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THE INTERPLANETARY PIONEERS

VOLUME I: SUMMARY

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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VOLUME I: SUMMARY

by

William R. Corliss

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Foreword

SOME EXPLORATORY ENTERPRISES start with fanfare and end with a quiet burial; some start with hardly a notice, yet end up significantly advancing mankind's knowledge. The Interplanetary Pioneers more closely fit the latter description. When the National Aeronautics and Space Administration started the program a decade ago it received little public attention. Yet the four spacecraft, designated Pioneers 6, 7, 8, and 9, have faithfully lived up to their name as defined by Webster, "to discover or explore in advance of others." These pioneering spacecraft were the first to systematically orbit the Sun at widely separated points in space, collecting information on conditions far from the Earth's disturbing influence. From them we have learned much about space, the solar wind, and the fluctuating bursts of cosmic radiation of both solar and galactic origin.

These Pioneers have proven to be superbly reliable scientific explorers, sending back information far in excess of their design lifetimes over a period that covers much of the solar cycle.

This publication attempts to assemble a full accounting of this remarkable program. Written by William R. Corliss, under contract with NASA, it is organized as Volume I: Summary (NASA SP-278); Volume II: System Design and Development (NASA SP-279); and Volume III: Operations and Scientific Results (NASA SP-280). In a sense it is necessarily incomplete, for until the last of these remote and faithful sentinels falls silent, the final word is not at hand.

HANS MARK
Director
Ames Research Center
National Aeronautics and Space Administration

Contents

Page

Chapter 1. ORIGIN AND HISTORY OF THE INTERPLANETARY PIONEER PROGRAM ---- 1
- The Scientific Challenge of Interplanetary Space ---- 1
- The Ames Solar Probe Studies ---- 2
- Selecting a Contractor ---- 4
- The Pioneer Organization ---- 5
- The Pioneer Schedule ---- 11
- The Pioneer Cost Picture ---- 14
- Pioneer Chronology ---- 22

Chapter 2. PIONEER SYSTEM DESIGN AND DEVELOPMENT ---- 25
- Defining the Pioneer System ---- 25
- Pioneer Launch Trajectory and Solar Orbit Design ---- 29
- Spacecraft Design Approach and Evolution ---- 34
- The Spacecraft Subsystems ---- 37
- Scientific Instruments ---- 62
- The Delta Launch Vehicle ---- 76
- Tracking and Communicating with the Pioneer Spacecraft ---- 78
- Pioneer Data Processing Equipment ---- 84

Chapter 3. PIONEER FLIGHT OPERATIONS ---- 89
- Prelaunch Activities ---- 89
- Launch to DSS Acquisition ---- 93
- From DSS Acquisition to the Beginning of the Cruise Phase ---- 98
- Spacecraft Performance during the Cruise Phase ---- 99

Chapter 4. PIONEER SCIENTIFIC RESULTS ---- 103
- The Goddard Magnetic Field Experiment ---- 103
- The MIT Plasma Probe ---- 105
- The Ames Plasma Probe ---- 107
- The Chicago Cosmic-Ray Experiment ---- 109
- The GRCSW Cosmic-Ray Experiment ---- 111
- The Minnesota Cosmic-Ray Experiment ---- 115
- The Stanford Radio Propagation Experiment ---- 116
- TRW Systems Electric Field Experiment ---- 120

	Page
The Goddard Cosmic Dust Measurements	121
The Pioneer Celestial Mechanics Experiment	123
Solar Weather Monitoring	125
BIBLIOGRAPHY	127
Appendix. MEMORANDUM: ORGANIZATION OF AMES SOLAR PROBE TEAM	129

CHAPTER 1

Origin and History of the Interplanetary Pioneer Program

THE SCIENTIFIC CHALLENGE OF INTERPLANETARY SPACE

WHEN WE LOOK UP AT THE STARS, we think we see the real universe, but the stars constitute only about 1 percent of the matter in the universe. The other 99 percent exists as dust and gas and occupies the space between the stars. The real drama of cosmic evolution may be unfolding in the cold space between the stars rather than in hot stellar interiors. But until recently, science has confined its study mainly to the astronomical bodies that shine by their own emissions or by reflected light. The bulk of the universe has been by necessity virtually ignored.

The only direct, *in situ* measurements we can make of this dominant fraction of the universe are from space probes and satellites that reach well beyond the distorting influences of the Earth's atmosphere and magnetic field. Even then, the probes measure interplanetary space rather than interstellar space. The region between the planets is swept by the solar wind and bursts of solar cosmic rays which usually overwhelm galactic phenomena. Still, this can be advantageous to science, because spacecraft in interplanetary space can monitor the interface between a typical star—the Sun—and interstellar space, recording the outward flow of solar electromagnetic energy, solar cosmic rays, and solar plasma. Similarly the inflow of galactic cosmic rays can be measured. Like all interface regions, interplanetary space is full of turmoil and is a rich region for scientific research.

The scientific mission of Pioneers 6 through 9[1] has been the synoptic measurement of the interplanetary milieu as it is affected by the Sun. The Pioneers have measured and transmitted back to Earth data on solar plasma, solar and galactic cosmic radiation, magnetic and electric fields, and the specks of cosmic dust that pervade interplanetary space. All of these phenomena, even the flux of galactic cosmic rays, are strongly affected by events occurring

[1] Also called Pioneers A through D prior to launch. Pioneer E, which would have been Pioneer 10, was a launch failure. Pioneers 1 through 5 were early lunar probes.

on the Sun. Spotted strategically around the Sun in the plane of the ecliptic, they have monitored the ever-changing fluxes and fields that wax and wane with solar activity. In purpose, the Pioneers have been akin to weather satellites, except that they are artificial planets of the Sun and not satellites of the Earth. In fact, data from the Pioneers have been used extensively in preparing "space weather" forecasts.

The main pulse of solar activity is the 11-year cycle of sunspots, a periodic phenomenon felt the length and breadth of the solar system. In 1961, when the National Aeronautics and Space Administration (NASA) formulated the Pioneer Program, scientists around the world were organizing a concentrated study of solar events expected during the 1964–1965 solar minimum. It seemed highly desirable to have some unmanned instrumented spacecraft out in deep space to support the growing number of International Quiet Sun Year (IQSY) projects. Data radioed back from these proposed spacecraft would supplement those received from NASA's OGOs, OSOs, and Explorer satellites in orbit around the Earth and a worldwide array of scientific sensors on the ground. A unique feature of such spacecraft in heliocentric orbits lay in the fact that they would range far ahead and behind the Earth as it swung around the Sun, giving scientists a more comprehensive picture of interplanetary space at various azimuths along the plane of the ecliptic. As the following chapters will show, the unexpectedly long lives of the Pioneers extended deep-space scientific coverage through the 1969–1970 solar maximum. Furthermore, lunar and solar occultations and unusual spacecraft alignments have occurred which increased the scientific payoff of the Pioneer Program far beyond original expectations. As Chapter 4 demonstrates, the Pioneers added immeasurably to our knowledge of the region between 0.8 and 1.2 Astronomical Units (AU)[2] as well as to our knowledge of the Sun itself.

THE AMES SOLAR PROBE STUDIES

The Pioneer Program began as an informal study of solar probes at the Ames Research Center in May 1960. At this time, NASA had been in existence only a year and a half, and the previous National Advisory Committee for Aeronautics (NACA) laboratories, such as Ames, were still working at defining their roles in space. The solar-probe study was an attempt to demonstrate Ames' potential as a spacecraft project manager and to also interest top management at

[2] The Astronomical Unit is equal to the mean distance from the Earth to the Sun; i.e. about 92.95 million miles or 149.6 million kilometers.

Ames in this role which departed from Ames' traditional function as an aeronautical research center.

The informal study team was headed by Charles F. Hall, who enlisted a dozen other Ames engineers in the effort.[3] The results of the study were published as an internal Ames report on July 22, 1960, bearing the title: "A Preliminary Study of a Solar Probe."

The spacecraft conceived during the study was conical in shape and was designed to point continuously at the Sun as it approached to about 0.3 AU. The Ames solar probe was quite different from the Pioneer spacecraft that it was to engender. However, the scientific rationale quoted in the report differed little from that adopted for the Pioneers: "The desirability of a solar probe was indicated by the thought that an increase in knowledge of solar phenomena through measurements made near the Sun would aid in an understanding of terrestrial phenomena in such areas as communication, weather prediction and control, and atomic and nuclear physics." The spacecraft was envisoned as small, simple, and long-lived, just as its progeny were to be in fact.

Although considerable opposition developed at Ames to getting into spacecraft project work, Smith J. DeFrance, the Center Director, among others, supported the solar-probe project. On September 14, 1960, DeFrance organized a formal Ames Solar Probe Team. (The text of the memorandum setting up the team is reproduced in the Appendix.) Headed by Hall, the team retained many of the members of the informal group and was charged with recommending a "practical system."

The Solar Probe Team now bent its efforts to fleshing out the skeleton concept described in the July 22, 1960, report. The objective was to show the practical feasibility of the Ames concept and demonstrate to NASA Headquarters Ames' capability for heading up a hardware project. The basic spacecraft concept changed somewhat during these studies. The major problem involved keeping the spacecraft and its instruments cool as it neared the Sun. Fuller descriptions of the spacecraft, its trajectory, and the proposed instruments can be found in references 1 and 2.

During late 1961 and early 1962, Hall and others tried to stimulate interest in the concept at NASA Headquarters. At one presentation, Jesse Mitchell, from NASA's Office of Space Science, became intrigued with the Ames spacecraft. Mitchell subsequently arranged a meeting between Hall and Edgar M. Cortright, who was the

[3] Specifically: Bader, M., Beam, B. H., Dimeff, J., Dugan, D. W., Eggers, A. J., Jr., Hansen, C. F., Hornby, H., Jones, R. T., Matthews, H. F., Mersman, W. A., Robinson, G. G., and Tingling B. E.

Deputy Director of the Office of Space Science at that time.[4] Cortright pointed out that Ames had no spacecraft experience, but he also remarked that he would like to see Ames get into the "hardware business." He posed the question: Would Ames be interested in building an Interplanetary Pioneer as a step on the way to the solar probe? Hall returned to Ames and received a go-ahead from Ames management. Ames management also recommended that an industrial contractor be brought in to do a feasibility study.

SELECTING A CONTRACTOR

The industrial contractor chosen was Space Technology Laboratories (STL)[5] at Redondo Beach, California. STL, acquainted with the Ames work, submitted an unsolicited proposal that was subsequently funded. In April 1962 STL completed the 2½-month, $250 000, feasibility study (ref. 3) under NASA Contract NAS2–884.

The STL Pioneer feasibility study was particularly significant because, during the 2½ months in early 1962, almost all of the important system-design decisions were made by STL engineers working in conjunction with NASA-Ames personnel. The key concept of a spin-stabilized spacecraft, with its spin axis perpendicular to the plane of the ecliptic, and a flat, fanlike, high-gain antenna pattern was originated by Herbert Lassen, of STL. As discussed in Vol. II, Chapter 1, this concept helped meet all the severe design constraints placed upon Pioneer by weight, cost, and schedule.

The next big step was obtaining formal project approval from Headquarters. The Ames group, backed by DeFrance, made the key presentation to NASA Associate Administrator Robert C. Seamans, Jr., on June 6, 1962. After Congress approved the NASA budget, Seamans signed the Project Approval Document (PAD) on November 9, 1962.

Pressing their advantage, STL followed up the feasibility study with an unsolicited proposal to design and fabricate four spacecraft, quoting a price of $10 million on a cost-plus-fixed-fee basis (ref. 4). Ames wished to go ahead with a sole-source procurement, but this was disapproved and competitive selection was stipulated.

Using the STL feasibility study as a foundation, Ames wrote the specifications for the Pioneer spacecraft and on January 29, 1963, issued a Request for Proposal (RFP–6669) to industry. Eight companies responded on March 4, 1963. Because of the price dis-

[4] Interview with Charles F. Hall, January 26, 1971.

[5] STL's name was later changed to TRW Systems. TRW refers to Thompson-Ramo-Wooldridge, the parent company.

parity between the two technically superior proposals (from Hughes and STL), NASA requested that these two companies resubmit bids on a fixed-price-incentive (FPI) basis.[6] The second submissions were received on May 24, 1963. STL was selected over Hughes in the final competition (ref. 5). The terms of a letter contract were agreed upon in July, and the letter contract was awarded on August 5, 1963. The contract authorized expenditures up to $1.5 million. Work began immediately at STL. The definitive contract (NAS2–1700) was negotiated later and was approved by NASA Headquarters on July 30, 1964. It is interesting to note here that the incentive provisions of the contract (as opposed to the cost-plus-fixed-fee contract then common in aerospace work) forced NASA to define everything it wanted with high precision. Contract negotiations were lengthy, and approximately 80 changes were made to the basic statement of work originally stated in RFP A–6669. With a contractor hard at work, Pioneer moved ahead rapidly toward the first launch, planned for 1965.

THE PIONEER ORGANIZATION

The Pioneer hardware, described in the next chapter, consisted of four major systems:

(1) The spacecraft itself
(2) The scientific instruments
(3) The launch vehicle
(4) The ground-based tracking and data acquisition stations

NASA assigned teams of engineers and scientists to each of these four technical elements. Many contractor personnel, especially at TRW Systems and the Deep Space Network (DSN) stations, were closely involved in the program.

The purpose of this section is the general recounting of how Pioneer was organized and who some of the key personnel were.

The overall NASA Pioneer organization is shown in figure 1–1, beginning with the NASA Administrator and showing the principal chains of command. This diagram shows overall management responsibility but does not highlight the groups where the bulk of the work was done. The actual work entailed:

(1) Spacecraft design, testing, and launching
(2) The design and testing of the scientific instruments and the presentation of final scientific results

[6] While the contract was being firmed up, STL was given a small side study to investigate the effects of uprating the Delta launch vehicle and going to a larger spacecraft.

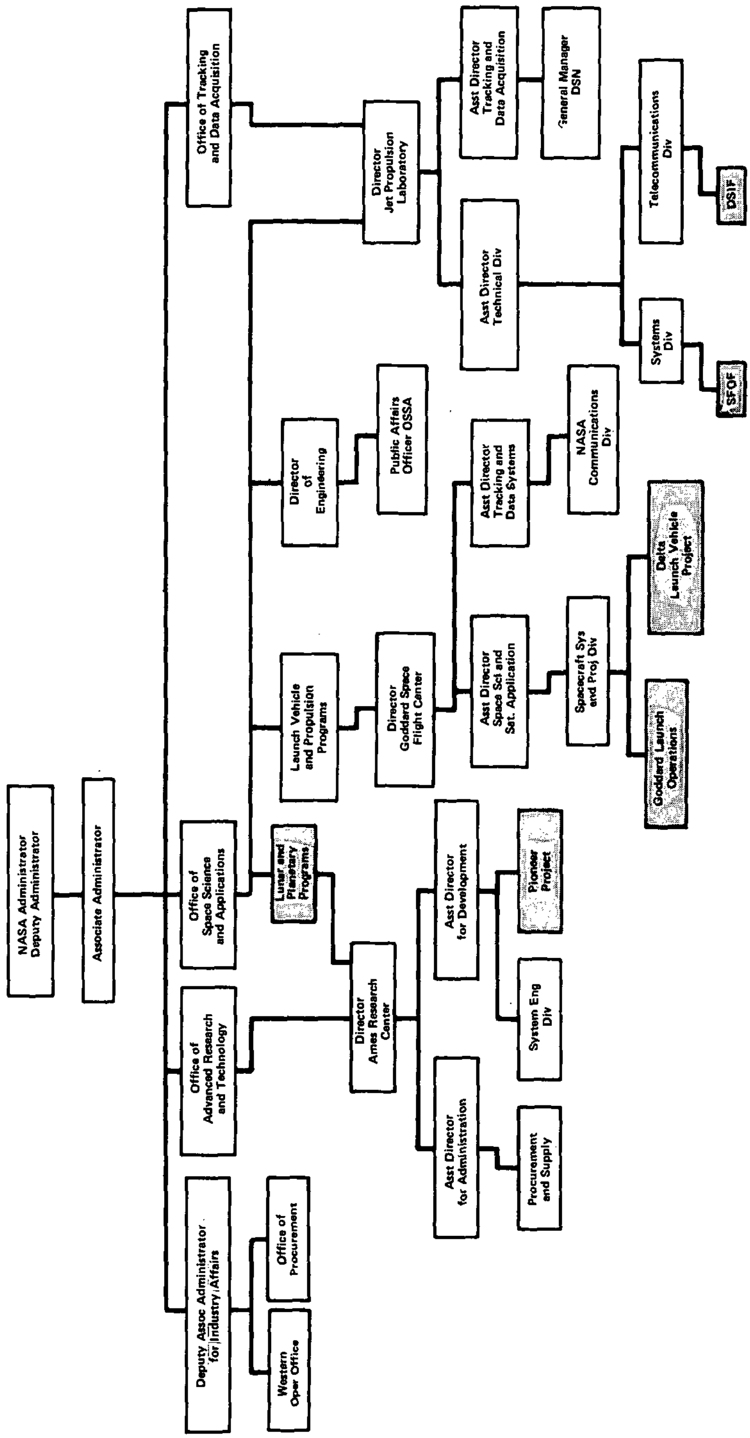

FIGURE 1-1.—Principal elements of the NASA organization early in the Pioneer Program. The shaded boxes indicate where most personnel assigned to Pioneer were located.

(3) The routine, but highly important, day-by-day control of the spacecraft and its tracking and data acquisition

(4) The huge volume of management chores that accompanies a program of this size

The shaded boxes on the diagram indicate the focal points of activity, but only those within NASA. Important contractors—TRW Systems and the experimenters, in particular—are not shown. What figure 1–1 does show well is the dual nature of the NASA organization. The Ames Research Center, for example, reported administratively through the Headquarters Office of Advanced Research and Technology, but project direction came from the Headquarters Office of Space Sciences and Applications. The Pioneer Program was one of the few NASA spacecraft programs assigned to a NASA research-oriented center. Obviously, the unusual arrangement worked very well in the case of Pioneer.

Basically Ames built, tested, and controlled the spacecraft and the scientific instruments provided by the experimenters; Goddard procured a Delta rocket and launched the spacecraft; the Jet Propulsion Laboratory (JPL), which operated the DSN, tracked the spacecraft and passed the acquired data on to Ames. Headquarters provided overall direction. This situation is spelled out more thoroughly in table 1–1 and figure 1–2. Figure 1–2 shows how the Ames Pioneer Project Manager, C. F. Hall, organized his group to tie together the different elements of NASA into a smoothly functioning team. The

TABLE 1–1.—*Responsibilities in the Pioneer Program*

Task	Organization	Individuals
Overall program direction	Lunar and Planetary Program Office, Office of Space Science and Applications, NASA Headquarters	Kochendorfer, F.D. (1962–1963) Reiff, G.A. (1963–1970) Kochendorfer, F.D. (1970 to date)
Project management	Ames Research Center	Hall, C.F.
Spacecraft system		
Design, fabrication, and testing of spacecraft and mission-dependent ground operational equipment	Ames Research Center TRW Systems	Holtzclaw, R.W. Mickelwait, A.G. (1962–1967) O'Brien, B.J. (1967 to date)
Scientific instrument system		
Assuring that overall scientific objectives are met	Ames Research Center	Wolfe, J.H.
Management of scientific instrument systems	Ames Research Center	Cross, H.V. Lepetich, J.E. (1962 to date)
Providing scientific instruments, data reduction and analysis, and scientific reporting:		

TABLE 1-1.—*Responsibilities in the Pioneer Program*—Concluded

Task	Organization	Individuals
Magnetometer (Pioneers 6, 7, 8)	Goddard Space Flight Center	Ness, N.F.
Magnetometer (Pioneers 9, E)	Ames Research Center	Sonett, C.P.
Plasma probes (Pioneers 6, 7, 8, 9, E)	Ames Research Center	Wolfe, J.H.
Plasma probes (Pioneers 6, 7)	Massachusetts Institute of Technology	Bridge, H.
Cosmic-ray telescope (Pioneers 6, 7)	University of Chicago	Simpson, J.A.
Cosmic-ray experiment (Pioneers 6, 7, 8, 9, E)	Graduate Research Center of the Southwest	McCracken, K.G.
Cosmic-ray experiment (Pioneers 8, 9, E)	University of Minnesota	Webber, W.R.
Radio propagation experiment (Pioneers 6, 7, 8, 9, E)	Stanford University	Eshleman, V.R.
Electric-field detector (Pioneers 8, 9, E)	TRW Systems	Scarf, F.L.
Cosmic dust detector (Pioneers 8, 9, E)	Goddard Space Flight Center	Berg, O.
Celestial mechanics (Pioneers 6, 7, 8, 9, E)	Jet Propulsion Laboratory	Anderson, J.D.
Engineering instrument system		
Provision of a convolutional coder and analysis of results (Pioneers 9, E)	Ames Research Center	Lumb, D.R.
Launch vehicle system		
Procurement of Delta launch vehicle	Goddard Space Flight Center	Schindler, W.R.
Design and fabrication of the Delta launch vehicle	McDonnell-Douglas Aircraft Company	
Launch activities		
Direction of launch operations	Goddard Space Flight Center	Gray, R.H.
Tracking and data acquisition during powered flight	USAF Eastern Test Range	
Spacecraft-launch vehicle interface and coordination of launch vehicle operations	Ames Research Center	Hofstetter, R.U.
Flight operations		
Mission planning and control	Ames Research Center	Jagiello, L.T. (1962–1966) Nunamaker, R.R. (1966 to date)
Tracking, data acquisition, and command transmission	Jet Propulsion Laboratory	Thatcher, J.W. (1962–1966) Siegmeth, A.J. (1966 to date)
Data processing and analysis	Ames Research Center	Erickson, M.D. (1966–1969) Natwick, A.S. (1969 to date)

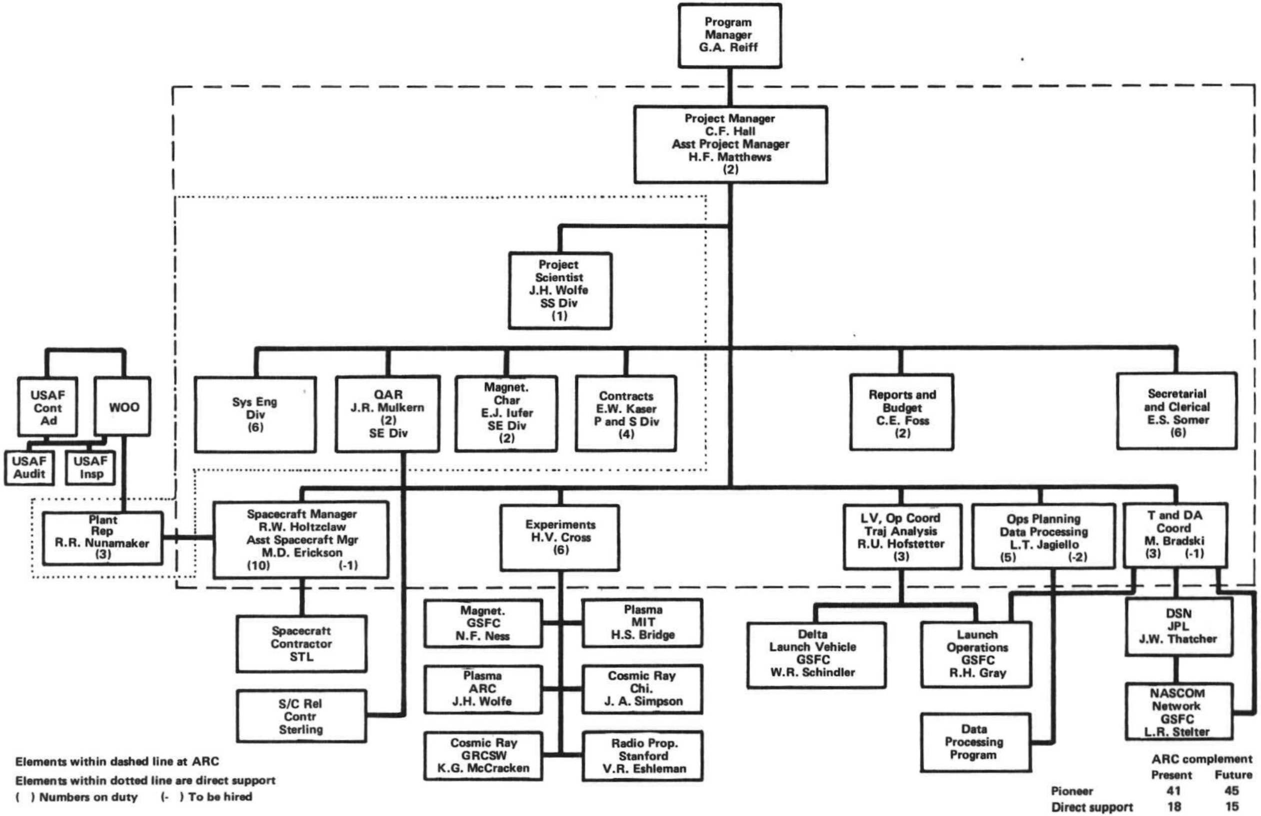

FIGURE 1–2.—The Pioneer team in 1964. This organization was remarkably stable. The few changes that were made are summarized in table 1–1.

