flight to the moon. The first command issued internally by the central computer and sequencer is to unfurl the solar panels to assume their cruise position. This is accomplished by explosive pin pullers and a spring-loaded mechanism. The same command drives the high-gain antenna dish out to a preset position. At approximately a half hour after launch the CC&S energizes the attitude control system (shown schematically in Fig. 12).

The Ranger attitude control system performs the following functions:

1. It removes the initial rates induced by separation from the Agena.
2. It orients the pitch and yaw axes of the spacecraft toward the sun for temperature control and for solar power.
3. Controls the spacecraft in roll to orient the high gain directional antenna toward the earth.
4. It servos the antenna toward the earth in one degree of freedom relative to the spacecraft.
5. It reorients the spacecraft to any angle relative to the earth and sun by ground command.

6. Provides three-axes control of the thrust vector direction during midcourse and terminal maneuvers.
7. Repeats the earth-sun acquisition after the midcourse maneuver.

The attitude control system consists of six sun sensors: four primary sensors on four of the six hexagon legs, and two secondary sensors mounted on the backs of the solar panels. These are light sensitive cadmium sulfide devices which are summed and differenced to obtain pitch and yaw null signals.

Three strapped down integrated rate gyros operating in a feedback mode measure the spacecraft roll, pitch and yaw rates and with the integrated position errors provide adequate damping signals for stable operation.

An earth sensor consists of three photomultipliers suitably masked to provide pointing sense to the antenna and also to provide roll sensing.

Torquing of the spacecraft in response to the sensed signals is provided by ten cold-gas expulsion jets.

In order to conserve gas the attitude control system permits a pointing error toward the sun of ±0.5 deg. The mixing network in the attitude control system is calibrated to keep the Ranger slowly swinging through this one degree of arc and pointed towards the sun. The limit cycle is approximately one hour. It is calculated that the gas jets will fire only 1/10 sec out of each hour. After sun acquisition is complete the secondary sun sensors are disconnected to avoid

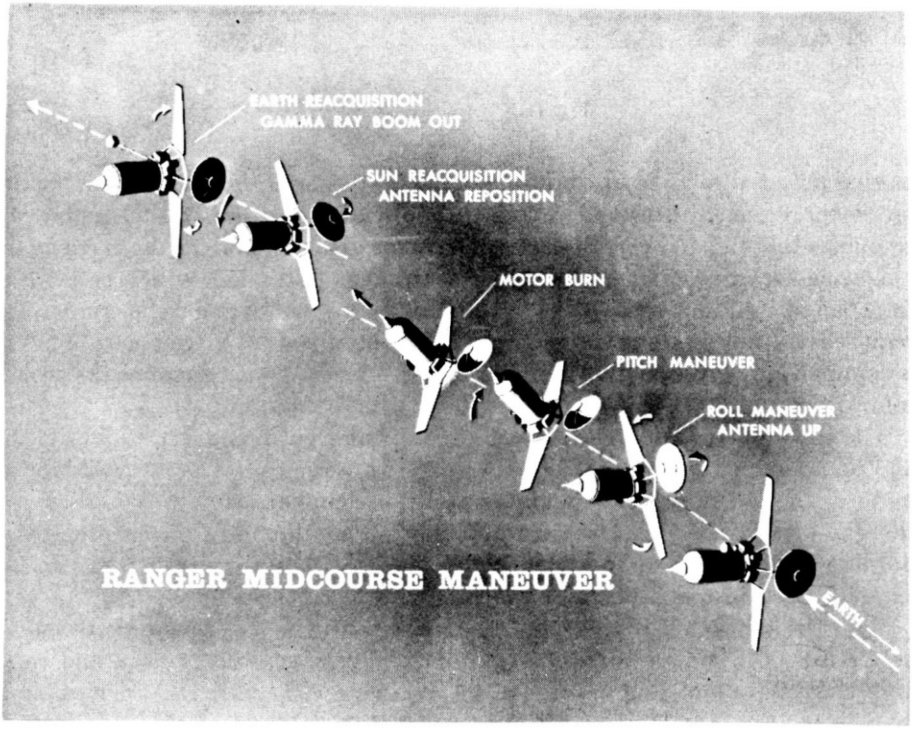

Fig. 13. Ranger midcourse maneuver.