Pioneer Project group at Ames was originally split into five groups, with almost a one-to-one correspondence with the four Pioneer systems—spacecraft, experiments, launch vehicle, tracking and data acquisition. Later, the correspondence was made exact when the five project groups were consolidated into four groups responsible for the spacecraft, the experiments, the flight operations (mainly tracking and data acquisition), and the launch vehicle and launch operations with groups from Goddard and JPL supporting the project. Figures 1–3 through 1–8 show some of the individuals who contributed to the Pioneer Program. In practice, Ames personnel from the Pioneer Project worked directly with those people in the support groups assigned to Pioneer, even though they reported through JPL, Goddard, or contractor managements. This synthesis of project-oriented and functionally oriented personnel has been quite common and very effective in the aerospace industry.

During any project extending over a decade, one would expect considerable turnover of key people within government and the contractor organizations. Pioneer is an exception to this rule in

FIGURE 1–3.—NASA Headquarters inspection of the mockup of the Pioneer instrument platform. Left to right: R. F. Garbarini, J. E. Naugle, C. F. Hall (Ames), A. B. Mickelwait (TRW Systems), O. W. Nicks, H. E. Newell, and H. A. Lassen (TRW Systems).

FIGURE 1-4.—Part of the Ames Pioneer Project team. Left to right: top row, G. J. Nothwang, C. F. Hall; middle row, A. J. Wilhelm, R. U. Hofstetter, R. L. Edens; bottom row, D. W. Lozier, J. E. Lepetich, R. W. Holtzclaw.

that personnel changes have been minor. People and organization structures have stayed remarkably stable. The important changes that have occurred are summarized in table 1-1. One of the most important factors in the success of the Pioneer Program has undoubtedly been the permanence, high capability, and dedication of the Ames Pioneer Project personnel.

THE PIONEER SCHEDULE

The Pioneer Program consisted of five flight spacecraft, the five Delta rockets for launching them, the experiments, and all the

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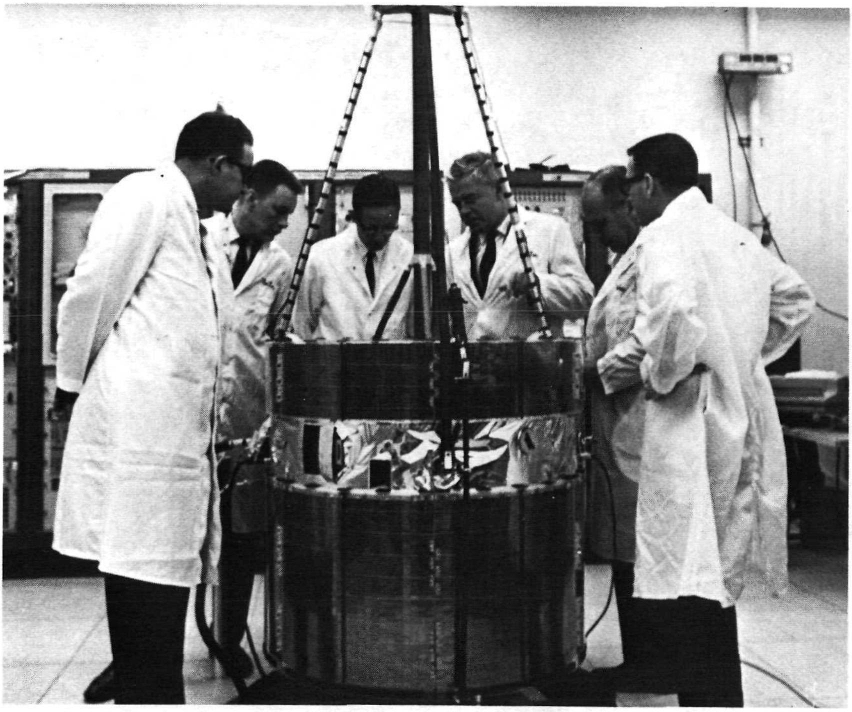

FIGURE 1-5.—Inspection of the Pioneer prototype at TRW Systems in 1965. Far left, A. B. Mickelwait; second from left, G. A. Reiff (NASA Headquarters); fourth from left, C. F. Hall (Ames). (Courtesy of TRW Systems.)

FIGURE 1-6.—Part of Pioneer management team at Cape Kennedy in 1967. Left to right: B. J. O'Brien (TRW Systems), J. Mitchell (NASA Headquarters), M. Aucremanne (NASA Headquarters), C. F. Hall (Ames).

FIGURE 1-7.—R. Gray, second from left, headed Goddard Operations at the Cape during the Pioneer Program. W. R. Schindler, third from left, managed Goddard's Delta program. At far left, J. Schwartz (WTR); at far right, H. Van Goey.

FIGURE 1-8.—JPL DSN personnel assigned to Pioneer. Left to right, A. J. Siegmeth, J. W. Thatcher, and N. A. Renzetti. (Courtesy of JPL.)

necessary ground equipment for tracking and the acquisition and processing of the data. Table 1–1 reveals many, but not all, of the government and contractor organizations that had to work together to produce scientific measurements from deep-space instrument platforms. In such a complex program, one can expect schedule slippages here and there. In the case of Pioneer, the schedule changes due to spacecraft engineering and fabrication were all relatively minor. The first two spacecraft were launched close to the original schedule, during the period of low solar activity as the scientists had intended.

Two kinds of schedules are presented here. First, figure 1–9 reproduces the Pioneer master schedule from the original Project Development Plan which was issued in March 1965. This particular schedule is of historical interest and, in addition, shows the many diverse program elements that had to be completed for a timely launch.

The second set of schedules is presented in figures 1–10 through 1–14—one for each of the five flight spacecraft. Each schedule slippage is explained in the right-hand margin; these explanations are indicative of the many different factors affecting the Pioneer Program.

Pioneers 6 and 7 were launched fairly close to the original target dates. The slippages in the launch schedules of the remaining three spacecraft were much greater. Many of the delays were attributable to troubles with the experiments. In the case of Pioneer 9, launch was delayed to provide a larger time interval between Pioneers 7 and 8 and to permit certain trajectories later. The launch date of the ill-fated Pioneer E was slipped for the same reasons.

THE PIONEER COST PICTURE

One of the original constraints placed upon the Pioneer Program when it was being formulated in 1962 was that the total cost be around $30 million.[7] During the years, the Pionêer Program was expanded for a number of reasons, as enumerated below and in figure 1–15. The net result has been that the entire Program has cost about $70 million. Here are the major reasons for the cost increases:

(1) Addition of data processing

(2) Addition of a fifth spacecraft

(3) Unexpected long lives of the spacecraft, requiring additional funds for tracking and data acquisition

[7] Other constraints were the use of the Delta launch vehicle, and the use of the Deep Space Network.

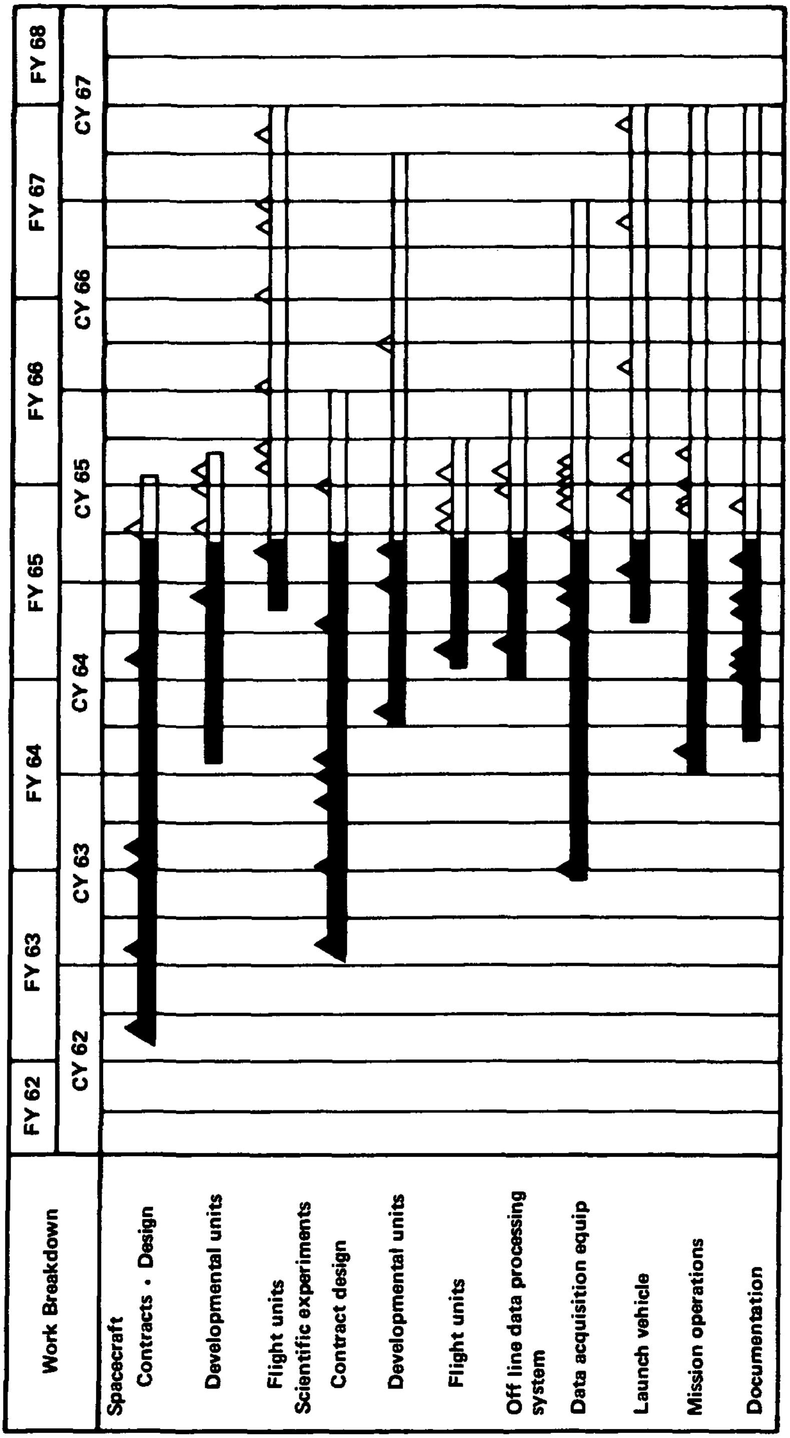

FIGURE 1-9.—Project Pioneer master schedule as of March 15, 1965.

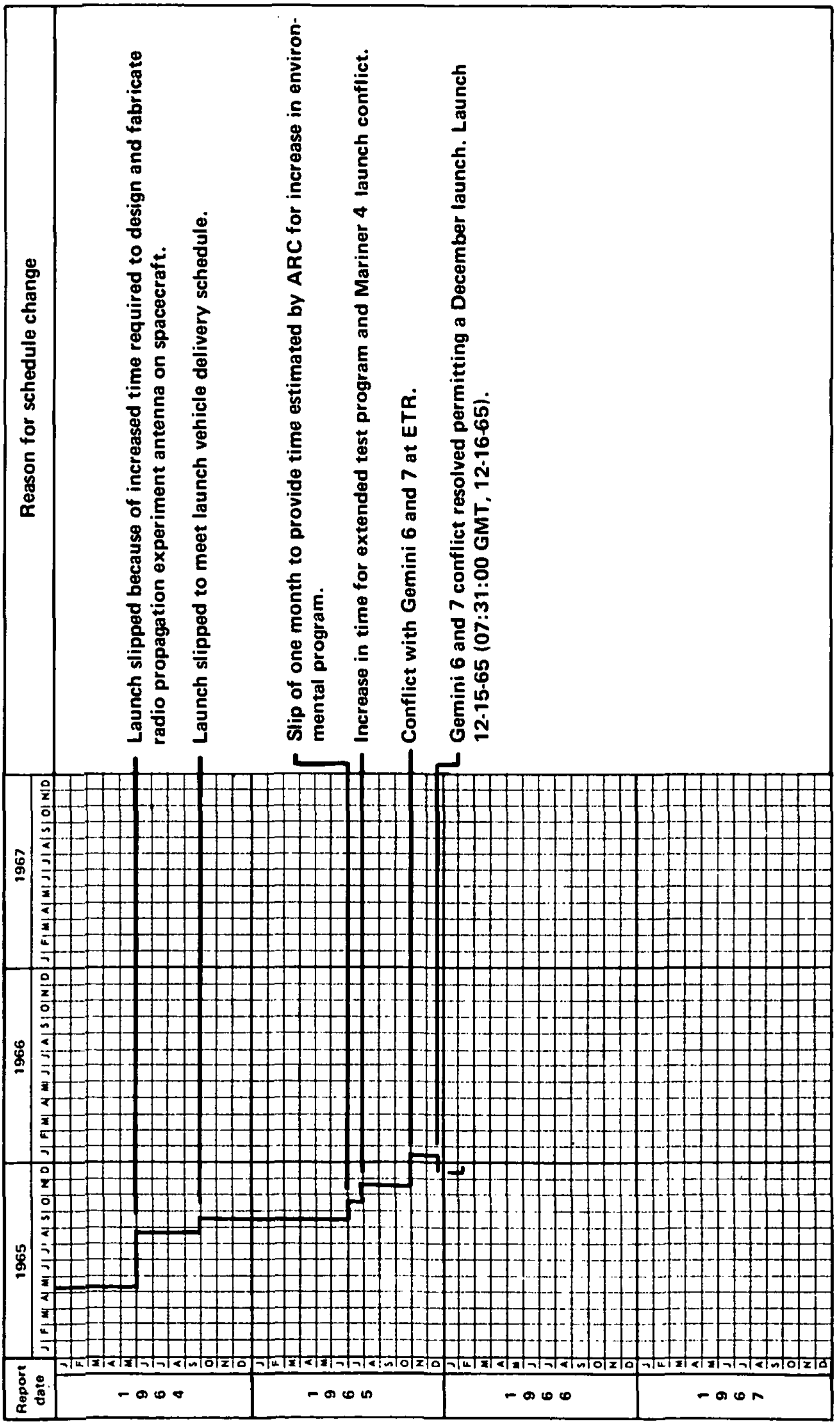

FIGURE 1-10.—Pioneer A schedule. Explanation for slippages are given at the right.

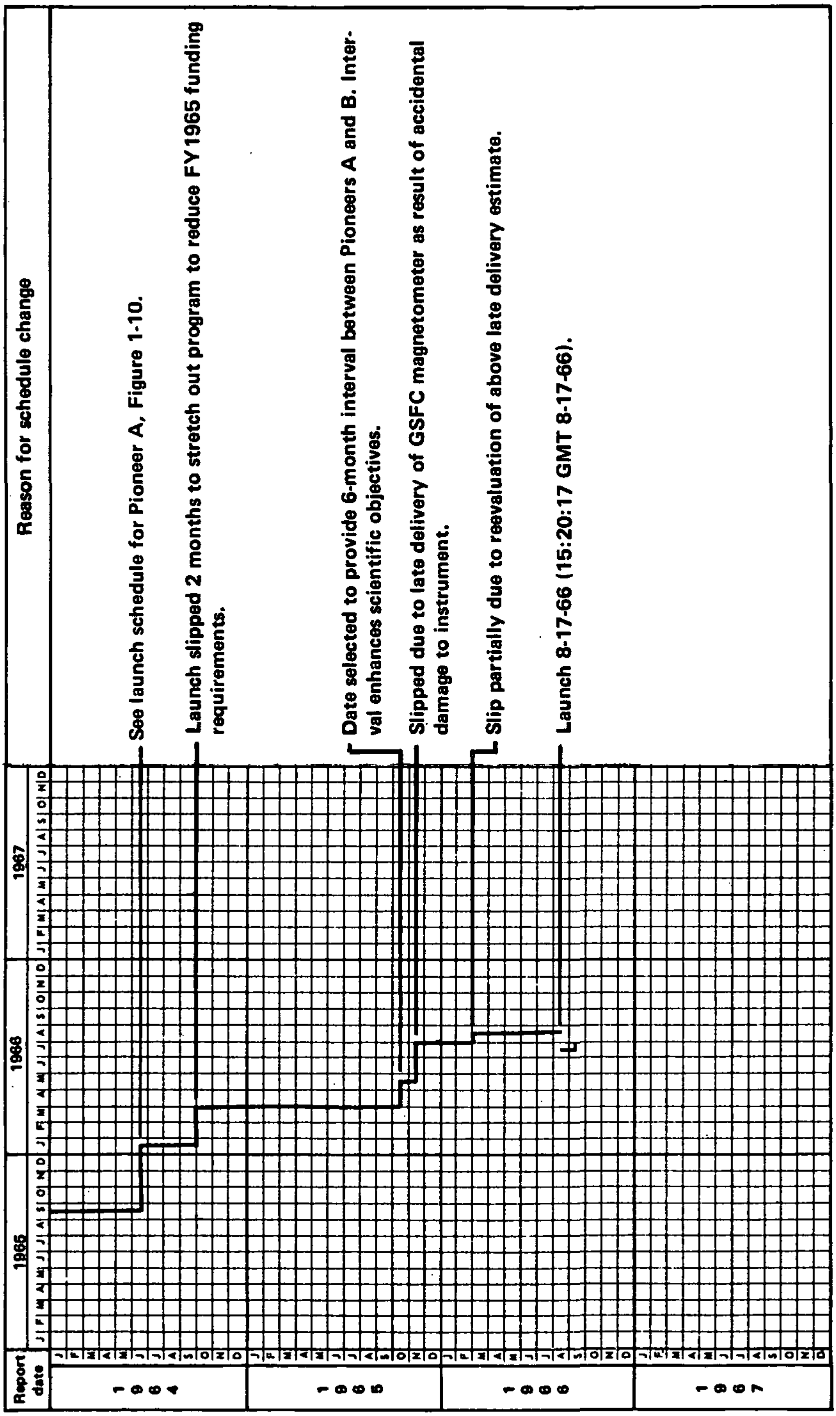

FIGURE 1-11.—Pioneer B schedule.

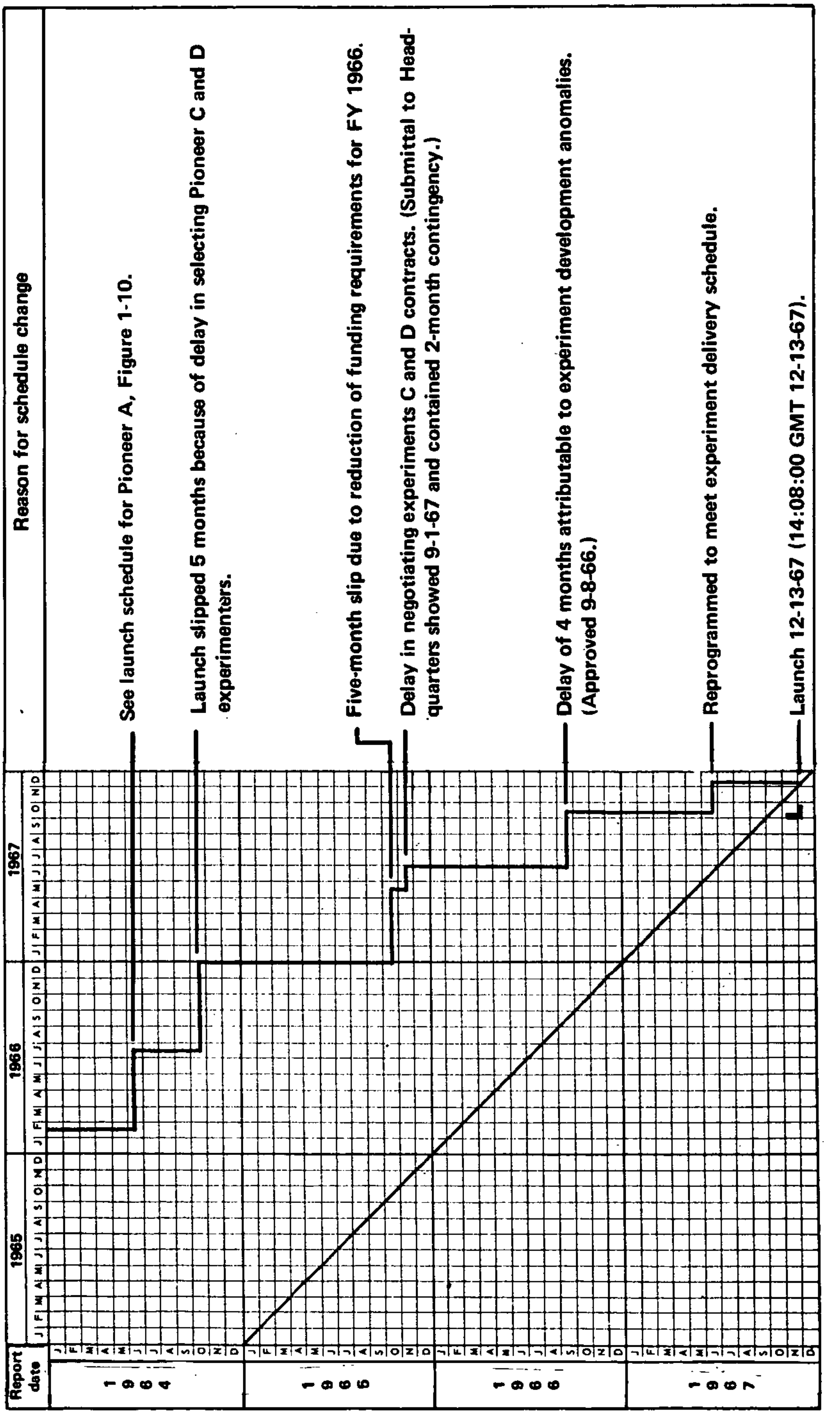

FIGURE 1-12.—Pioneer C schedule.

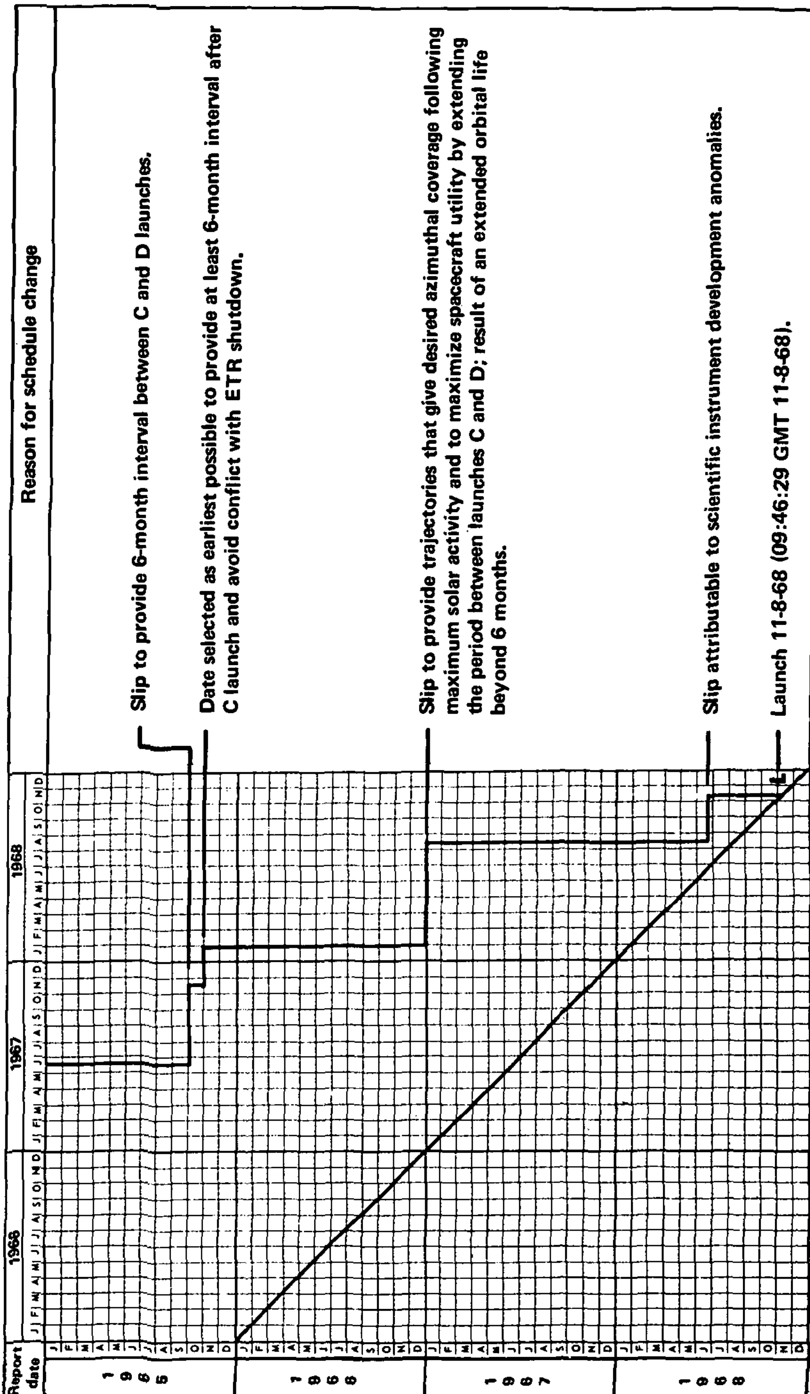

FIGURE 1-13.—Pioneer D schedule.

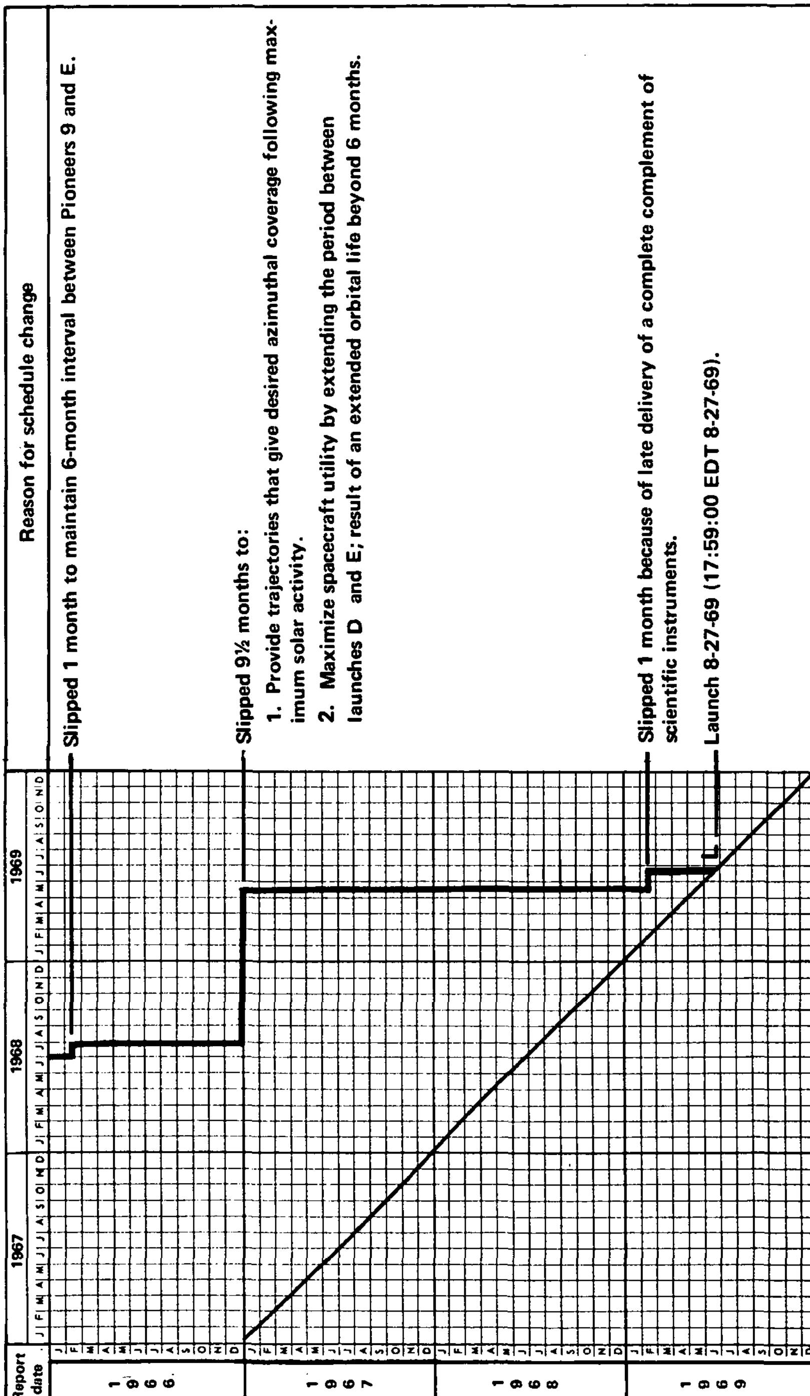

FIGURE 1-14.—Pioneer E schedule.

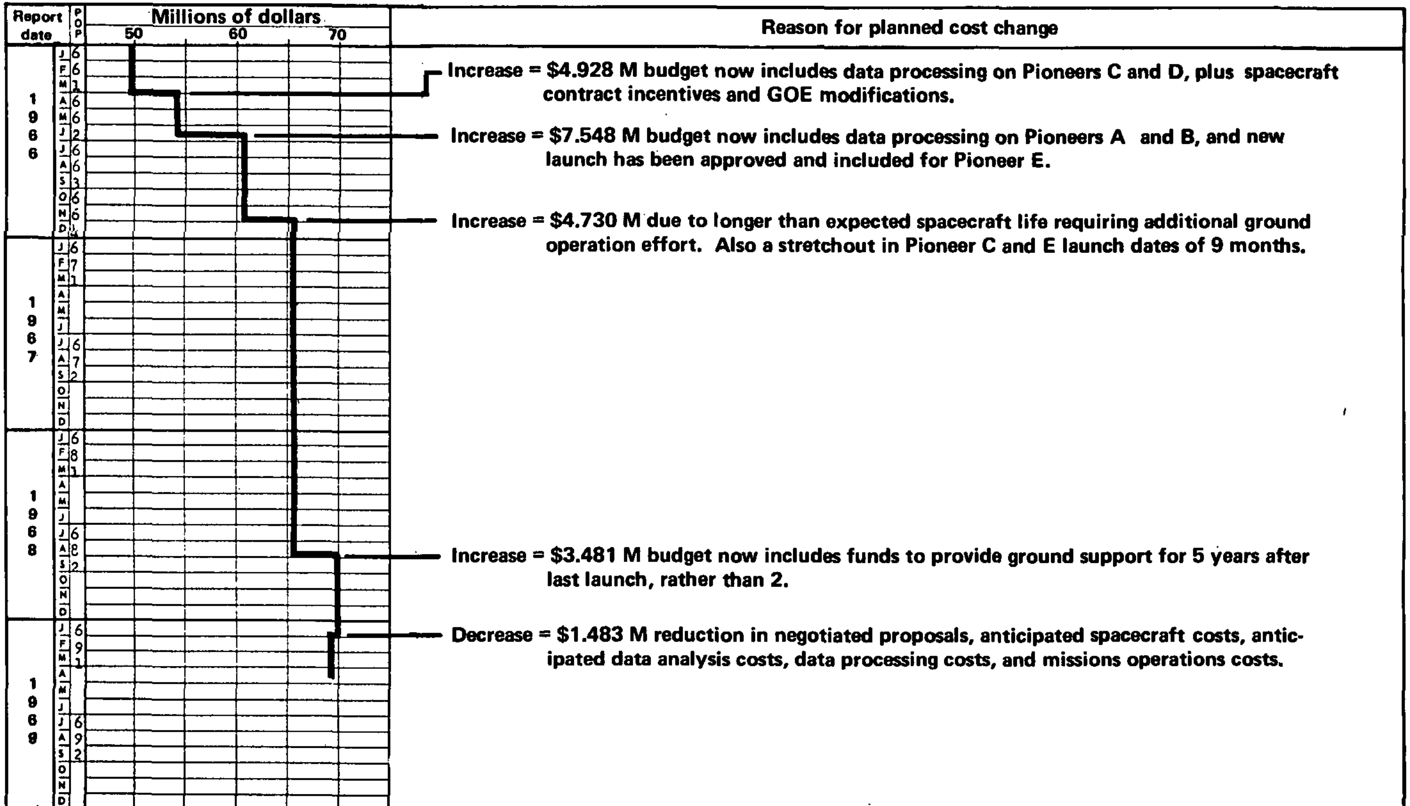

FIGURE 1–15.—Pioneer Program cost trends as of spring, 1969. Reasons for increases and decreases are indicated at the right.

(4) Delays due to late deliveries of experiments

(5) Differences between Pioneers 6 and 7 (the Block–I spacecraft) and Pioneers 8, 9, and E (the Block–II spacecraft) because different experiments were selected for each block

When the long useful lives of the four successfully launched Pioneers are considered (more than 5 years for Pioneer 6), this Program is incontestably one of the least expensive of all NASA spacecraft programs in terms of scientific results per dollar spent.

PIONEER CHRONOLOGY

Table 1–2 is a chronology which summarizes the major historical events related in earlier pages and also adds a few points not brought out in the text. Much more detailed chronologies covering operations at Cape Kennedy and postlaunch events are presented in Volume III.

TABLE 1–2.—*Chronology of Major Historical Events in the Pioneer Program*

Date	Event
July 22, 1960	Release of Ames report, "A Preliminary Study of a Solar Probe"
Sept. 14, 1960	Formation of Ames Solar Probe Team
Apr. 1962	STL study of an interplanetary Pioneer completed
June 6, 1962	Presentation of Ames and STL work on interplanetary Pioneer to R.C. Seamans, Jr., and other NASA Headquarters personnel
Nov. 9, 1962	Pioneer PAD signed
Jan. 10, 1963	Pioneer procurement plan approved
Jan. 29, 1963	RFP for spacecraft sent to industry
Feb. 1, 1963	RFP for experiments sent to potential experimenters for Pioneers A and B
Mar. 4, 1963	Eight proposals received at Ames
Mar. 30, 1963	Spacecraft Selection Board evaluations complete
Apr. 8, 1963	Experiment proposals received by NASA Headquarters
Apr. 11, 1963	Procurement briefing to NASA Administrator. Decision to readvertise the Pioneer spacecraft to STL and Hughes on FPI basis
May 14, 1963	New RFP to STL and Hughes
May 24, 1963	Second set of proposals received at Ames
Jun. 7, 1963	Second procurement briefing for NASA Administrator. Decision to negotiate with STL
Aug. 5, 1963	Letter contract signed with STL
Apr. 1964	Final spacecraft design review
July 30, 1964	Definitive contract with STL approved by NASA Headquarters
Dec. 5, 1965	Pioneer-A flight model arrives at Cape Kennedy
Dec. 15, 1965	Pioneer-6 launch successful
Feb. 22, 1966	Contract with TRW Systems amended to delete fifth spacecraft in series for budgetary reasons
Mar. 2, 1966	Pioneer-6 inferior conjunction or syzygy

TABLE 1-2.—*Chronology of Major Historical Events in the Pioneer Program*—Concluded

Date	Event
Apr. 28, 1966	Contract with TRW Systems amended to fabricate fifth spacecraft out of spares
Aug. 17, 1966	Pioneer-7 launch successful
Aug. 31, 1966	Traveling Wave Tube (TWT) 2 switched in to replace TWT 1 on Pioneer 7 [a]
Sept. 30, 1966	Pioneer-7 inferior conjunction or syzygy
Jan. 19, 1967	Pioneer-7 lunar occultation
Dec. 13, 1967	Pioneer-8 launch successful
Jan. 17, 1968	Pioneer-8 inferior conjunction or syzygy
Jan. 27, 1968	Pioneer-8 emerges from geomagnetic tail
Oct. 6, 1968	First use of Deep Space Network-Manned Space Flight Network (DSN-MSFN) hybrid configuration on Pioneer-8
Nov. 8, 1968	Pioneer-9 launch successful
Nov. 23, 1968	Pioneer-6 superior conjunction (behind Sun)
Jan. 30, 1969	Pioneer-9 inferior conjunction or syzygy
Feb. 16, 1969	Sun pulse lost from Pioneer-7
Aug. 27, 1969	Pioneer-E launch unsuccessful due to failure of Delta rocket guidance system
Nov. 28, 1969	First simultaneous tracking of two spacecraft (Pioneers 6 and 7)
Jan. 20, 1970	Electromagnetic interference tests of Pioneers 8 and 9 to check effects on cosmic dust experiment
July 26, 1970	Pioneer-6 magnetometer lost
Oct. 30, 1970	Simultaneous tracking of Pioneers 6 and 8
Dec. 18, 1970	Pioneer-9 superior conjunction (behind Sun)

[a] The TWT is used in the transmitter power amplifier. This was the only serious trouble experienced with this vital component during all Pioneer flights.

REFERENCES

1. DUGAN, D.W.: A Preliminary Study of a Solar-Probe Mission. NASA TN D-783, April 1961.
2. HALL, C.F.; NOTHWANG, G.J.; and HORNBY, H.: A Feasibility Study of Solar Probes. IAS Paper 62-21, 1962.
3. ANON: Space Technology Laboratories, Final report on the Interplanetary Probe Study. August 15, 1962.
4. ANON: Space Technology Laboratories, A Proposal for an Interplanetary Probe during the International Quiet Sun Year. STL Proposal No. 1536.00. August 1962.
5. ANON: Space Technology Laboratories, Proposal under RFP-A-6669 to Produce the Pioneer Spacecraft for Study of Particles and Fields in Interplanetary Space during the International Quiet Sun Year. STL Proposal No. 1943.00. March 4, 1963.
6. HALL, C.F.; AND MICKELWAIT, A.B.: Development and Management of the Interplanetary Pioneer Spacecraft. NASA TM X-60264, 1967. (Also in Proc., 18th International Astron. Congress, vol. 2, M. Lunc, ed., Pergamon Press, Oxford, 1968, pp. 173-187.)

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CHAPTER 2

Pioneer System Design and Development

DEFINING THE PIONEER SYSTEM

THE PIONEER SYSTEM was predicated upon the use of the Delta launch vehicle and the Deep Space Network for tracking and data acquisition. The decision to use the Delta meant a spacecraft of modest weight —something just over 100 lb plus 20 to 40 lb of scientific instruments. Financial resources for the entire program were set at between $50 and $100 million. The scientific objectives also helped shape the design of the spacecraft. The more important of these follow:

(1) The ability to point instruments at all azimuths along the plane of the ecliptic

(2) Continuous data sampling from the instruments

(3) High data transmission rates back to Earth

(4) Many commandable modes of operation, enabling experimenters to modify their apparatus from Earth

(5) A favorable instrument environment, particularly very low residual magnetic fields

(6) A long life—at least 6 months, possibly longer

(7) The inclusion of a wide variety of scientific instruments

Within the resources at hand, all of the scientific desiderata could not be realized, but some inspired design innovations increased the scientific payoff well beyond that expected from so small a spacecraft, as we shall see.

The overall Pioneer system consisted of the four systems portrayed in figure 2–1. The scientific instruments are considered a separate system rather than a spacecraft subsystem.

All four systems will be described in more detail later in this chapter. For the moment, let us consider the functions to be performed by the spacecraft. These functions are listed in table 2–1 where they are also assigned to one of the seven spacecraft subsystems. These subsystems are shown schematically in figure 2–2. By understanding how all of the subsystems fit together, one can appreciate better the many engineering tradeoffs that were considered in formulating the concept of the Pioneer spacecraft—a new and unusual

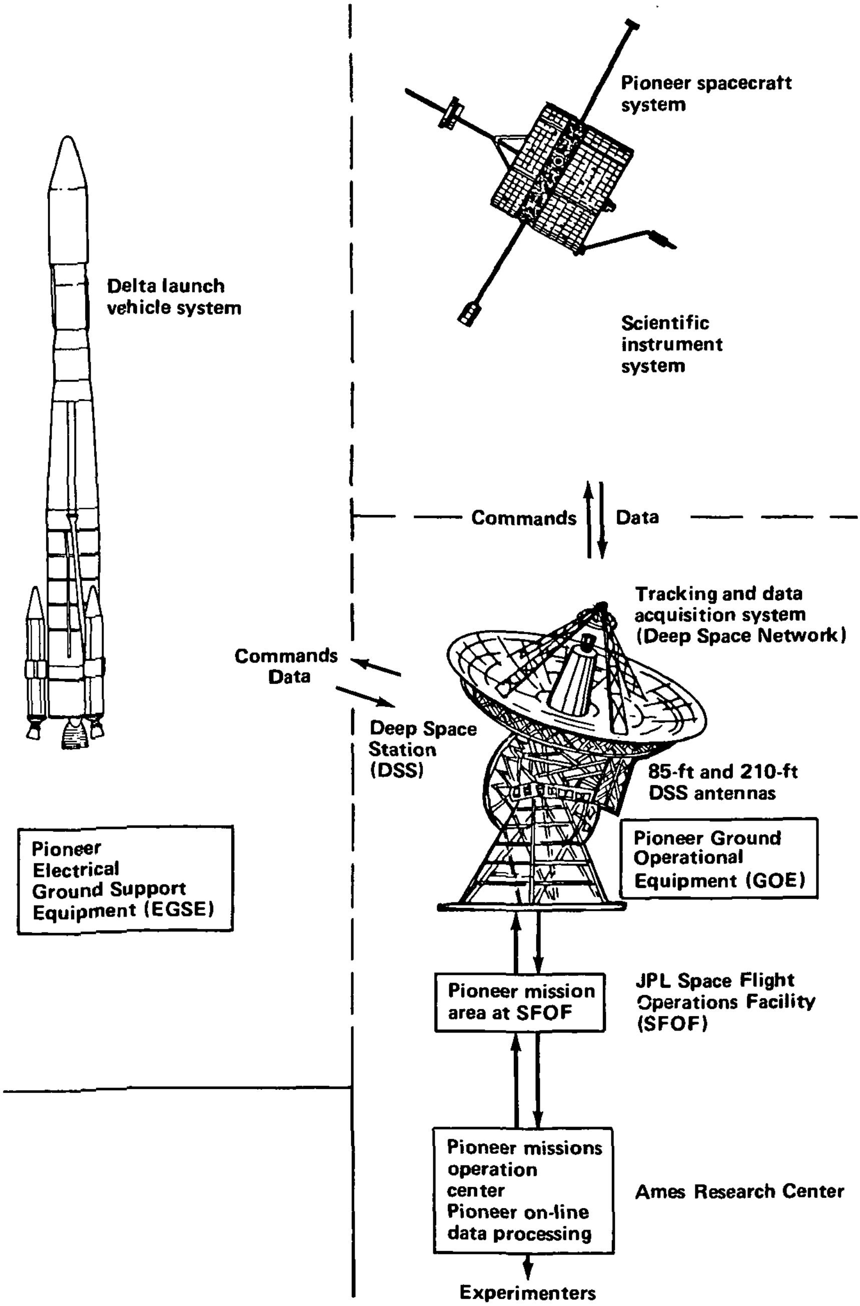

FIGURE 2–1.—The four Pioneer systems.

TABLE 2-1.—*Definition of Pioneer Spacecraft Subsystems*

Subsystem	Functions performed
Communication	Relays scientific and spacecraft status data from the spacecraft to Earth. Receives commands from Earth. Makes possible the two-way Doppler shift measurements required for orbit determination.
Data-handling	Accepts data from scientific and housekeeping instruments and arranges them in proper format for transmission back to Earth. Provides for limited data storage.
Electric-power	Provides electrical power to all spacecraft subsystems and the scientific instrument system.
Orientation	Orients the spacecraft spin axis as required; damps out wobble. Attitude sensors and gas jets are included within this subsystem.
Thermal-control	Maintains temperatures within specified ranges within the spacecraft.
Command	Decodes commands received via the communication subsystem; distributes commands to the spacecraft subsystems specified in the command addresses.
Structure	Supports and maintains spacecraft configuration under design loads. Provides booms for instrument isolation.

concept that strongly affected the spacecraft's interfaces with the Deep Space Network and the scientific instruments.

Restricted weight and the simplicity necessary for high reliability dictated a spin-stabilized spacecraft. However, random spin stabilization entailed three problems:

(1) A high-gain transmitter antenna was needed on the spacecraft if it was going to telemeter data to the Earth across the wide expanse of the solar system. Yet a high-gain, highly directional antenna could not be aimed at the Earth from a spinning spacecraft without unacceptably complicated control equipment.

(2) The scientists preferred to have their instruments scan the plane of the ecliptic, not any of the infinity of other planes possible with a randomly oriented spinning spacecraft.

(3) If the spin vector of the spacecraft were random, solar cells would have to be mounted on all sides of the spacecraft, increasing the weight.

These thoughts led to the concept of an *orientable,* spin-stabilized spacecraft with a spin axis that could be torqued by a simple gas jet until it was aligned perpendicular to the plane of the ecliptic. The laws of motion predicted that such torquing would cause wobbling, but this could be largely eliminated by a simple wobble damper. If the spacecraft is spin stabilized with its equator in the

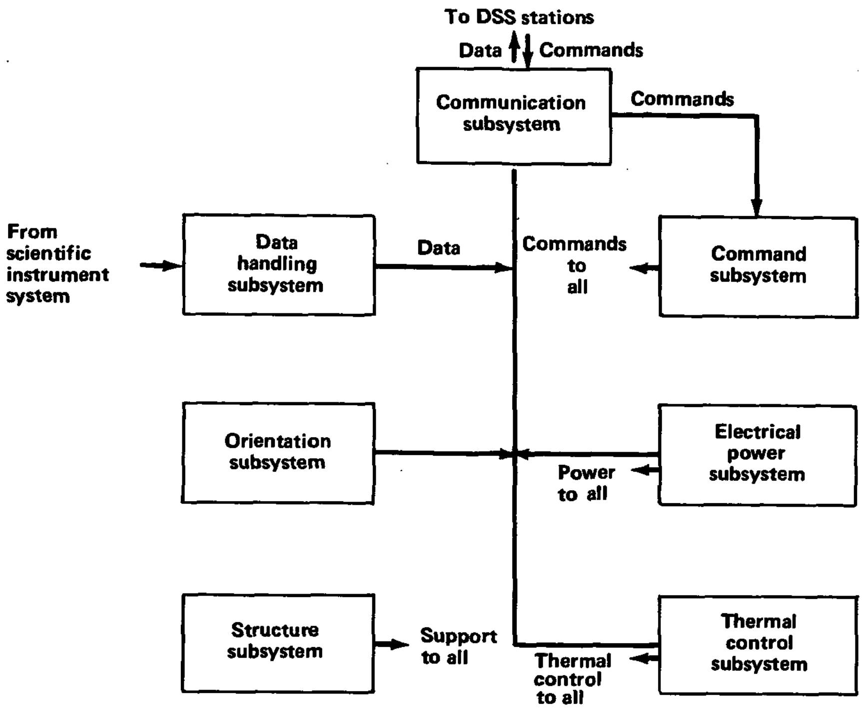

FIGURE 2-2.—Generalized block diagram showing Pioneer spacecraft subsystems. Magnetic, thermal, and other forces crossing subsystem interfaces are not shown.

plane of the ecliptic at all times, two of the three problems mentioned above could be solved easily. The scientific instruments could be mounted on an instrument platform perpendicular to the spin vector, and they could then scan the plane of the ecliptic as the spacecraft rotated. By making the spacecraft a right circular cylinder, solar cells need be mounted only on the curved sides because the Sun is in the plane of the ecliptic.

Only the antenna problem would remain. The capstone of the Pioneer concept is the use of a mastlike antenna (a modified Franklin array) mounted along the spin axis (fig. 2-3). This kind of antenna concentrates the radiated energy into a flat disk which, because of the unique spacecraft orientation, would lie in the plane of the ecliptic and thus be received by DSN antennas on Earth.

In fact, given the original weight constraints (imposed by the Delta and the mission), the Pioneer Project would not have been feasible without this novel concept; i.e., an orientable, spin-stabilized, cylindrical spacecraft with a disk-shaped antenna beam.

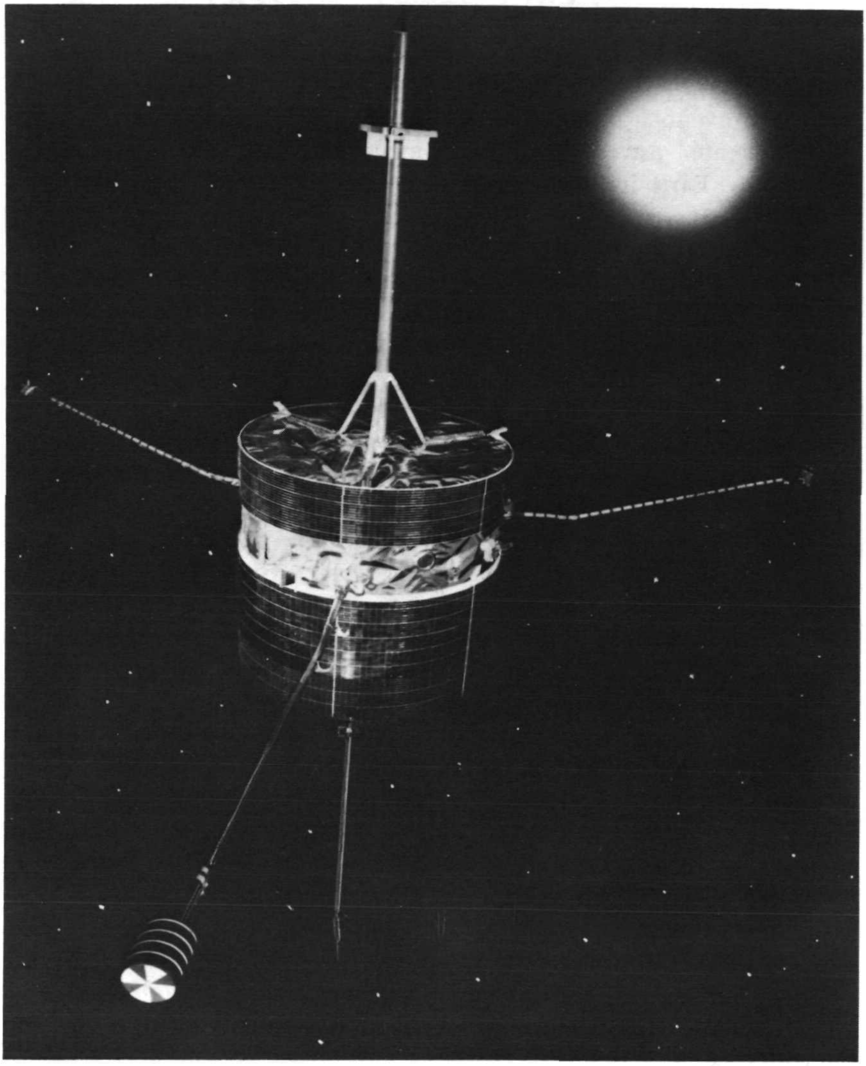

FIGURE 2-3.—View of the Pioneer spacecraft showing the three radial booms deployed, the telemetry antenna mast (top), and the Stanford radio propagation experiment antenna (bottom).