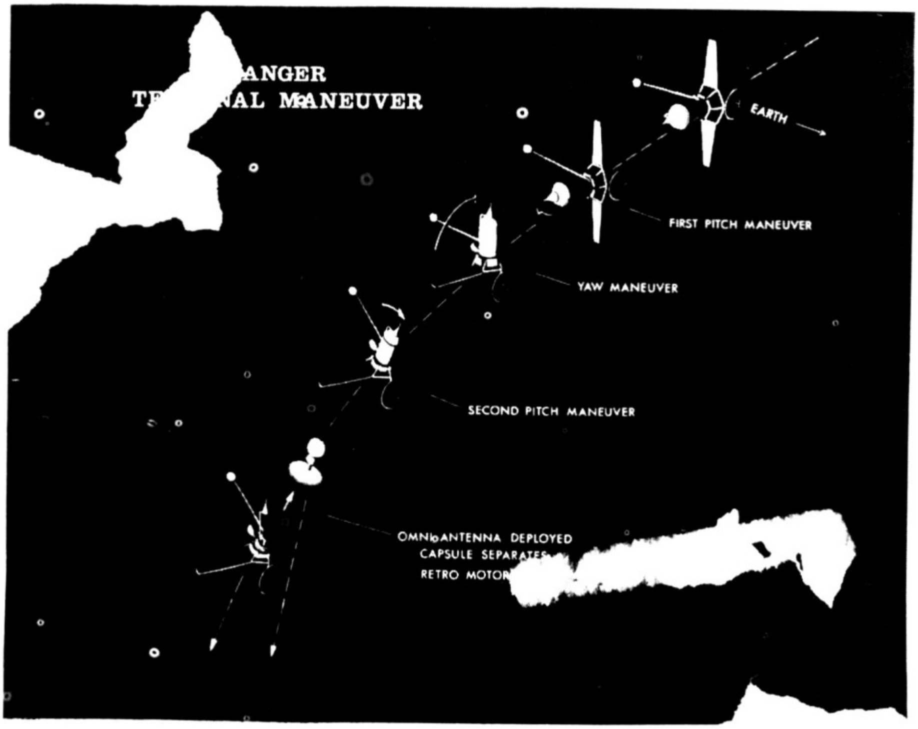

Fig. 14. Terminal maneuver.

having reflected earth light confuse them. The danger of the earth sensor locking on to the moon rather than the earth is obviated because the telemetry will recognize this and an override command can be given to look for the earth again.

During the midcourse maneuver the central computer and sequencer switches from earth and sun sensors to an inertial lock condition on the gyros. The required midcourse sequence which has been obtained from trajectory analysis is commanded by the central computer and sequencer upon receipt of the ground information.

The spacecraft is oriented to the desired angular position as shown in Fig. 13, and a midcourse velocity correction imparted by the rocket motor. The rocket motor is shut off by means of an integrating accelerometer and the CC&S. While the gas jets on all three axes are probably on continuously during the motor burning, there is no harmful effect because jet vanes deflecting the rocket exhaust are used to stabilize the spacecraft during this period.

To provide high-bit-rate communication with the earth again and obtain the power from the sun the spacecraft automatically reacquires the sun and earth after this maneuver and continues on its flight path until the final terminal maneuver (Fig. 14) is achieved. The 6,000-mph velocity of the spacecraft is canceled out by the thrust of the capsule retro-motor and the capsule free falls the last thousand feet to the lunar surface.

OTHER SYSTEMS

I have limited the detailed discussion to the Ranger spacecraft because we have had most flight experience with this project; although none of the early flights has been fully successful, most mission elements have been validated in flight.

Similar principles are applied to the Surveyor, (Fig. 15), which is our next step in the lunar category, and will begin flying in 1964. The Surveyor is intended to soft-land the whole spacecraft (at about the speed of an earth parachute drop) on the surface of the moon, and conduct several experiments there. It uses a large solid-propellant retro-motor in conjunction with a system of three liquid-propellant vernier engines, which also will accomplish the midcourse maneuver. Attitude control is maintained by the use of cold-gas jets situated at the ends of the landing legs, which are extended shortly after injection. The attitude references are the sun and the star Canopus. Finally, because the scientific experiments do not become active until lunar encounter, the high-gain communications antenna is not brought into play until the landing maneuver.