PIONEER LAUNCH TRAJECTORY AND SOLAR ORBIT DESIGN

The original plan for the Pioneer Program involved sending small spacecraft into orbits about the Sun where they could monitor solar events in interplanetary space without the perturbations of the Earth's magnetosphere and atmosphere. Trajectory analysis soon showed that the scientific productivity of the flights could be enhanced greatly by shaping the launch trajectories and heliocentric orbits to:

(1) Improve solar system coverage in the radial direction

(2) "Create" astronomical phenomena, such as solar occultations,

(3) Study Earth-induced space phenomena, such as the geomagnetic tail

The Pioneer flights were designed with these objectives in mind.

Pioneers 6 and 9 followed an inward trajectory, perihelion near 0.8 AU, in order to extend solar system coverage by Pioneer instruments into the sector ahead of the Earth as it plies its orbit about the Sun. Solar occultation of the spacecraft as seen by the tracking antennas on Earth was also planned for these two flights.

Pioneers 7 and 8 followed an outward trajectory, aphelion near 1.1 AU, in order to extend solar system coverage in the Earth's "wake." A lagging spacecraft actually detects solar events before terrestrial instruments because the outwardly spiraling solar magnetic lines of force sweep around the solar system faster than the planets due to the Sun's 28-day rotation.

Since the trajectory of an outward-bound Pioneer can be designed to swing through the Earth's magnetic tail, plans for geomagnetospheric tail analysis were included for Pioneers 7 and 8.

On both inward- and outward-bound missions, scientists have a "sporting chance" to see an occultation of the Earth by the Moon through the "eyes" of the Pioneer instruments. Intrinsic launch vehicle inaccuracies precluded any guarantee, however. The first attempt at lunar occultation analysis was made with Pioneer 7.

Pioneer E was to follow an inward-outward combination trajectory, with final near-Earth (1.0 AU) heliocentric orbit. The objective was to have the spacecraft linger in the vicinity of the Earth, allowing the use of high-bit-rate telemetry over a period of several hundred days. The design of Pioneer E also included plans for geomagnetospheric tail analysis similar to Pioneer 7.

The trajectory designer had to program the Delta vehicle in such a way as to attain the proper heliocentric orbit and accomplish other scientific objectives, such as lunar occultation, as the spacecraft left the Earth's vicinity.

The Delta launch vehicles carrying Pioneer payloads were all launched southeastward from Cape Kennedy along the Eastern Test Range. During the flight, the Deltas passed over Ascension Island in the South Atlantic and NASA tracking stations in the vicinity of Johannesburg, Republic of South Africa (fig. 2–4). Approximately 500 sec after liftoff, the second-stage engines cut off (fig. 2–5). The Delta second and third stages, the Pioneer spacecraft, and any Test

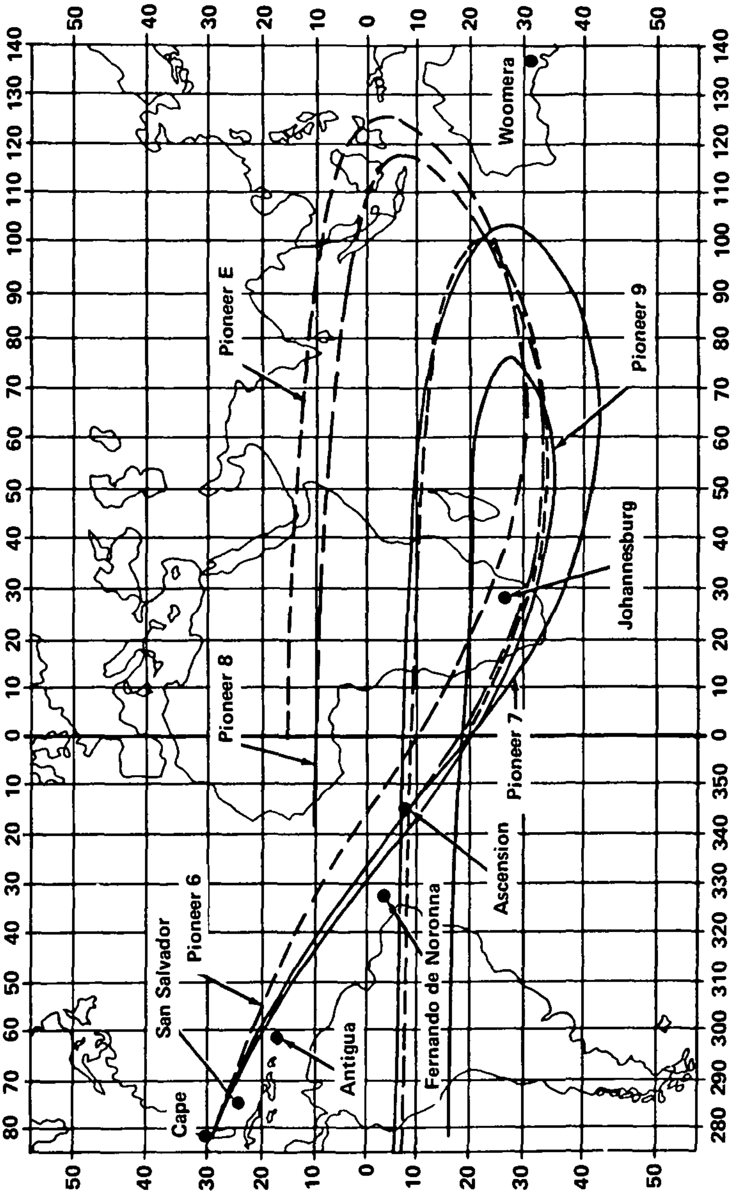

FIGURE 2-4.—Ground tracks of the four successful Pioneers plus the projected track of Pioneer E.

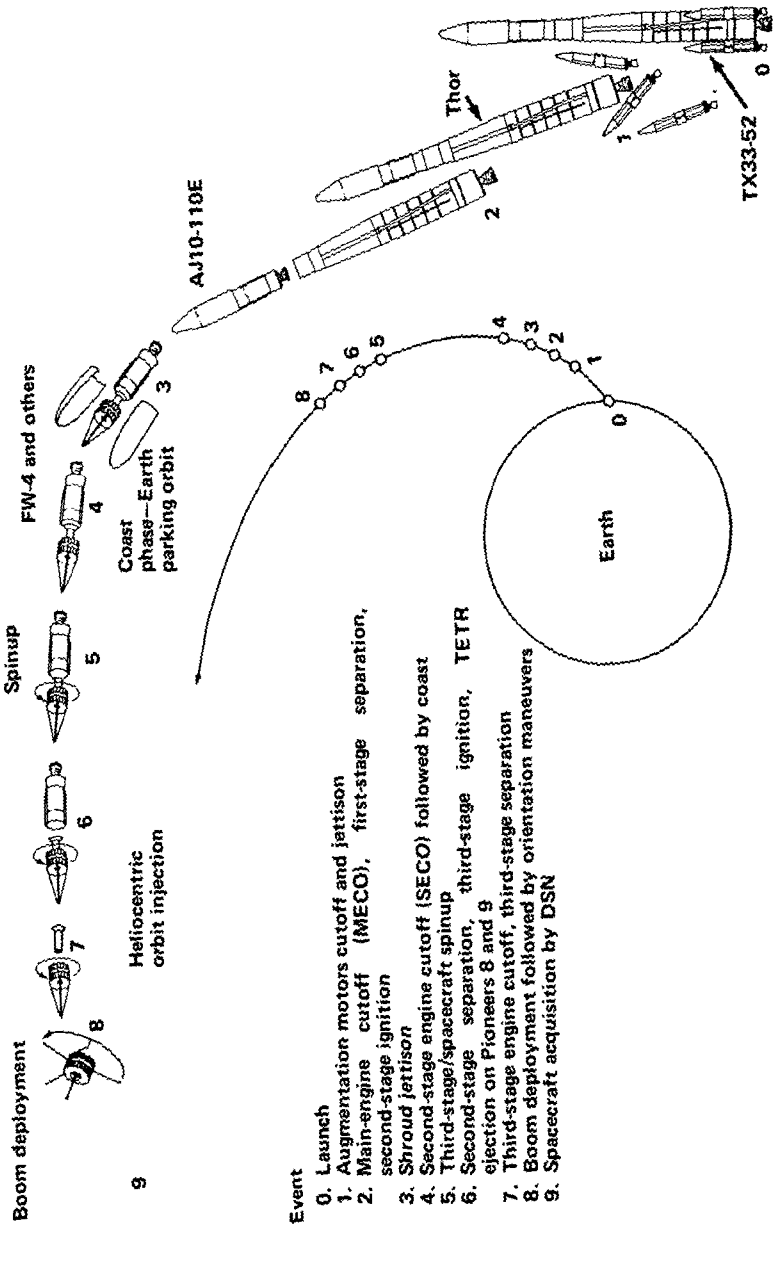

FIGURE 2-5.—The Pioneer launch sequence.

and Training Satellite (TTS) piggyback spacecraft are then in Earth orbit over Johannesburg.[8] This coast phase is essential if the spacecraft is to be launched properly into an orbital plane nearly parallel to that of the ecliptic. At a point before the spacecraft and attached Delta upper stages reach the plane of the ecliptic, the small rockets on the spin table on the Delta second stage fire, imparting a spin to the spacecraft and Delta third stage. Next, the Delta third stage fires at that precalculated point in the coast trajectory where the velocity added by the third stage will carry the spacecraft into an escape hyperbola and thence into orbit around the Sun. Only after third-stage ignition is the second-priority TTS injected into Earth orbit. The inward Pioneers (6 and 9) were injected with velocity vectors approximately opposite to the Earth's velocity. Thus slowed, they "fell" in toward the Sun and initially fell behind or lagged the Earth. The inward Pioneers essentially converted gravitational energy into orbital velocity and, after about 75 days, caught up with the Earth and led it by ever-increasing distances in its journey around the Sun. The outward Pioneers (7 and 8) were injected with velocities parallel to that of the Earth; they initially led the Earth but after 30 to 40 days they fell behind and, like the outer planets, lagged the Earth.

To achieve solar orbits that were very nearly in the plane of the ecliptic, Pioneer launches were ideally made during launch windows a few minutes wide that occur only once a day. The Pioneer Project Office at Ames Research Center required that launch windows be greater than 8 min, however, so that short holds would not scrub a mission for a whole day.

Several kinds of charts are employed to show how the Pioneers move in various coordinate systems once they are in heliocentric orbit. Only two of these plots are of general interest:

(1) the Sun-centered, vernal-equinox ecliptic reference (fig. 2–6), which shows how inward Pioneers draw farther and farther ahead of the Earth as both swing around the Sun; and

(2) the "snapshots" of the four successfully launched Pioneers (fig. 2–7) taken at four different times looking down on the plane of the ecliptic from the north ecliptic pole. The latter illustration has a physical meaning for those attempting to forecast solar weather. The Sun's spiral magnetic field, which rotates with the Sun, rotates much faster than the Pioneers and the Earth do in their heliocentric orbits. Therefore, the streams of plasma that propagate along the Sun's magnetic lines of force are always sweeping past the Pioneers and the Earth, spraying them with plasma like a rotary water

[8] The TTSs were used to give tracking stations practice prior to Apollo flights.

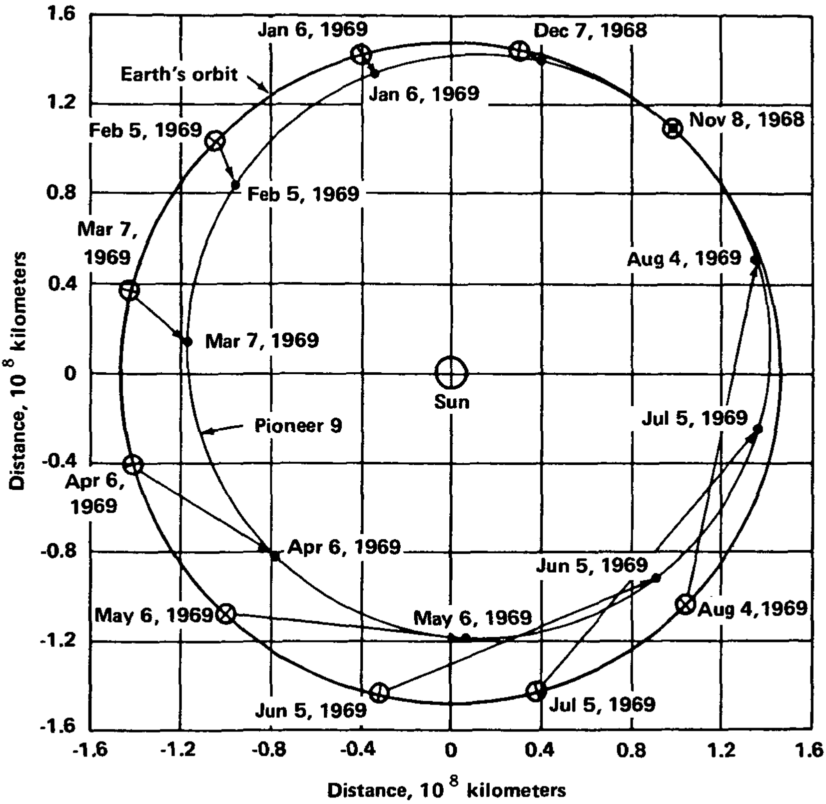

FIGURE 2-6.—Actual heliocentric orbit for Pioneer 9 using vernal equinox reference.

sprinkler. The Pioneers lagging the Earth are thus in good positions to forecast solar-related events for Earth.

Finally, table 2-2 summarizes Pioneer trajectory and orbital data as of March 1969.

SPACECRAFT DESIGN APPROACH AND EVOLUTION

In addition to the constraints imposed by the selection of the Delta launch vehicle and the DSN, it was also stipulated that the spacecraft be state-of-the-art; i.e., no untried equipment was to be employed because it might affect the success and long-term reliability of the spacecraft. Two important exceptions were allowed. The TWTs, though unproven in deep-space use in 1962, had no acceptable alternatives. The convolutional coders used on Pioneers 9 and E were also new, but they were installed on an experimental basis

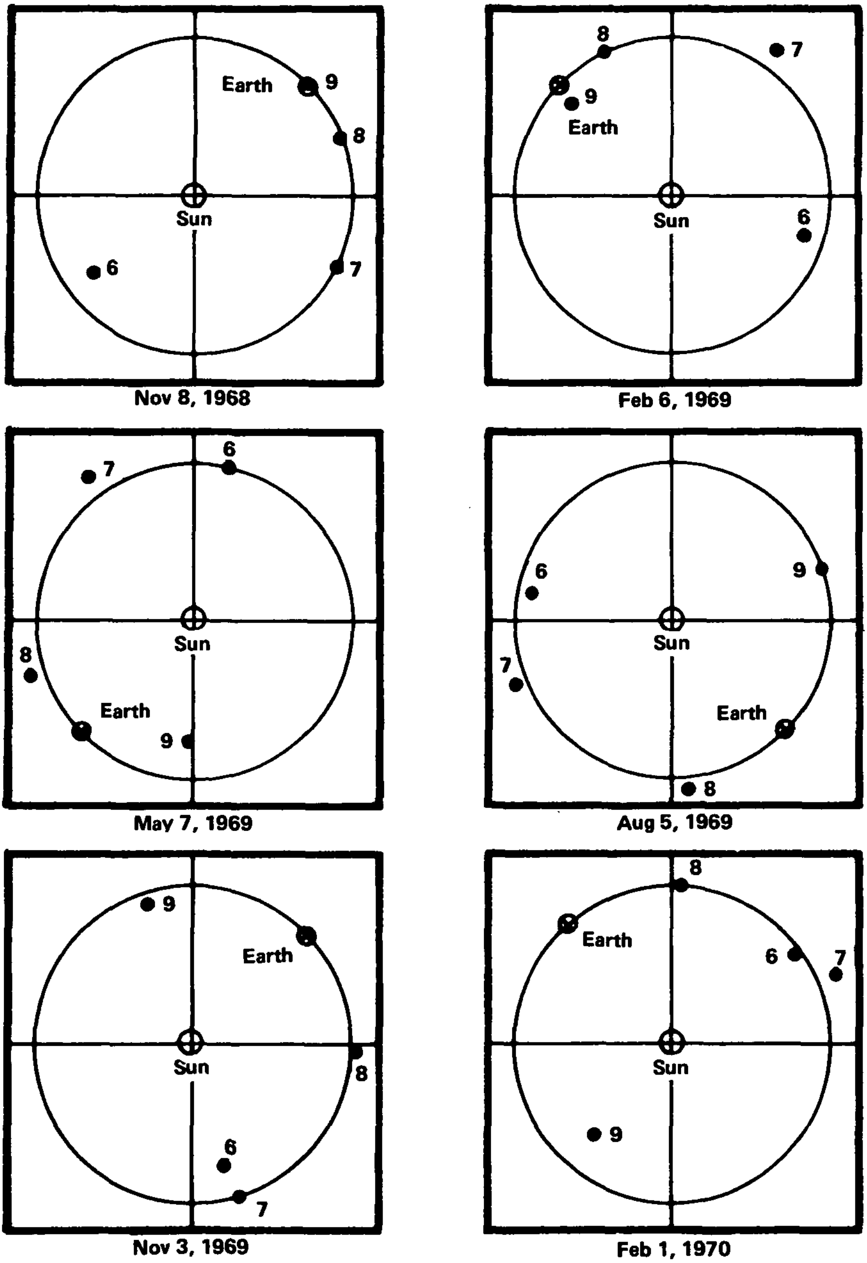

FIGURE 2-7.—Relative positions of the four successful Pioneers with respect to the Earth at various times.

TABLE 2–2.—*Pioneer Orbital Parameters*

Parameters	6	7	8	9
Orbital Injection Conditions				
Date of injection	12–16–65	8–17–66	12–13–67	11–8–68
Time of injection (GMT)	0756:41.1	1545:38.6	1439:32.5	1007:22.4
Injection latitude	7.8° S	14.48° S	22.83° S	3.36° S
Injection longitude	4.6° W	6.8° W	9.385° E	23.26° W
Injection altitude (km)	564.1	378.476	486.02	467.054
Injection velocity (km/sec)	10.8488	10.939	10.7837	11.035674
Flight path angle (deg)	1.7	2.1	−0.364	2.413724
Azimuth angle (deg)	119.3	106.98	129.374	101.04027
Elements of Heliocentric Orbits				
Semimajor axis (km)	134 481 910	159 713 300	155 372 610	130 500 710
Eccentricity	0.0942	0.05397	0.0476	0.1354
Inclination to ecliptic plane	0.1693	0.09767	0.0578	0.0865
Aphelion (AU)	0.936	1.1250	1.0880	0.9905
Perihelion (AU)	0.8143	1.0100	0.9892	0.7542
Period (days)	311.327	402.91	386.60	297.594

and could be bypassed if necessary. Although the TWTs did perform well, they caused much concern early in the program.

Given the mission objectives and the constraints enforced by the mission and the state-of-the-art, a design philosophy evolved to guide the hardware designers. The most important element of the Pioneer design philosophy was the desire for long spacecraft life and magnetic cleanliness. To meet the reliability goals, the following guidelines were set down:

(1) Provide failure modes of operation wherever possible

(2) Use only proven components (in practice, many components came from military space programs) except for the TWTs

(3) Qualify parts rigorously

(4) "Burn-in" components before use on spacecraft

Magnetic cleanliness was achieved by enforcing magnetic guidelines that permitted the use of only certain parts and specified certain construction practices. As a result the Pioneers have been the cleanest spacecraft—magnetically speaking—that the United States has built. The Pioneers have also been the longest lived spacecraft ever built. Both facts are a tribute to the design philosophy employed during the Pioneer Program and, of course, the capabilities of the engineers who designed and built the craft.

The major elements of the spacecraft design were sketched out in the STL feasibility contract. After the formal Pioneer contract was awarded, a more detailed design was made. A few minor features were changed in this process, as indicated in table 2–3.

The experiment complement was changed between the Block–I Pioneers (6 and 7) and the Block–II Pioneers (8, 9, and E). This change engendered a few more changes, noted in table 2–3. Overall spacecraft weight increased by more than 10 lb from Pioneer 6 to Pioneer E. This was permissible because the Delta was also improved as the Program progressed.

THE SPACECRAFT SUBSYSTEMS

The seven Pioneer spacecraft subsystems are defined by their various functions (table 1–1). It is now appropriate to replace the very generalized subsystem block diagram in figure 2–2 by one that employs Pioneer terminology and indicates some of the major components in the subsystems (fig. 2–8).

The Communication Subsystem

The basic problems in long-distance communication are distance and natural radio noise from the Sun and the rest of the galaxy. The following factors have given the relatively small Pioneer spacecraft the ability to telemeter data to and receive commands from the Earth over distances of nearly 200 million miles despite natural radio noise:

(1) A relatively high transmitter power level (8 W) for such a small spacecraft

(2) The focusing of radio energy into a flat disk-shaped beam by the Franklin-array antenna

(3) The use of very low bit rates (8 bps) at great distances, reducing the bandwidth required as well as power

(4) The very sensitive "ears" of the DSN—the 85-ft and 210-ft paraboloidal antennas (During the Pioneer Program, the DSN improved its signal detection capability by about 10 dB, mainly through the addition of the 210-ft antenna shown in figure 2–9.)

The major components of the communication subsystem are one high-gain and two low-gain antennas, two receivers, a transmitter-driver, two TWT power amplifiers, and five coaxial switches that can be activated by command from Earth to switch in redundant components should failures occur (fig. 2–8). Telemetry, commands, and tracking information are all handled by the communication

TABLE 2–3.—*Evolution of the Pioneer Spacecraft*

Pioneer spacecraft	Point in time	Weight	Changes
6	Completed design	Spacecraft 102.7 lb Experiments 34.3 137.0 lb	(from first version A–6669) Ames micrometeoroid experiment deleted Stanford radio propagation experiment antenna added Solar sail added to antenna mast Three booms now located on spacecraft viewing band Solar cells removed from viewing band Thermal insulation added to protect spacecraft from X–258 exhaust plume Magnetometer moved from antenna mast to radial boom
7	Completed design	Spacecraft 103.26 lb Experiments 35.09 138.35 lb	(from Pioneer 6) Magnetometer range reduced to $\pm 32\gamma$ Energy windows and angular resolution of cosmic-ray experiment changed
8	Completed design	Spacecraft 106.1 lb Experiments 38.0 144.1 lb	(from Pioneer 7) Block-II experiments substituted Telemetry format altered Larger battery added for experiments
9	Completed design	Spacecraft 107.13 lb Experiments 41.27 148.40 lb	(from Pioneer 8) Ames magnetometer substituted for Goddard magnetometer Convolutional coder experiment added Texas Instruments solar cells substituted for RCA cells Thick glass covers placed on Sun sensors
E	Completed design	Spacecraft 106.54 lb Experiments 41.06 147.60 lb	(from Pioneer 9) Ultraviolet filters substituted for thick glass covers on Sun sensors

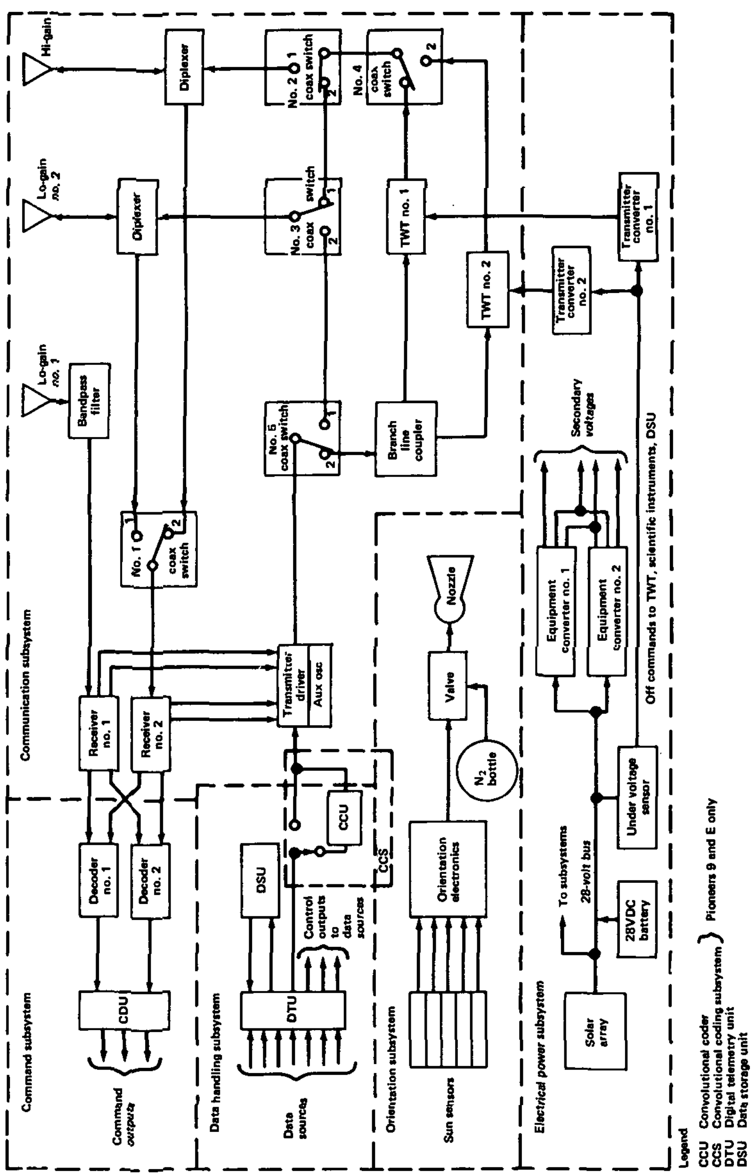

FIGURE 2-8.—Simplified block diagram showing the Pioneer spacecraft subsystems.

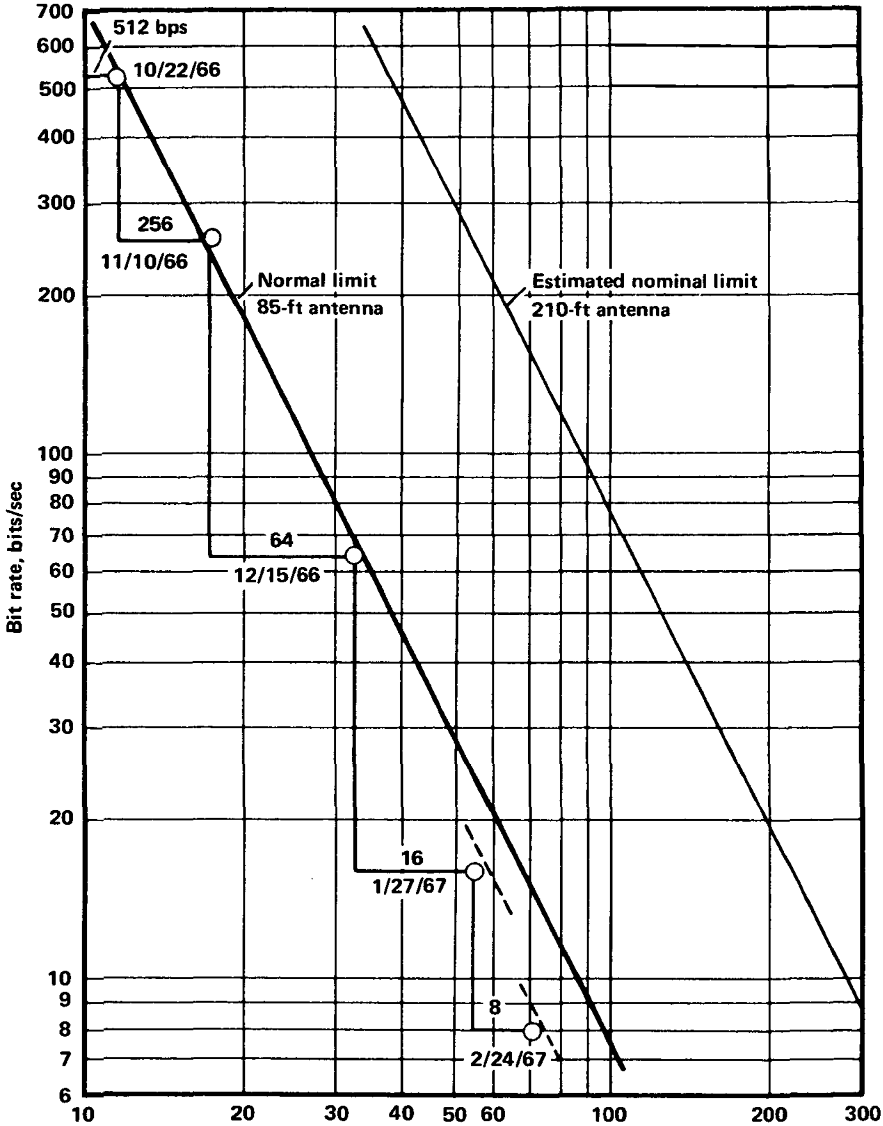

FIGURE 2-9.—Distance limitations for Pioneer 7, showing dates when telemetry bit rate was changed. Note the improved performance with the 210-ft antenna.

subsystem. The communication subsystem utilizes the phase-lock loop concept developed at JPL for deep-space and planetary probes.

To understand phase-lock loop operation, picture a Pioneer spacecraft 100 million miles or so ahead of the Earth in its orbit about the Sun. Assume first that the terrestrial DSN antennas are busy with some other spacecraft. In this situation, both spacecraft receivers are waiting, as it were, for further instructions from Earth. The transmitter, however, still transmits any scientific and housekeeping information it receives from the data-handling subsystem even though no terrestrial antenna intercepts it. Thus, even if both spacecraft receivers should fail, DSN antennas can still acquire the spacecraft and record whatever data it transmits. During these periods when the spacecraft is "on its own," the spacecraft transmitter frequency is controlled by an internal crystal-controlled oscillator. This mode is called the *noncoherent* mode of operation. One-way Doppler tracking of limited accuracy can be accomplished by merely listening to the spacecraft.

Next, suppose that a DSN antenna is swung around to point in the direction where orbital computations predict the spacecraft will be. DSN receivers pick up the weak telemetry signal and lock onto it. Lock is attained by means of a feedback loop involving a narrow bandpass filter and a voltage-controlled oscillator. A down-link lock exists when the voltage-controlled oscillator generates a signal at precisely the carrier frequency received from the spacecraft but with a 90° phase change. The feedback circuit in essence operates as a servomechanism to force the oscillator to match the spacecraft carrier frequency. Once a down-link lock has been established, the ground transmitter sends its own carrier in the direction of the spacecraft. Since the two spacecraft receivers are tuned to operate at different frequencies, the ground transmitter can select either one by using the proper carrier frequency. The presence of a signal in the spacecraft receiver automatically disconnects the spacecraft crystal-controlled oscillator and switches in a voltage-controlled oscillator that generates a frequency precisely 12/221 times that received from the DSN. This frequency is then multiplied by 20 in the transmitter driver. A phase-coherent transmitter signal with a frequency 240/221 times the frequency received from Earth is amplified in the operational TWT and dispatched to Earth via the high-gain antenna. The waiting DSN antenna locks onto this signal, which may be slightly different from that originally acquired because the spacecraft's crystal-controlled oscillator may have drifted slightly. Only when the spacecraft and Deep Space Instrumentation Facility receivers are *both* locked on the signals received from Earth and spacecraft, respectively, can coherent, much more accurate, two-way tracking measurements be made. This coherent mode can be disabled on command, so that the transmitted frequency is always governed by the crystal-controlled oscillator.

The two tasks of the small, lightweight spacecraft receiver were:

(1) to detect, demodulate, and amplify the commands received from the DSN station working the spacecraft; and (2) to provide the transmitter-driver with a phase-coherent signal 12/221 times the frequency of the received DSN carrier. When an external signal is received from a DSN station, a threshold detector in the receiver disables the on-board, crystal-controlled, noncoherent oscillator when in the coherent mode. The coherent receiver then generates the phase-coherent signal which ultimately drives the TWT when in the coherent mode. The Pioneer receiver components were of the discrete-circuit type rather than the newer integrated circuits, that were not proven sufficiently for the Pioneer designers in 1962.

The transmitter driver consists of a transistorized amplifier-modulator and a varactor multiplier. The driver provides either the noncoherent signal from its crystal-controlled oscillator or a phase-coherent signal that is 240/221 times the DSN carrier frequency. The amplified signal of approximately 50 mW is fed to the power amplifier stage, which is built around the TWT.

Three antennas serve the communication subsystem. Two are low-gain, multislot types with broad beam widths. One of these is permanently connected to one of the receivers to guarantee that the spacecraft will always be able to receive commands regardless of the operability of the coax switches. The low-gain antennas are essential during spacecraft acquisition before the initial orientation maneuvers when the high-gain antenna is being torqued into a position perpendicular to the plane of the ecliptic. The high-gain antenna is a collinear broadside array (a modified Franklin array) consisting of nine driven and nine parasitic elements.

The Data Handling Subsystem

The end product of most spacecraft—the Pioneers included—is information. Data flows not only between Earth and spacecraft but also among the various spacecraft subsystems. In the guises of telemetry, commands, and control signals, information is ubiquitous onboard a spacecraft. The data handling subsystem acts as a central clearinghouse where data are received, formatted, processed, stored, and sent back to Earth or to other Pioneer subsystems.

More formally, the functions of the data handling subsystem are:

(1) The sampling and encoding of analog and digital measurements taken by the scientific instruments (In special cases, the encoding is done by the scientific instrument.)

(2) The sampling and encoding of spacecraft engineering or "housekeeping" measurements

(3) The storage, upon command, of data when DSN stations are not available to acquire spacecraft data

(4) The storage, upon command, of special data formats when the spacecraft is communicating with the DSN

(5) The changing, upon command, of data bit rate and/or format as the spacecraft recedes and approaches Earth. (Bit rates available are 8, 16, 64, 256, and 512 bps.)

(6) The provision of sundry clock and control signals throughout the spacecraft (Clock signals, in effect, force spacecraft experiments and subsystems to work together in synchronism.)

Two elements make up the data handling subsystems: the digital telemetry unit (DTU) (really the data processor) and the data storage unit (DSU) (fig. 2–10). On Pioneers 9 and E, a third unit was added on an experimental basis, a convolutional coder unit (CCU), which could be switched in-line from a standby status or vice versa.

When the Pioneer Program was being formulated in 1962, there existed a trend toward pulse code modulation (PCM) for space telemetry. The Mariner space probes, NASA's observatory series of satellites, and both the Gemini and Apollo programs had adopted PCM. PCM has many advantages, such as unlimited accuracy (in principle), the existence of self-checking and error-correcting codes, and instant compatibility with computers. Because the Pioneers were going to interface with the DSN, with its already strong bias toward digital techniques, it was logical to follow the PCM trend.

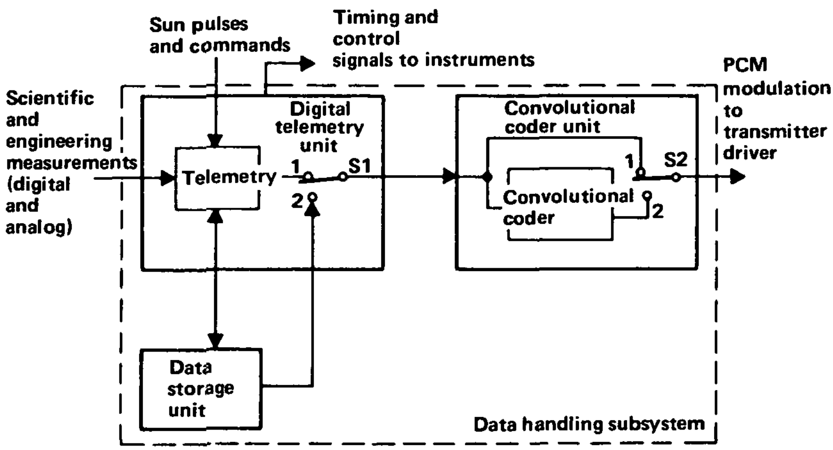

FIGURE 2–10.—Block diagram of the data handling subsystem.

The bits that constitute each PCM telemetry word can be communicated by any one of several two-valued properties of a modulated radio signal. Following JPL practice, Pioneer PCM bits are impressed upon the transmitter carrier by phase-modulating the 2048-Hz square wave subcarrier. More technically, the subcarrier is biphase modulated by a time-multiplexed train of bits, using a non-return-to-zero-mark (NRZ-M) format, and this subcarrier is used to phase-modulate the carrier.[9]

The basic unit of information in a telemetry message from a Pioneer spacecraft is a seven-bit word. The first six bits represent the instrument reading or datum, with the most significant bit appearing first. The last, or seventh, bit is a parity bit based upon the first, third, and fifth bits in the preceding word. If the sum of these bits is even, the parity bit will be odd; i.e., one.

The parity bit represents a self-checking feature of the code. Words containing errors introduced during transmission and the many processing steps along the way can be identified and flagged in most instances by recomputing and checking the parity bit for the word that finally arrives at its terrestrial destination. The parity bit, as used in Pioneer telemetry, was worth roughly 2 dB, in the sense that transmitted messages could be edited and made more accurate.

Just as bits are organized into words, the words themselves are ordered into "frames" consisting of 32 words each. The frames keep repeating one after the other, but the arrangement of words can be modified by command. This separation of words by interspersing them in the time dimension is called time-division multiplexing. In effect, each scientific and engineering instrument gets read periodically and the data are strung together in the 32-word frames. The flexibility of the formats represents one of the strong points of the Pioneer system design.

There are four basic Pioneer telemetry formats. The formats themselves are too long and overly complex to describe in detail here. They can be found in Volume II, Chapter 4. Formats A and B are primarily for scientific data. Format C consists mainly of engineering data and is employed during orientation maneuvers and when the spacecraft is in trouble. Format D consists of data from the Stanford radio propagation experiment only and is switched on during lunar occultations and other special events.

During the launch and reorientation maneuver, the spacecraft normally transmitted Format C. While the spacecraft was still near

[9] On Pioneers 9 and E, the non-return-to-zero-level (NRZ-L) format was introduced.

enough to the Earth to support a high bit rate, Format A was usually employed. As the spacecraft receded from Earth, forcing the use of lower bit rates, Format B was adopted. If the trajectory of a Pioneer should be favorable for lunar occultation, a command from Earth will switch to Format D. Out in the relatively calm reaches of deep space, the spacecraft transmits Format B most of the time.

Although variable bit rate and telemetry format confer considerable flexibility, provision is needed for storing and thus delaying data transmission back to Earth. Suppose, for example, that an important solar event occurs and one or more of the Pioneers are too far away to telemeter plasma-probe data rapidly enough to catch the details of the fast-breaking action. With onboard data storage, data could be recorded at a high rate during the event and then retransmitted later at a bit rate compatible with the spacecraft's transmitter power and distance from the Earth.

Based on the above illustration, three of the four Pioneer telemetry modes are easy to justify: (1) real-time operation, (2) telemetry store, and (3) memory read-out. The fourth mode, the duty-cycle store mode, simply stores data in the memory periodically, in short bursts a frame at a time, when the spacecraft is not being worked by a DSN station. Any of the four modes can be started with a specific command from Earth.

The digital telemetry unit is not only the central clearinghouse for all spacecraft-generated data, it is also the spacecraft coxswain that keeps all spacecraft components operating in step. To do this and impose order upon the variegated data requires a rather complex array of logic circuits, counters, and A/D converters (fig. 2–11).

The coxswain function is performed by a crystal-controlled-oscillator clock producing a 16 384-Hz output signal. This signal is then divided by 32, 64, 256, 1024, and 2048 to establish the five standard bit rates. Armed with timing signals, the multiplexers and submultiplexers sample the various analog and digital outputs of the scientific and engineering instruments. All instruments are usually on all the time, and the only stimulus needed to make them provide a reading is an electronic "gate." (An exception is the Stanford radio propagation experiment which is usually turned off at great ranges.) The multiplexers simply open and close gates leading to the instruments in the order specified by the last command from Earth. Electronic switches or gates are the mainstays of computers and other logic circuits. It is the spacecraft clock, of course, that ultimately drives all subsystem circuits.

The solid-state memory of the DSU is not large by terrestrial standards—only 15 232 bits—but this is sufficient for Pioneer's pur-

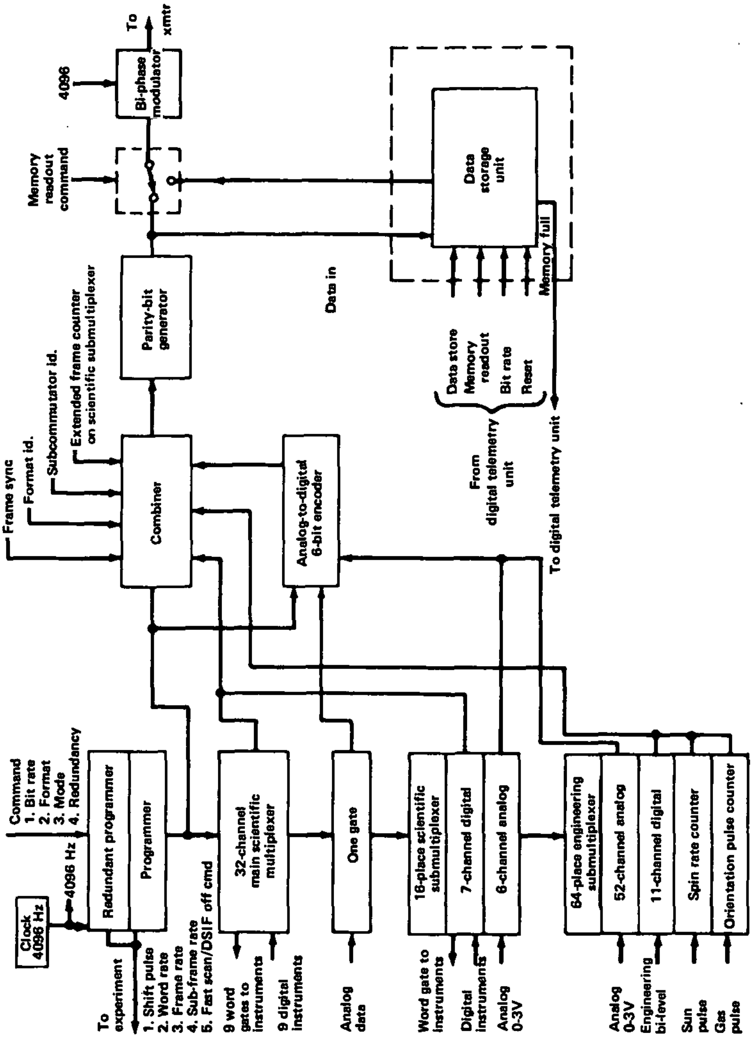

FIGURE 2-11.—Simplified block diagram of the digital telemetry unit (DTU).

poses in view of the very low data rates possible for transmission back to Earth. It takes more than half an hour to read out a 15 232 bit memory at 8 bps.

The Command Subsystem

None of the flexibility and reliability gained through alternate modes of operation and redundancy can be realized without switches commandable from the Earth. To substitute a new TWT for one that falters or to change the bit rate, the mission controller dispatches a command to the spacecraft directing a specific switch to open or close. All told, the Pioneers employ between 57 and 67 commands (each spacecraft was slightly different) to activate the same numbers of spacecraft switches. About two-thirds of the commands pertain to spacecraft functions and the rest to experiments.

Let us say that the mission controller at Ames Research Center wishes to change Pioneer 6's bit rate from 16 bps to 8 bps because the spacecraft is too far from Earth for the higher bit rate to be received without an excessive error rate. He constructs a 23-bit command word that is sent through JPL along NASA's global communication system (NASCOM) lines to the DSN station working Pioneer 6. The command is modulated onto the up-link carrier in what is called frequency-shift keying (FSK). If a digital one is to be sent, a 240-Hz tone is phase-modulated (PM) on the DSN carrier. A 150-Hz tone represents a digital zero. The bit stream representing the command is thus a series of 23 beeps (in two pitches) on the DSN carrier.

The Pioneer command is much longer than the standard telemetry word—23 versus 7 bits. If merely the command number were sent, seven bits would be sufficient. Pioneer 9, which used the most commands (67), just barely needed seven bits. As figure 2–12 indicates, the basic Pioneer command number was actually seven bits long. Preceding the seven-bit segment, however, was a seven-bit complement of the command, in which the ones in the command number were replaced by zeros and vice versa. It is common spacecraft practice to promote high command accuracy by sending considerable redundant information. The consequences of a garbled command are too serious to settle for simple parity checks. While the 23-bit command is in the decoder register, it is compared bit by bit with its complement. Complete correspondence is required before the command is released for execution. Incomplete or distorted commands are not executed.

Command tones are modulated on the DSN carrier at the rate of only 1 bps. Including the time required for processing the com-

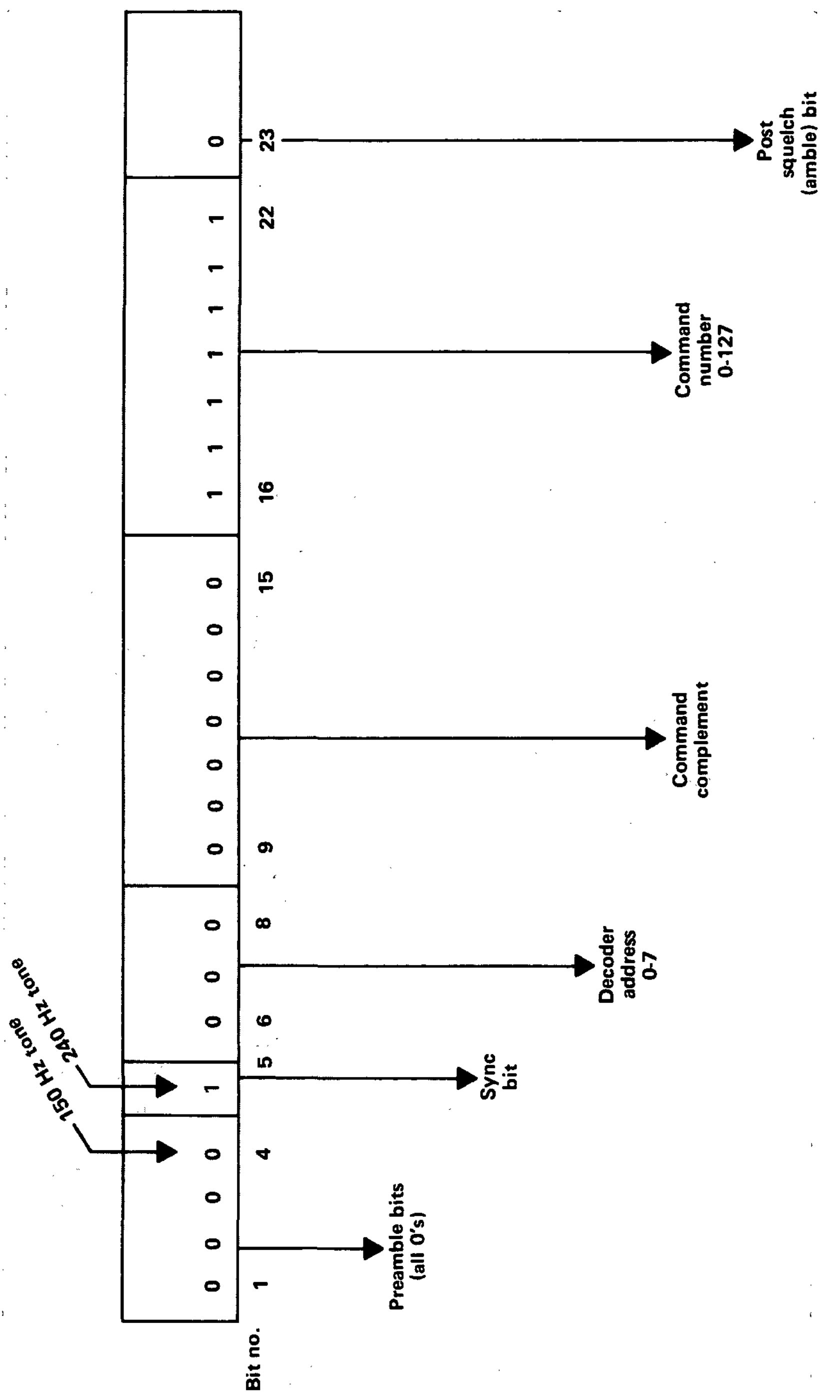

FIGURE 2-12.—Structure of the Pioneer command word.

mand in the decoder and executing it, it takes 27 sec to receive and execute a command aboard the spacecraft. Also, the Pioneers are often several light minutes away from Earth and are therefore out of touch to some degree, regardless of the low command rate.