Also, the same general activities take place with the planetary probes, except that the range and time scale, and hence the risk, are expanded greatly. The JPL Planetary Program opened with an attempt to fire a probe to Venus in

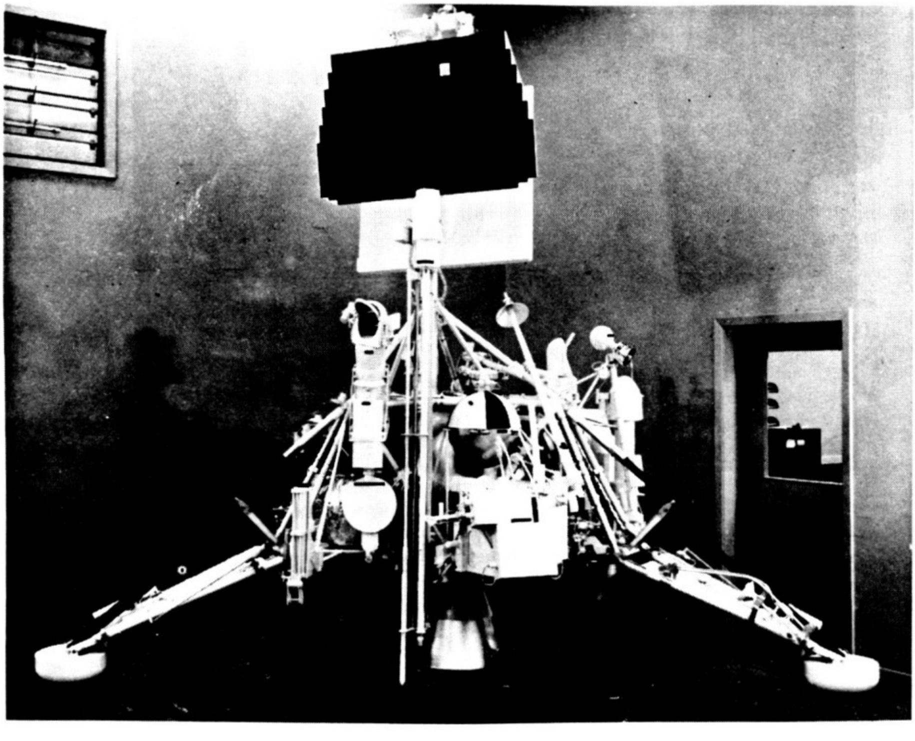

Fig. 15. Surveyor spacecraft.

July (unfortunately launch vehicle problems rendered this a failure). The Mariner II launched the day before yesterday is by all present indications a success, and latest reports to me by overseas telephone forecast a successful encounter sometime in December.‡ It is planned to apply the midcourse correction through the command system sometime this weekend.

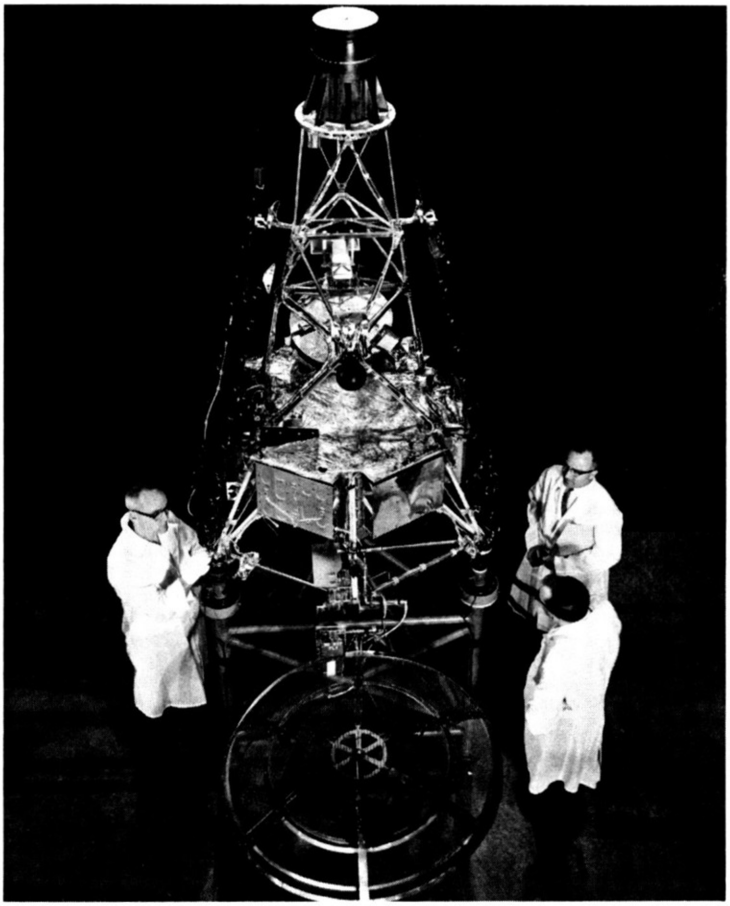

Fig. 16. Mariner 1962 spacecraft.

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‡ On December 14, 1963, Mariner II flew by Venus at a distance of 21,594 miles—Ed.