The assigned task of the command decoder is the delivery of a verified bit train to the command distribution unit (CDU). Four different kinds of signals flow out of the CDU, each tailored for triggering a specific action—the end result of the command transmitted from Earth:

(1) Most command pulses are short (10 μsec), low current (about 10 mA), at 10 V. These signals are sufficient to drive most Pioneer electronic circuits.

(2) Some devices, such as the coaxial switches, require somewhat longer pulses; the CDU provides a 160-msec, 28-V pulse for such devices.

(3) Where solid-state switches are inadequate because of the high currents involved, as in the case of the battery, the CDU activates relays.

(4) A "state" output, i.e., one of two voltage levels, is available for instrumentation. On the Pioneers, state commands were simply "voltage on" or "voltage off" commands.

The Electric Power Subsystem

Once they leave the Earth far behind, the Pioneer spacecraft are in full sunlight. It is not surprising to find spacecraft so situated converting solar energy into electricity to operate its scientific instruments and also to drive the spacecraft subsystems that enable the vehicle to survive in outer space and maintain a communication link with the Earth.

The power picture becomes more complicated once the Pioneer mission is studied in detail. First, a basic program ground rule states that the spacecraft must be flexible enough to operate between 0.8 and 1.2 AU without modification. And second, for purposes of acquisition, the spacecraft must be operable while it is in the Earth's shadow prior to escaping the Earth and breaking into full sunlight. The Pioneer shadow problem is a one-time affair, not repeating every few hours like that of an Earth satellite. Yet it can be solved in the same way—with a battery serving as a reservoir of energy. In a satellite the battery is discharged and charged through several cycles each day; but with Pioneer, the battery becomes largely excess baggage once the Earth's shadow is traversed. "Largely" is appropriate here because even in full sunlight the spacecraft depends upon the battery for an assist in meeting sudden, brief surges in power during normal operation, due in particular to pneumatic valve pulses and, on Pioneers 6 and 7, to the MIT experiment (fig. 2–13). The solar-cell array keeps the battery charged at a low level for this purpose if it is still in the subsystem. (Pioneer practice was to command the battery off after a year or so of operation.)

The total electric power subsystem consists of:

(1) The solar array, the only source of new energy after launch

(2) The battery, which acts as a temporary source of power during the shadow period and as a reservoir to supply peak demands in space

(3) Converters that change bus power into the voltages and current levels required by the TWTs and other spacecraft equipment

(4) Current and voltage sensors and protective devices

(5) Power switching and distribution equipment

Pioneer power requirements changed slightly from mission to mission. The largest change took place between the 8 and 9 missions, when the convolutional coder was added and the Goddard magnetometer was replaced by one from Ames. These changes are summarized in table 2–4.

The Pioneer solar cell is a high-efficiency, solderless, n-on-p type, with 1 to 3 ohm-cm base resistivity. Each cell is 1 by 2 cm and is covered by a 0.15-mm glass slide for radiation protection. Early in the program, the average cell efficiency target was 12 percent; this was never achieved and the cells finally launched on the spacecraft average about 10.5 percent.

Individual cells were fabricated into two types of modules. In the first type, 12 cells were interconnected so that 3 were in series and 4 in parallel; in the second, there were 6 in series and 4 in parallel. A close look at figure 2–14 seems to show the cells "shingled together along the long edges according to conventional practice. Actually each cell was soldered to metal connectors that made the modules both self-supporting and flexible. It was this flexibility that allowed the modules to be affixed (with silicone rubber adhesive) to a curved substrate conforming to the cylindrical spacecraft surface.

Each of the 48 solar-cell strings was made from interconnected modules and a blocking diode. The diodes, in effect, permit power to flow out of, but not into, the strings. The strings cover a total area of 22.8 sq ft—essentially all of the spacecraft's cylindrical surface except for the 7.5-in. viewing band—also the locus of the heaviest boom shadowing. Solar cells along the edge of the bellyband are provided with shunt diodes arranged so that, even if they are shadowed, other cells in the string can still provide useful power to the spacecraft.

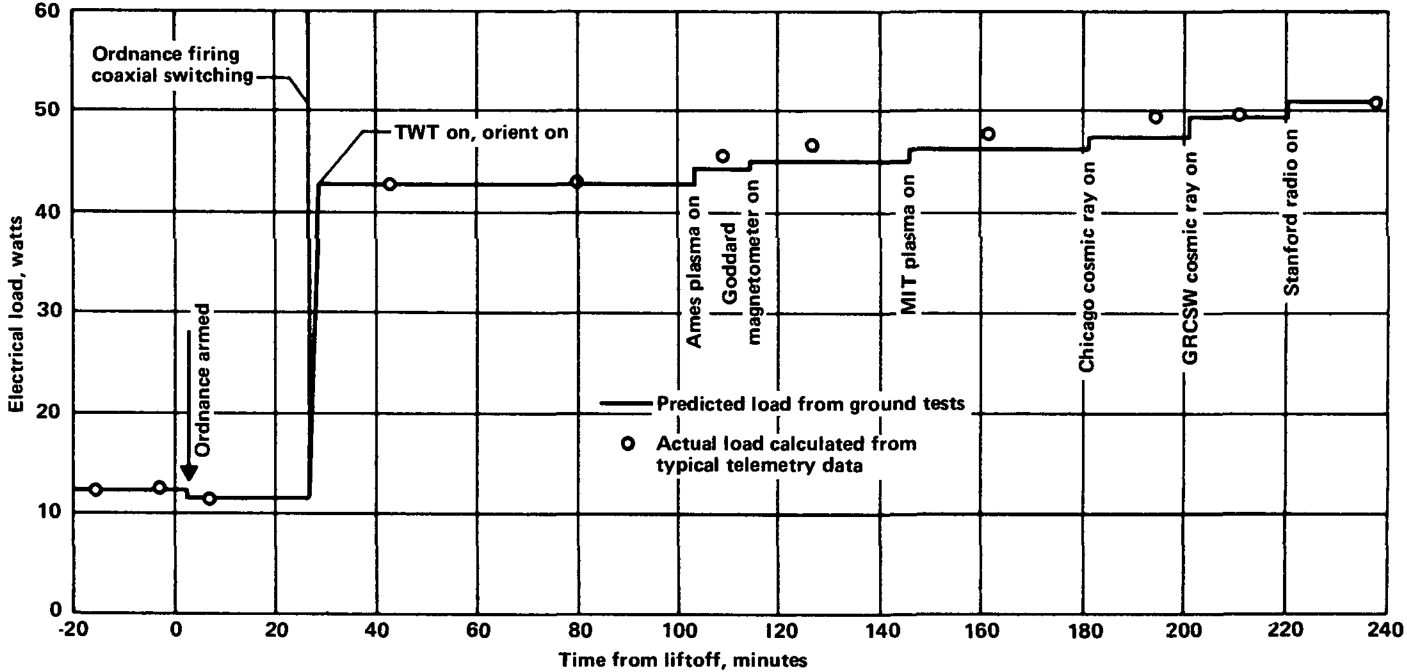

FIGURE 2–13.—Pioneer 6 power profile during the first 4 hr of flight. Superimposed upon the average power level are peaks up to 10 W high from the MIT experiment and 7 to 8 W from the pneumatic valve solenoid in the orientation subsystem.

TABLE 2-4.—*Pioneer Power Budgets*

Pioneer spacecraft	6	7	8	9	E
	Average electrical loads, W				
Spacecraft system [a]	43.4	43.6	43.1	43.66	41.86
Experiments	9.2	8.2	12.3	17.57	17.80
Total	52.6	51.8	55.4	61.23	59.66

[a] Includes 30 W for the TWTs.

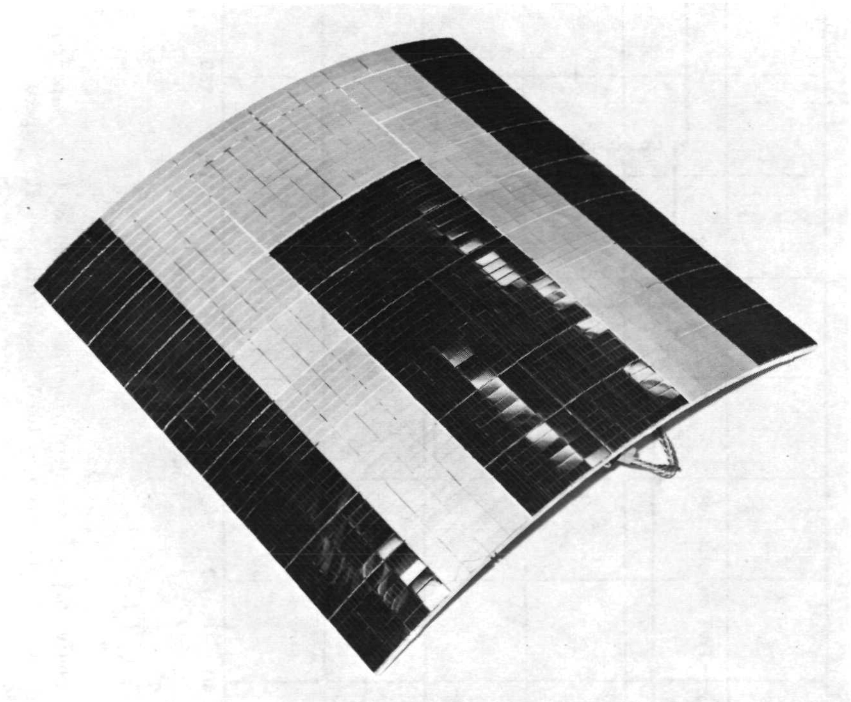

FIGURE 2-14.—One of the Pioneer solar panels, showing both 12- and 24-cell modules mounted on a curved substrate. (Courtesy of TRW Systems.)

A Pioneer is completely dependent upon its battery from the time ground power is severed on the launch pad until the fairing is jettisoned, as well as while the spacecraft is in the shadow cast by the Earth. During this latter period, the battery must supply about 12 W. After orientation, at the discretion of the mission controller back on Earth, the battery is left connected across the bus bar dominated by the solar-cell array. The mission controller can disconnect the battery by command if it begins to compromise the mission for some reason. Normally, the battery is left on for 6 to 12 months to accommodate any temporary power shortages or overloads. So far as is known, no power shortages have occurred.

The battery chosen for Pioneer was of the sealed, silver-zinc type, which lends itself well to operation in the floating mode. The sealed case was made from fiberglass, a nonmagnetic material. As already mentioned, it can be wired for inward and outward missions. Built with 18 cells, taps were provided at 16, 17, and 18 cells, for the sake of mission flexibility.

The Orientation Subsystem

The success of the Pioneer mission depended completely upon twisting the spacecraft's spin axis around after injection until its high gain antenna mast pointed within 2° of the south ecliptic pole. The same orientation equipment could also be used to adjust spacecraft orientation if the axis drifted out of the 90° ± 2° attitude range with respect to the plane of the ecliptic.

The most important components needed in such an orientation maneuver are:

(1) A device to torque the angular momentum vector of the spacecraft

(2) Sensors to distinguish the direction of precession

(3) Sensors to signal the status of the orientation maneuver

(4) A nutation or wobble damper to dissipate nutation energy induced during the orientation

A small solar sail was added at the tip of the high-gain antenna mast to offset any residual torque due to solar pressure.

Let us sketch out the orientation concept completely. After the spacecraft is injected into the plane of the ecliptic, two pairs of Sun sensors determine the attitude of the spacecraft with respect to a line joining Sun and spacecraft. The Type–I orientation maneuver commences automatically. The Sun sensors will cause the nitrogen gas jet to fire and torque the spacecraft spin axis through the smallest angle until it is perpendicular (within ±0.5°) to the spacecraft-Sun line. At this point, thermal control is possible and the solar array generates full power. With the spin axis perpendicular to the Sun-spacecraft line, the Type–II orientation moves the spin axis in a plane perpendicular to the Sun-spacecraft line. The Type–II orientation is commanded from the ground and is controlled by monitoring the strength of the signal from the high-gain antenna. At maximum, the Pioneer spin axis is also perpendicular to the spacecraft-Earth line. Here, the desired accuracy is ±1°. If the spacecraft is perpendicular to both the spacecraft-Sun and spacecraft-Earth lines, it is also perpendicular to the plane of the ecliptic. Orientation is now complete. Spin-axis orientation is maintained through spin stabilization at roughly 60 rpm.

The sensitive elements of the Sun sensors were quad-redundant, photosensitive silicon-controlled rectifier (PSCR) chips, manufactured by Solid State Products, Inc. The chips were developed especially for Pioneer. They delivered a signal to the orientation-control circuitry whenever the Sun was in view. The view of each Sun sensor was restricted by aluminum shades. On Pioneers 6 and 7 the light-sensitive chips were protected against space radiation damage by 20-mil quartz covers. However, several months after launch, it was discovered that the Sun sensor thresholds had changed. Laboratory testing implied that radiation damage was the primary cause; therefore, the quartz covers on Pioneer 8 were made 100 mils thick. The trouble persisted. The real cause was discovered by chance at TRW Systems when the sensors were tested under ultraviolet light to see if it degraded the adhesives used in sensor construction. It was discovered that the sensors were ultraviolet-sensitive. In space, the ultraviolet light from the Sun had caused the change in the sensor thresholds. Simple ultraviolet filters were then added to 60-mil quartz covers on Pioneers 9 and E.

The five Pioneer Sun sensors are mounted on the spacecraft with the fields of view specified in figure 2–15. Sensors A and C, located on the spacecraft bellyband, looking up and down, respectively, help position the spacecraft during the Type–I orientation. As long as the spin axis does not point within 10° of the Sun, except for a small overlap of the field of view, sensors A and C will see the Sun once each revolution as the spacecraft spins. The Type–I orientation proceeds as sensor A or C, whichever one is illuminated, stimulates a succession of gas pulses from the jet on the end of the orientation boom. Each pulse lasts for 45° of spacecraft rotation and torques the spin axis about 0.15° in the direction of the smallest angular displacement toward maneuver completion. The pulses cease when the other sensor finally sees the Sun. When both sensors see the Sun at the same time, the spin axis will be perpendicular to the spacecraft-Sun line within about ±0.5°.

The Type–II orientation employs sensors B and D, also located on the spacecraft bellyband, but with 20° fields of view centered on the spacecraft meridian plane. These sensors do not exercise complete control over the gas pulses that torque the spin axis during Type–II orientations; they only time the pulses. Sensor B, for ex-

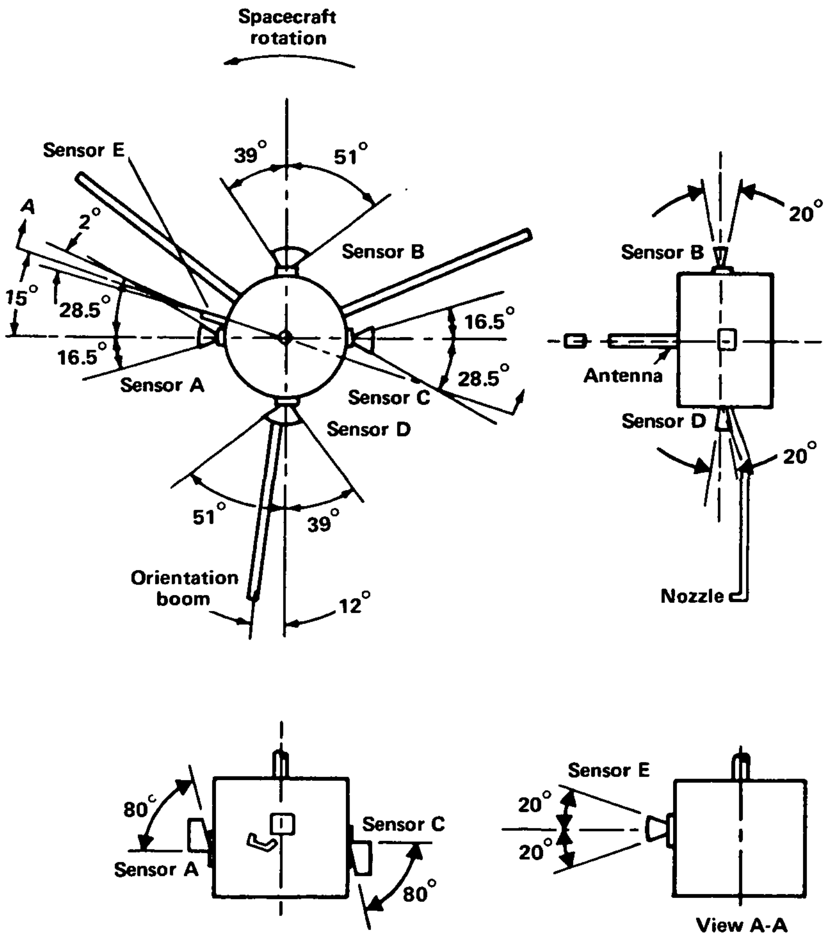

FIGURE 2–15.—Sun-sensor locations and fields of view.

ample, triggers the gas pulse at just the right time for clockwise rotation of the spin axis around the spacecraft-Sun line. (Note that the spacecraft is already perpendicular to the spacecraft-Sun line by virtue of the Type–I orientation. It retains this attitude during Type–II orientation.) Sensor D times the gas pulses for counterclockwise torquing of the spin axis. Thus, sensors B and D control the direction and pulse duration but not the extent of the rotation about the spacecraft-Sun line. The number of pulses for Type–II orientation is controlled by individual commands from the ground. As the angle change progresses, measurements are made of the strength of the carrier signal from the spacecraft's high-gain antenna. When maximum signal strength is obtained, the spin axis is perpendicular to the spacecraft-Earth line, and orientation is perpendicular to the ecliptic plane established.

Sensor E establishes the reference position of the spacecraft with respect to the Sun and sends signals to the scientific experiments. Also mounted on the viewing band of the spacecraft, sensor E possesses only a 2° field of view that provides short, sharp pulses as it sees the Sun roughly once each second. Because the field of view is only 40° in the other direction (fig. 2–15), Sun pulses appear only when the spin axis is within 20° of being perpendicular to the spacecraft-Sun line. The appearance of Sun pulses also indicates that the Type–I orientation is proceeding successfully and near its end.

The pneumatic assembly is a titanium-alloy pressure vessel containing about 0.9 lb of nitrogen at 3250 psi, a pressure regulator, a solenoid valve, a pressure switch, and a nozzle. The nitrogen had to be very dry to preclude valve icing at low temperatures. An electrical signal opens the solenoid valve for a moment, releasing a burst of gas at about 50 psi which provides the desired impulse. The solenoid valve and nozzle are located at the end of a 62-in. boom to increase the angular impulse and isolate the valve solenoid's iron core from the magnetometer.

On the Pioneer spacecraft, the energy of nutation (wobble) was dissipated by beryllium-copper balls rolling inside and impacting at the ends of a pair of tubes located at the end of the 62-in. boom. Rolling friction and inelastic collisions at the ends of the tubes extracted the energy of nutation, converting it to heat.

The Thermal Control Subsystem

The task of the thermal control subsystem is to keep the spacecraft cool enough (less than 90° F) on the inward missions and warm enough (more than 30° F) on those swinging away from the Sun to 1.2 AU. The solar heat flux varies between 690 and 307 Btu/hr-sq ft between 0.8 and 1.2 AU; and Pioneer ground rules stipulated that these conditions must be handled without spacecraft design changes for inward and outward missions. The internal heat loads were also variable as electrical equipment was switched on and off. These load changes were small, however, roughly a swing of 12 W or about 20 percent, compared to the greater than 2:1 fluctuation in solar flux.

NASA and STL engineers also had to examine several transient events or situations that occurred before the spacecraft broke into full sunlight following launch:

(1) The launch-pad environment (The spacecraft determined air-conditioning requirements here.)
(2) Aerodynamic heating of the shroud during launch and the consequent transfer of heat to the spacecraft
(3) Aerodynamic heating of the spacecraft at very high altitudes after shroud ejection (Analysis showed that no problem existed here.)
(4) Radiant heating of the bottom of the spacecraft by the third-stage rocket plume
(5) Cooling during eclipse of the Sun by the Earth during ascent

Passive thermal control, employing no moving parts, would have been the simplest and most reliable approach in the Pioneer program. However, the more than 2:1 variation in solar flux and changing internal heat loads ruled out passive control.

The whole Pioneer mission depended upon the concept of a spin-stabilized spacecraft with a spin axis normal to the plane of the ecliptic. The curved sides of the cylinder receive essentially all solar radiation, while the ends point toward cold space. This situation is ideal for a thermally insulated spacecraft with active thermal control. Insulation around the sides of the structure allows only a small portion of the solar heat load to reach the inside of the spacecraft. Insulation on the top leaves the bottom as the only possible exit for heat (fig. 2–16). This heat leakage, which varies depending on the distance from the Sun, can be radiated out the spacecraft bottom along with the variable internally generated heat load. The variability is handled by changing the effective radiating area of the bottom of the spacecraft. Mechanization of the concept consisted of a set of louvers that varies the effective radiating area, increasing it as the internal temperature rises and reducing it when the inside of the spacecraft became too cool. The setting of the louvers is controlled by bimetallic actuators sensitive to internal temperature.

The Structure Subsystem

The Pioneer structure (figs. 2–17 to 2–19) consists of the following major sections:

(1) The interstage ring and cylinder
(2) The equipment platform and struts
(3) High-gain antenna mast supports
(4) Solar-array substrate and supports
(5) Boom dampers and wobble dampers
(6) The booms and associated deployment and locking equipment
(7) The Stanford experiment antenna

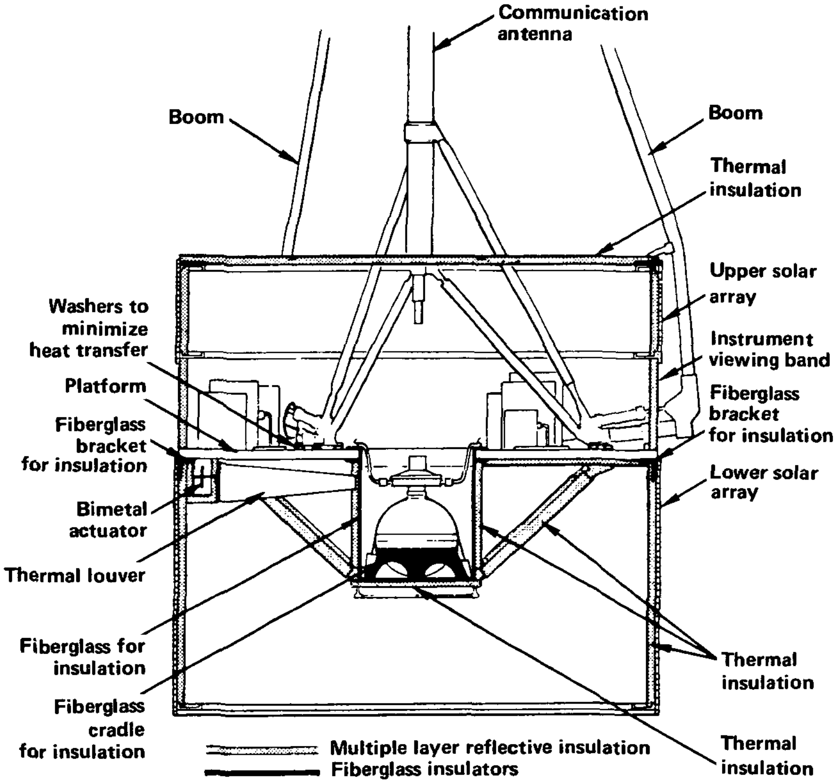

FIGURE 2–16.—Diagram of the components affecting thermal control.

Spin-stabilized spacecraft need not be cylindrical in shape; only symmetry about the spin axis is required. Spheres, for example, also lend themselves to spin stabilization. With Pioneer, however, there was good reason to choose a cylinder. The spacecraft was to be oriented with its spin axis perpendicular to the plane of the ecliptic. Thus, body-mounted solar cells would always be perpendicular to sunlight once each revolution (roughly once per second). Axis perpendicularity was a condition for maximum power generation and obviously a factor enhancing the whole Pioneer concept.

Externally, the Pioneers were cylinders 37.3 in. in diameter and 35.14 in. long, with three booms 120° apart extending 82.44 in. from the spin axis (fig. 2–17). The Stanford experiment antenna projects downward when deployed, being in appearance and complexity a fourth boom. The high-gain antenna mast projects roughly 53 in. above the top edge of the cylinder. Pioneer presents appendages in all directions, in contrast to the relatively clean configuration first suggested.

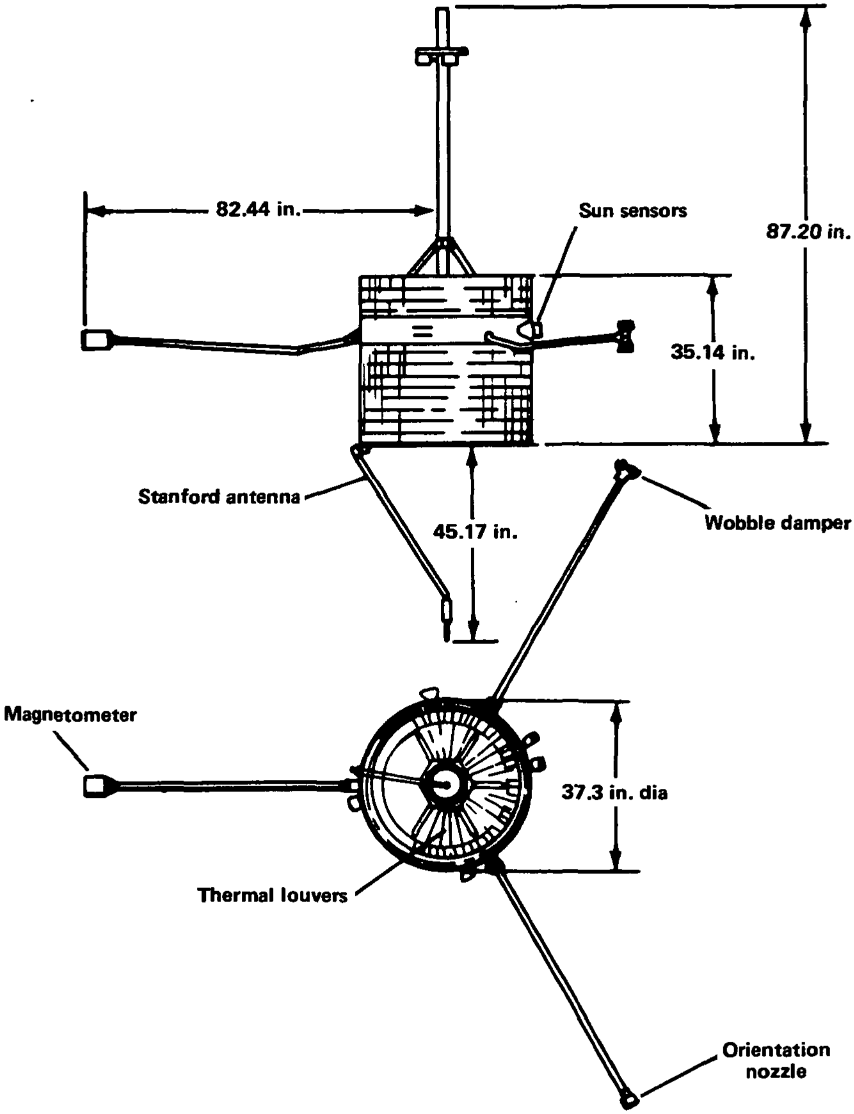

FIGURE 2–17.—External dimensions of spacecraft in-flight configuration.

Internally the major requirements were support for scientific instrumentation and spacecraft subsystems and, once again, spin-axis symmetry. Symmetry must be taken here to mean the judicious placement of mass around the spin axis to preclude the spacecraft's wobbling like a poorly loaded washing machine. Of course, the farther that components were located from the spin axis, the

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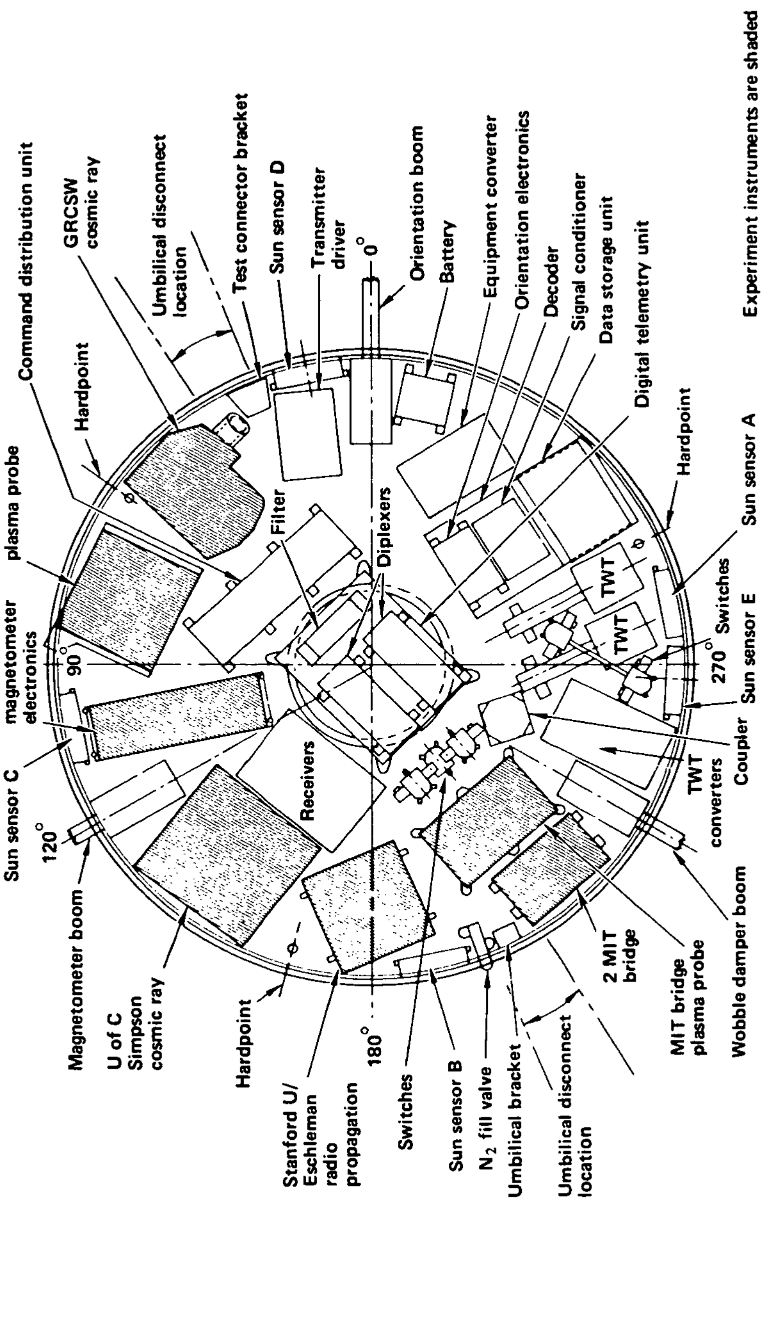


FIGURE 2-18.—Equipment platform layout for Pioneers 6 and 7. Layouts for the Block-II Pioneers were very similar.

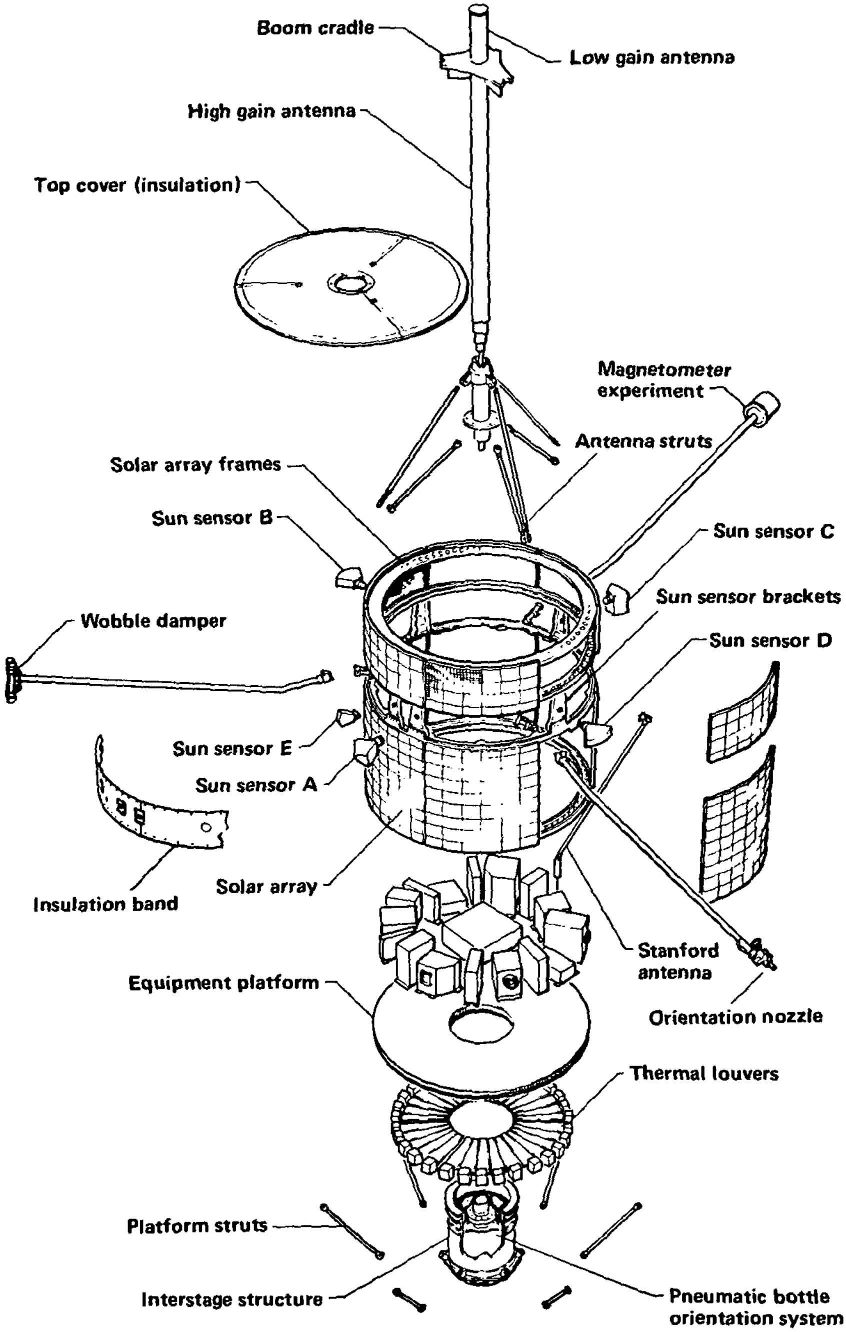


FIGURE 2-19.—Exploded view of the Pioneer spacecraft.

greater the spin stability; that is, the better the spinning spacecraft could resist destabilizing influences. The internal configuration (fig. 2–18) followed general spacecraft practice by making the major structural element a strong equipment platform. This platform supports all internal components, three radial booms, and the high-gain antenna mast. The equipment platform is the internal skeleton. The cylindrical shell, which is rigidly attached to the equipment platform, was constructed of aluminum honeycomb with fiberglass face sheets and is the structural skin that forms the base of the solar array. Sun sensors and the Stanford antenna are attached to the equipment platform. The major structural elements are equipment platform, appendages, and cylindrical shell.

SCIENTIFIC INSTRUMENTS

The initial scientific objective of the Pioneer Program was the *in situ* measurement of interplanetary phenomena during the minimum in the solar cycle. The later launches in the program and the unexpected longevities of the first Pioneers extended coverage through the following solar maximum well into the 1970's. The facets of the space environment of interest were the solar plasma, solar and galactic cosmic rays, magnetic fields, electric fields, cosmic dust, and radio propagation properties—all with reference to solar activity.

The experiments for the Pioneers were selected carefully by NASA on the basis of scientific merit, pertinence to the Pioneer mission, and other factors detailed in Volume II, Chapter 5. The instruments selected, the experimenters and their affiliations, and the assigned flights are summarized in table 2–5.

The Goddard Magnetometer (Pioneers 6, 7, and 8)

The interplanetary magnetic field is created by the Sun and modulated by the streams of plasma that stream out into interplanetary space. Magnetic field measurements, particularly those recording transients following solar activity, are critical to our understanding of the space surrounding the Sun.

The spin-stabilized Pioneers permitted the use of a unique magnetometer design whereby all three components of the magnetic field could be measured with a single-axis sensor. If the sensor axis is mounted at an angle of 54°45′ to the spin axis and if the sensor is sampled at three equally spaced intervals during the rotation of the spacecraft, the experimenter receives three independent measurements of three orthogonal components of the magnetic field. These completely define the instantaneous magnetic field.

TABLE 2-5.—*Experiments Selected for Pioneer Flights*

Instrument	Principal experimenter	Pioneer spacecraft 6	7	8	9	E
Single-axis fluxgate magnetometer	N. F. Ness, Goddard Space Flight Center	X	X	X		
Triaxial fluxgate magnetometer	C. P. Sonett, Ames Research Center				X	X
Faraday-cup plasma probe	H. Bridge, Massachusetts Institute of Technology	X	X			
Plasma analyzer	J. Wolfe, Ames Research Center	X	X	X	X	X
Cosmic-ray telescope	J. Simpson, University of Chicago	X	X			
Cosmic-ray anisotropy detector	K. G. McCracken, Graduate Research Center of the Southwest	X	X	X	X	X
Cosmic-ray gradient detector	W. R. Webber, University of Minnesota			X	X	X
Radio propagation experiment	V. R. Eshleman, Stanford University	X	X	X	X	X
Electric-field detector	F. L. Scarf, TRW Systems			X	X	X
Cosmic dust detector	O. Berg, Goddard Space Flight Center			X	X	X
Celestial mechanics	J. D. Anderson, Jet Propulsion Laboratory	X	X	X	X	X

The sensor of the single-axis fluxgate magnetometer employed in the Goddard experiment is a saturable inductance driven by a gating magnetic field applied by a winding. The flux induced in the saturable core is modified by the presence of the external magnetic field in such a way that the contribution of the external field can be easily separated and quantified.

The fluxgate sensor is mounted on one of Pioneer's three booms at a distance of 2.1 m from the spin axis in a cannister employing passive thermal control. An unusual feature of this experiment is an explosive-actuated indexing device, which permits the experimenter back on Earth to flip the sensor over by 180° so that magnetic fields created by the spacecraft can be taken into account. The Goddard sensor is rotated by a spring-driven escapement mechanism. Because of their very high reliabilities, 11 pairs of small explosive charges were used to activate the escapement mechanism. Thus, 11-sensor flip-overs are possible by remote control.

Magnetic interference is a critical problem for the experimenter flying a magnetometer in interplanetary space. The fields are usually less than 10γ and may be overwhelmed by the fields generated by the spacecraft.[10] For this reason, the Pioneers were made as magnetically clean as possible, and the magnetometer sensor was located on a spacecraft boom 2.1 m from the spacecraft spin axis. Detailed mapping indicated that the magnetic interference from the spacecraft was less than 0.125γ, 0.35γ, and 0.2γ on Pioneers 6, 7, and 8, respectively. The Pioneers were among the cleanest spacecraft ever built from a magnetic standpoint. Therefore, the data telemetered to Earth have been of great utility in mapping the magnetic structure of solar disturbances and (from data gathered during the first few hours of flight) the Earth's magnetic tail.

The Ames Magnetometer (Pioneers 9 and E)

The Ames magnetometer instrumentation consists of a fluxgate-sensor package located at the end of one of the 62-in. spacecraft booms and an electronics package mounted on the spacecraft equipment platform. Like the Goddard magnetometer, the Ames instrument is based on the fluxgate saturable inductance sensor. The instrument, however, employs three sensors mounted along mutually orthogonal axes rather than a single sensor as in the Goddard instrument. One fluxgate is parallel to the spacecraft spin axis and a second oriented radially. The Ames experimenters hoped that their three-axis magnetometer would provide a better measure of the interplanetary magnetic field during disturbances involving large, rapid magnetic fluctuations.

The three sensors comprise two packages: one single-axis fluxgate is located in a package mounted so that the sensor axis is parallel to the spacecraft boom axis; the second package contains two orthogonally mounted fluxgates with both axes perpendicular to the boom axis. The Ames instrument includes a flipping mechanism, but it is powered by two resistance-heated bimetallic motors rather than the pyrotechnic devices used by the Goddard magnetometer. The motors on the Ames instrument flip the dual sensor assembly 90° upon command from Earth. One motor flips the sensors clockwise; the other counterclockwise. The Ames magnetometer sensors can be flipped again and again and are not limited to the number of pyrotechnic charges launched with the spacecraft (11 flips for the Goddard instrument). However, an additional burden is placed upon the spacecraft power supply by the resistance heaters in the motors.

[10] $1\gamma = 10^{-4}$ gauss.

MIT Faraday-Cup Plasma Probe (Pioneers 6 and 7)

By 1965, plasma probes flown on several Earth satellites and planetary probes had confirmed that the interplanetary plasma originates in the Sun's corona and flows outward toward the planets at some 300 km/sec, remaining ionized out to several AU. Further, this plasma is electrically conductive and interacts in complex ways with solar and planetary magnetic fields. The scientific objectives of the MIT plasma probes were to measure the following characteristics of the interplanetary plasma:

(1) Positive ion flux as a function of energy and direction
(2) Electron flux as a function of energy and direction
(3) The temporal and spatial variations of these physical quantities
(4) Correlation of plasma measurements with magnetic field measurements

MIT scientists had flown Faraday-cup plasma probes on the Interplanetary Monitoring Platform (IMP) and Orbiting Geophysical Observatory (OGO) series of Earth satellites prior to the Pioneer 6 and 7 flights. The Pioneer instruments were basically similar to these flight-proven plasma probes. The Pioneer sensors (fig. 2–20), the Faraday cups, are 6 in. in diameter with the open side normal to the spacecraft spin axis so that it sweeps out the plane of the ecliptic as the spacecraft spins. At the bottom of the cup, two halves of a split collector intercept those electrons and positive ions from the external plasma that are able to pass through a modulator grid. This grid electrically sorts out the particles in the plasma according to species and energy. The collector is split parallel to the spacecraft equatorial plane to provide directional information about the plasma fluxes in the meridian plane.

The energy spectra of the plasma ions and electrons are measured by applying square waves at different voltage amplitudes to the modulator grid directly in front of the split collector. For example, an 1800-Hz square wave varying between V_1 and V_2 will admit only those particles in the plasma with energies between V_1 and V_2 eV. Further, the square wave will modulate the stream of particles impinging on the collectors so that the currents collected and resultant signals delivered to the electronics section of the experiment will vary at 1800 Hz, a signal that can be amplified and filtered conveniently. The amplitude of the square wave is varied between 100 and 10 000 V in 14 contiguous intervals to scan the positive ion spectrum and between 100 and 2000 V in four intervals for the electron spectrum.

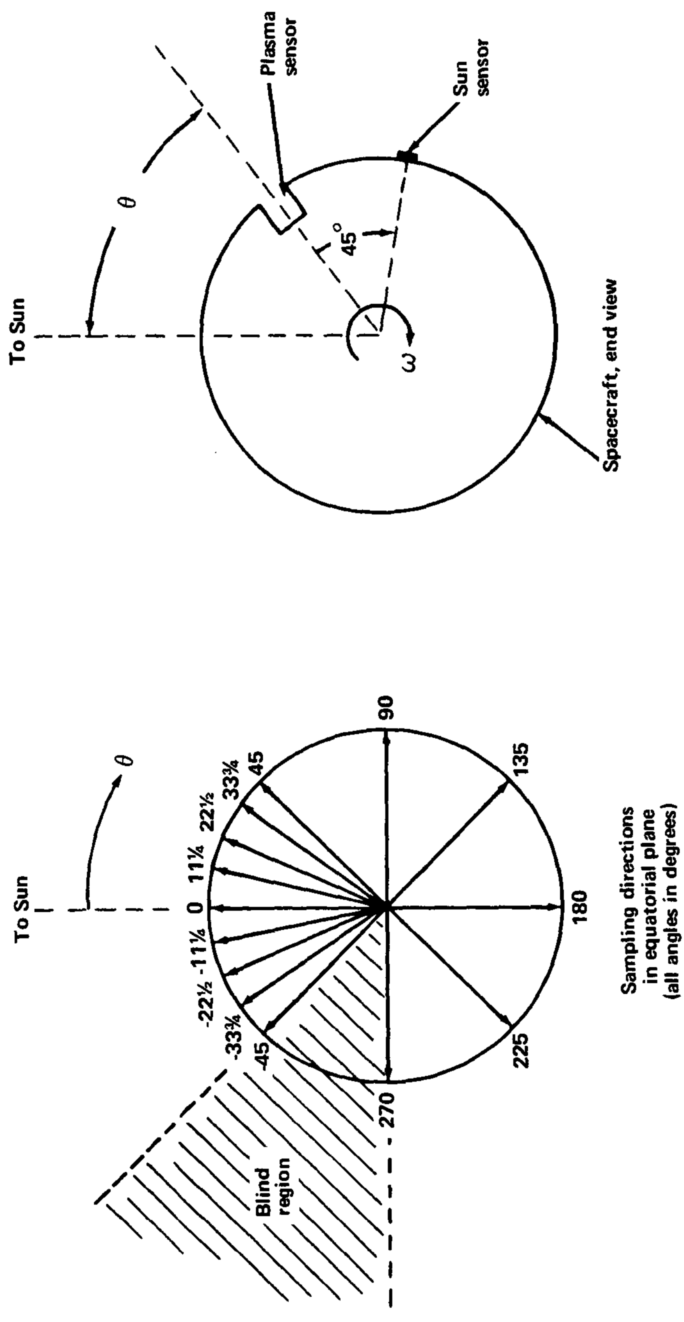


FIGURE 2–20.—Sampling intervals of the MIT plasma probe.

Ames Plasma Probe (Pioneers 6, 7, 8, 9, and E)

When the angular distributions of the ions and electrons comprising the interplanetary plasma are not well known, the response of the Faraday-cup probe is often hard to interpret. The curved-surface electrostatic plasma analyzers provide more detail, but they are correspondingly more complex. Plasma analyzers work on a different principle. They separate the plasma components into different energy-per-unit-charge (E/q) groups and also into much smaller solid angles. In other words, their E/q and solid-angle discriminations are better.

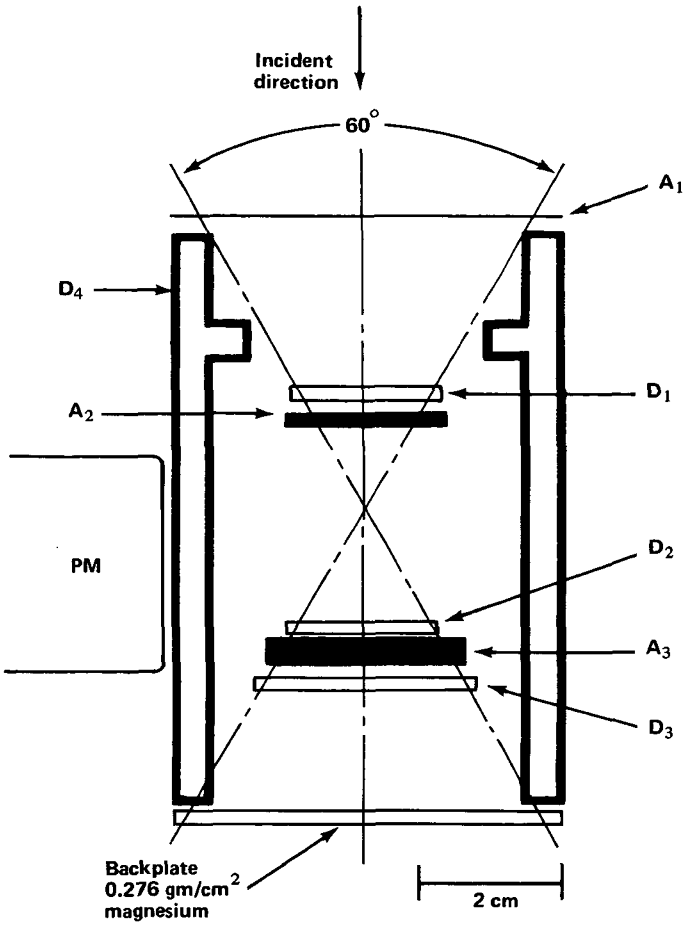
The curved-surface plasma analyzers work by applying stepped voltages to a pair of curved plates. Positively charged particles in the plasma are deflected toward one plate, negatively charged particles toward the other. Depending upon the voltage difference across the plates, only those particles within a narrow range of energy-to-charge ratio and within a narrow solid angle will reach the particle collector at the end of the curved plates. In effect, the curved plates form a filter through which passes only a certain range of energy-to-charge ratios. By making the plates portions of spherical surfaces and segmenting the collectors, the plasma flux arriving from different directions may be analyzed. Energy-to-charge spectrum scanning is possible by stepping the applied voltages.

Although the basic principles of operation were the same, the plasma analyzers flown on the Block–I Pioneer spacecraft were significantly different from those on Block–II spacecraft. The Block–I instruments used quadrispherical plates, eight current collectors, 16 positive ion groups between 200 and 100 000 eV, and eight electron groups between 0 and 500 eV. Block–II instruments differed from Block–I instruments by using truncated hemispherical plates, three current collectors, 30 positive ion groups between 150 and 15 000 eV, and 14 electron groups between 12 and 1000 eV.

The Chicago Cosmic-Ray Experiment (Pioneers 6 and 7)

The scientific objective of the Chicago cosmic-ray experiment was the measurement of the heliocentric, radial gradient of the proton and alpha particle fluxes in various energy ranges. Such information is useful in helping decide between various models of the interplanetary magnetic field that modulates solar cosmic rays.

The basic instrument is a four-element, solid-state, cosmic-ray telescope (fig. 2–21). Three telescope elements (D1, D2, and D3) are lithium-drifted silicon semiconductor wafers. These detectors are surrounded by a plastic scintillator (D4), which defines the 60°



Legend

A_1	Aluminized Mylar window 0.5 mg/cm^2	D_2	Lithium drift silicon detector 0.230 gm/cm^2
D_1	Lithium drift silicon detector 0.122 gm/cm^2	A_3	Platinum absorber 8.46 gm/cm^2
A_2	Aluminum absorber 0.103 gm/cm^2	D_3	Lithium drift silicon detector 0.22 gm/cm^2
		D_4	Plastic scintillator
		PM	Photomultiplier tube

FIGURE 2–21.—Arrangement of detectors and absorbers in the Chicago cosmic-ray telescope.

acceptance cone for incident charged particles. A photomultiplier tube monitors the plastic scintillator. The silicon wafers and the photomultiplier tube are all sensitive to sunlight, making a light-tight enclosure a necessity. Particle absorbers between the telescope elements define the response of the elements to various particles at various energies.

Consider particles entering the instrument through the solid angle defined by the plastic scintillator. The particles pass through D1, producing pulses with heights proportional to the amount of energy lost in transit through the silicon wafer. The detectors D2 and D3 have the same general characteristics. From this type of information, along with knowledge of the energy-loss characteristics of the absorbers placed between D1, D2, and D3, and with pulse-height analysis, the experimenters can deduce considerable information about the cosmic-ray environment seen by the instrument as it scans the plane of the ecliptic.

The energy discriminating capabilities of the experiment (when pulse-height analysis is employed) are summarized below:

(1) For protons—6 to 8 MeV and 80 to 190 MeV

(2) For alpha particles—8 to 80 MeV per nucleon and 80 MeV per nucleon to relativistic energies

(3) For electrons—1 to 20 MeV in the mode $D1D2\overline{D3D4}$[11] and in excess of 160 keV when D1 counts are considered alone

Electrons can be distinguished in the pulse-height analysis of D1 signals because they cause mainly low-amplitude pulses. Counting rates alone without pulse-height analysis can also provide significant energy-and-particle discrimination in themselves. Two examples follow: (1) for protons plus alphas, $D1\overline{D2D4}$ logic provides counts in the 0.8 to 8 MeV per nucleon range; (2) for protons and alphas, $D1D2\overline{D3D4}$ logic yields counts between 8 and 80 MeV per nucleon.

The GRCSW Cosmic-Ray Experiments (Pioneers 6, 7, 8, 9, and E)[12]

The Earth-based study of cosmic-ray anisotropy has always been hampered by the presence of the Earth's magnetic field and atmosphere. Scientific satellites do not get far enough away from the Earth to avoid its magnetic field completely. The crucial test of one theory that describes the motion of cosmic rays within the

[11] A bar over a detector designation signifies anticoincidence. For example $D1\overline{D2}$ "logic" means that detector D1 detects a particle at a given instant in time but D2 does not.

[12] GRCSW was later renamed Southwest Center for Advanced Studies (SCAS) and is now known as The University of Texas at Dallas.

solar system depends upon the careful measurement of cosmic-ray anisotropy at energies below 1000 MeV. For such measurements, the *instruments must be carried well away from the Earth.* The Pioneer probes were ideal for this purpose.

The Graduate Research Center of the Southwest (GRCSW) instruments were part of all five Pioneer payloads, but those on Pioneers 8, 9, and E (Block II) represented second-generation equipment. The later equipment was more sophisticated because additional low-energy measurements were made in, above, and below the plane of the ecliptic.

In both generations of equipment, the principal cosmic-ray detector consisted of a flat cylindrical CsI(Tl) scintillator crystal (detector C) contained within a cuplike cylindrical container of scintillating polytoluene (detector D), which functioned as a guard detector. On all five Pioneers the CsI(Tl) and plastic scintillators were connected in anticoincidence so that the detector was directional with an acceptance cone of about 107°. Particles with energies greater than 90 MeV/nucleon were also eliminated because even if they entered the instrument's aperture, they passed right through the CsI(Tl) scintillator and activated the guard scintillator. Separate photomultiplier tubes watched the two scintillators (fig. 2–22).

The same basic scintillator arrangement was employed for the Block–II flights, but it was supplemented with a three-way coincidence telescope consisting of four 100-μ, totally depleted silicon, surface-barrier detectors.

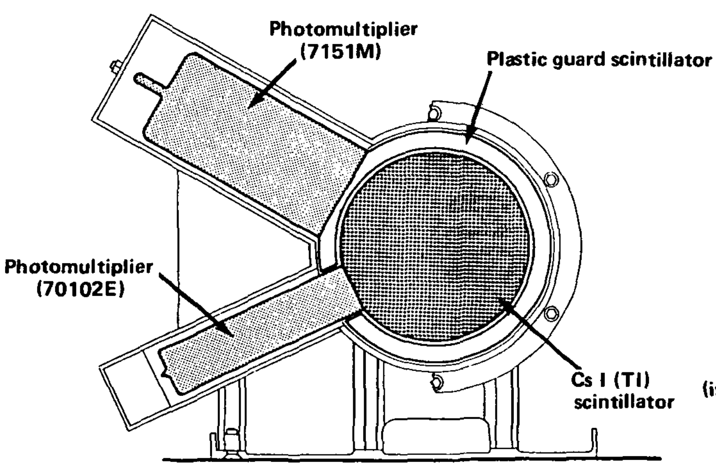


FIGURE 2–22.—Axial view of the GRCSW cosmic-ray telescope, Block–I Pioneers. The detector dimensions and positions were changed for the Block–II flights (see text).

The goal of the experiments was the study of cosmic-ray anisotropies as small as 10^{-3} of the mean cosmic-ray flux. Consequently, the count-accumulation times for the four quadrant registers had to be identical to at least one part in 10^4 to provide meaningful experimental results. A unique and critical part of the experiment, therefore, was the precision, crystal-controlled aspect clock that controlled the gating pulses.

Minnesota Cosmic-Ray Detector (Pioneers 8, 9, and E)

The Minnesota cosmic-ray experiment had a purpose entirely different from that of the GRCSW instrument. The experiment objectives listed below are indicative of the lack of high precision cosmic-ray experiments flown on spacecraft prior to the spring of 1964.

(1) Measure the quiet-time energy spectrum of protons, alphas, and heavier nuclei up to a charge of 14 over a wide energy range with better energy and background discrimination than previously obtained.

(2) Measure the variations in these spectra, including the features of Forbush decreases as well as the 11-year variation during the solar cycle.

(3) Measure the radial and azimuthal cosmic-ray gradients existing in interplanetary space during quiet and disturbed periods on the Sun.

(4) Measure comprehensively the charge, isotopic composition, and energy spectrum of solar cosmic rays.

The Minnesota instrument incorporates seven separate detectors (fig. 2–23), which are, in effect, electronically arranged into five different telescopes by Earth commands. Detector G is a two-piece guard counter made of Pilot B plastic; it is viewed by a photomultiplier tube. Detector D, at the bottom of the telescope, is a 1-cm-thick piece of synthetic sapphire and functions as a Cerenkov counter. Another photomultiplier tube views this detector. The remaining five detectors—B1A, B1B, B2, B3, and C—are all of the semiconductor type. The coincidence-anticoincidence conditions that electronically create five different telescopic arrangements are listed in table 2–6, along with the ranges and particles which they can detect.

The Stanford Radio Propagation Experiment (Pioneers 6, 7, 8, 9, and E)

The Stanford experiment measured the integrated electron density along the radio transmission path between the Earth and space-

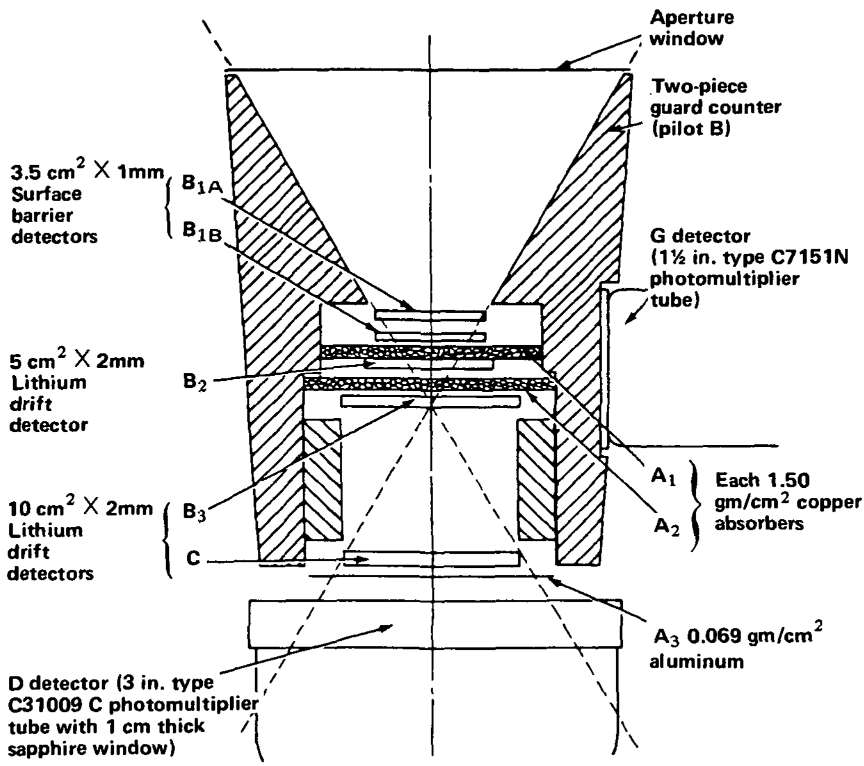


FIGURE 2-23.—Arrangement of detectors and absorbers in the Minnesota cosmic-ray telescope.

craft. For successful operation the experiment required that a special dual-channel, phase-locked-loop receiver in the spacecraft lock onto signals transmitted from the 150-ft parabolic antenna located on the Stanford campus. When the experiment is in progress, two modulated coherent carriers of approximately 49.8 and 423.3 MHz are sent to the spacecraft from the 150-ft Stanford antenna. The special Stanford receiver on the spacecraft measures the relative phase change between the modulation envelopes. Since the higher frequency is relatively unaffected by the presence of ionization, the comparison provides the information needed to compute the integrated electron number density, or the total number of electrons per square meter between Earth and spacecraft. The rate of phase change of one signal with respect to the other is also measured to very high precision to determine the time variation of the integrated electron number density. The experiment also measures the strength of the signals sent from Earth.

TABLE 2–6.—*Minnesota Cosmic-Ray Telescope Arrangements*

Telescope	Coincidence-anticoincidence requirements	Charge and energy ranges of the particles detected	
T1, T2	$B1A \cdot B1B \cdot B2 \cdot B3 \cdot C$	$Z \geq 1$	$E \gtrsim 64$ MeV per nucleon
		$e\pm$	$E \gtrsim 8.4$ MeV
T3	$B1A \cdot B1B \cdot B2 \cdot \overline{C} \cdot \overline{G}$	$e\pm$	4.2 MeV$\leq E \leq$8.4 MeV
		$_1H^1$	39.6 MeV$\leq E \leq$64.3 MeV
		$_2He^4$	39.4 MeV per nucleon $\leq E \leq$64.1 MeV per nucleon
T4	$B \cdot \overline{B2} \cdot \overline{G}$ ($B1 = B1A + B1B$)	$e\pm$	0.34 MeV$\leq E \leq$4.3 MeV
		$_1H^1$	3.5 MeV$\leq E \leq$39.7 MeV
		$_2He^4$	6.6 MeV per nucleon$\leq E \leq$39.7 MeV per nucleon
T5	$B1A \cdot B1B$	$Z \geq 1$	$E \gtrsim 14$ MeV per nucleon
		$e\pm$	$E \gtrsim 0.6$ MeV

Both the 49.8- and 423.3-MHz transmissions to the spacecraft originate at the Stanford computer-controlled "Big Dish." The 49.8-MHz signal is fed to a crossed, folded dipole and reflector located just below the focal point of the 150-ft dish. This signal is generated in a 300-kW linear amplifier transmitter. The high frequency signal, 423.3 MHz, is radiated directly from the horn of the dish.

Both carriers from the Earth are received by the Stanford antenna on the spacecraft and sent to the Stanford dual-channel receiver, which consists of two separate coherent phase-locked receivers. The main reasons for the phase-lock design are (1) to increase the sensitivity of the receiver and (2) to detect the difference in radio frequency cycles between the 49.8 MHz and the 2/17 harmonic of the 423.3-MHz carrier.

Because the Stanford experiment must have transmitter operators at Stanford in the loop during its operation, real-time teletype data are relayed directly from JPL's Space Flight Operations Facility (SFOF) to Stanford. Teletyped parameters include the modulation phase-difference measurements and the radio frequency difference counts. The Stanford operator uses this information to adjust the transmitter frequencies, powers, and modulation phase offset for best operation. At the experiment design range of 300 000 000 km, it takes about 33 min before the effects of transmitted changes are seen in the teletype messages from JPL.

The TRW Systems Electric Field Detector (Pioneers 8, 9, and E)

The Stanford and TRW Systems experiments are closely related. In fact, the TRW Systems experiment makes direct use of the Stanford antenna. Whereas the purpose of the radio propagation experiment was essentially macroscopic in nature—measuring integrated electron density over long distances—the TRW Systems experiment is *microscopic in design. Its purpose is the detection of charge* differences over small distances in interplanetary space through the electric fields they create along the Stanford antenna. Plasma waves and other cooperative actions in the 100- to 100 000-Hz VLF range of charged particles in collisionless interplanetary space can be detected with the instrument.

The decision to add the electric field detector was made well after the Block–II payload was selected. Six spare words from the Pioneer telemetry format were made available. The weight of 0.9 lb and power drain of 0.5 W made it possible to squeeze this experiment onto the spacecraft without major changes, particularly since it could use the Stanford antenna. In a sense, it is an addendum to the Stanford experiment, and it is often treated as such in the literature.

The electric field experiment makes use of the short (6.4 in.) 423.3-MHz segment of the Stanford antenna as a capacitively coupled sensor with which local plasma waves can be detected. The sensor is relatively insensitive but adequate for the purposes of the experiment. A number of Earth satellites have carried similar VLF radio receivers for the same purpose.

The portion of the wave spectrum to be studied had to be selected carefully in advance on the basis of our limited knowledge of plasma waves in space. The high-frequency channel selected was at 22 kHz for Pioneer 8 and 30 kHz for Pioneers 9 and E. The low-frequency channels were at 400 Hz and 100 to 100 000 Hz (for the broadband survey) on all Block–II spacecraft.

The Goddard Cosmic-Dust Experiment (Pioneers 8, 9, and E)

The cosmic-dust experiment objectives were:

(1) To measure the cosmic-dust density in the solar system well away from the Earth

(2) To determine the distribution of cosmic-dust concentrations (if any) in the Earth's orbit

(3) To determine the radiant flux density and speeds of particles in meteor streams

(4) To perform an in-flight determination of the reliability of the microphone as a cosmic-dust detector

The instrument consists of two film-grid sensor arrays spaced 5 cm apart followed by an acoustical impact plate (microphone) upon which the last film is mounted. Three types of cosmic-dust particles were considered in the design of the experiment:

(1) High-energy, hypervelocity particles (> 1.0 erg)
(2) Low-energy, hypervelocity particles (< 1.0 erg)
(3) Relatively large, high-velocity particles (> 10^{-10} g)

As a high-energy, hypervelocity particle pierces the front film sensor (fig. 2–24), some of its kinetic energy generates ionized plasma at the front, or "A" film. The electrons in the plasma are collected on the positively biased grid (+24 V) creating positive pulses as shown. The positive ions in the plasma are collected on the negatively biased film (−3.5 V), producing a positive pulse that is pulse-height-analyzed to measure the particle's kinetic energy. The same thing occurs at the rear sensor or "B" film, generating a second set of plasma pulses. Impact on the plate produces an acoustical pulse. A peak-pulse-height analysis is performed on the acoustical sensor output as a measure of the particle's remaining momentum.

A low-energy, hypervelocity particle will yield all of its kinetic energy at the "A" film. A pulse-height analysis measures the particle's kinetic energy. A high-energy hypervelocity particle may be erroneously registered as a low-energy hypervelocity particle if, because of its angle of entry, it fails to hit the "B" film. If a relatively large, high-velocity particle enters, it may pass through the front and rear film arrays without generating detectable plasma because of its comparatively low velocity; but it may still impart a measur-

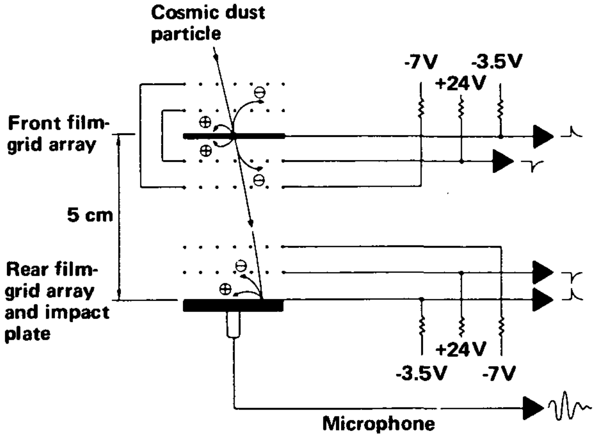


FIGURE 2–24.—Schematic of the Goddard micrometeoroid sensor.

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able impulse to the acoustical sensor. An electronic "clock" registers the times of flight of particles. The time lapses between positive pulses from the "A" and "B" films are used to derive particle speeds.

The time-of-flight sensor is one of 256 similar sensors that comprise the portion of the Pioneer instrument measuring particle speed and direction. Four vertical film strips are crossed by four horizontal grid strips that create 16 front and 16 rear film sensor arrays (each 2.5 by 2.5 cm) or 256 total combinations. Each grid strip and film strip connects to a separate output amplifier. The output signals from these amplifiers are used to determine the segment in which an impact occurred. Thus, by knowing the front film-grid segments penetrated and the rear film-grid segment affected by the impact, one can determine the direction of the incoming particle with respect to the sensor axis and the spacecraft attitude. The solar-aspect sensor determines the Sunline at the time of an impact.

The JPL Celestial Mechanics Experiment (Pioneers 6, 7, 8, 9, and E)

The celestial mechanics experiment required no special equipment on the spacecraft or at the tracking stations. The tracking data provided by the Deep Space Stations (DSS) were sufficiently accurate to support the following primary objectives:

(1) To obtain better measurements of the masses of the Earth and Moon and of the Astronomical Unit (AU)

(2) To improve the ephemeris of the Earth

(3) To investigate the possibility of testing the General Theory of Relativity using Pioneer tracking data

The methods employed in obtaining the tracking data are discussed in Chapter 4, where the results from all experiments are presented.

THE DELTA LAUNCH VEHICLE

The Delta launch vehicle, sometimes called the Thor-Delta, has been one of NASA's most successful launch vehicles. The use of the Delta was basic in planning the Pioneer Program, primarily because it was low cost and also because it had already proven to be a reliable spacecraft launcher when the Pioneer Program was being formulated in 1962.

The Delta is basically a three-stage rocket. The liquid-fueled first and second stages are topped by a small solid-propellant third stage (fig. 2–25). The first-stage core is the Thor military rocket, burning a hydrocarbon fuel similar to kerosene (RP–1, RJ–1, etc.) with liquid oxygen. This stage is manufactured by the McDonnell Douglas Astronautics Company. The liquid first-stage engines are made by

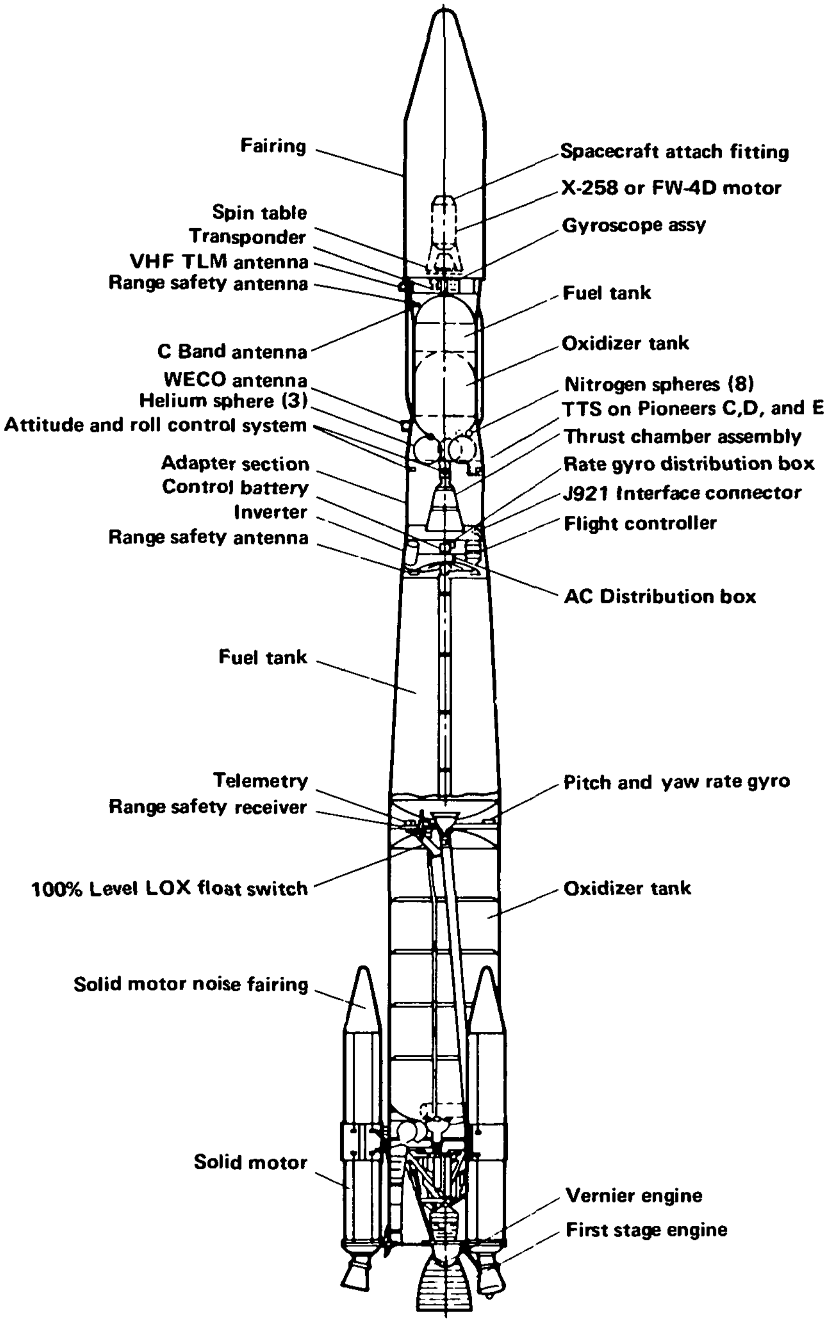

FIGURE 2–25.—The thrust-augmented improved Delta (TAID).

the Rocketdyne Division of North American Rockwell. The solid, thrust-augmentation rockets strapped on the first stages of later models are Castor rockets, usually produced by the Thiokol Chemical Corporation. The much smaller second stage uses unsymmetrical dimethyl hydrazine (UDMH) as fuel, oxidized by inhibited red fuming nitric acid (IRFNA). The second stage is also a product of McDonnell Douglas Corporation. It employs an Aerojet-General engine. The third-stage solid rockets have been manufactured by various concerns during the evolution of the Delta: Allegheny Ballistics Laboratory, United Technology Center, and Thiokol Chemical Corporation. The Delta is one of NASA's smaller launch vehicles (first-stage thrust, about 175 000 lb; plus about 160 000 lb from solid strap-ons on later models).

No launch vehicle that has seen as much use as the Delta remains unchanged. Almost every launch vehicle is different at least in some minor detail, because the interface with each payload is different. More significant changes arise when rocket motors are uprated, propellant tank sizes are changed, and solid-fuel rockets are strapped on for first-stage augmentation. The Delta has gone through over a dozen of these upratings and improvements. The characteristics of the Pioneer Deltas are summarized in table 2–7.

TRACKING AND COMMUNICATING WITH THE PIONEER SPACECRAFT

When the Pioneer Program began in 1962 there was no question about network choice. The DSN was the only one of NASA's three networks that could track and communicate with a deep-space probe. Like the Delta launch vehicle, the DSN became a pillar of the Pioneer Program. It helped shape spacecraft design as well as the launch trajectories and heliocentric orbits.

Three basic concepts are necessary to the successful tracking of and acquisition of data from Pioneer space probes that are tens or hundreds of millions of miles out in space:

(1) The concept of a high-gain, highly directional, paraboloidal antenna with a large diameter shown in figure 2–26. (High gain permits reception of very weak spacecraft signals; high directionality provides the accurate angular bearings needed for tracking.)

(2) A measure of two-way Doppler shift (in the coherent mode) of radio signals between Earth and spacecraft and back again (Spacecraft radial velocity comes from these measurements.)

(3) The JPL phase-lock-loop, conceived by JPL's Eberhardt Rechtin during the 1950's, and adopted by the DSN and later by the

TABLE 2-7.—*Physical Characteristics of the Pioneer Deltas* [a]

Characteristic		Pioneer 6	Pioneer 7	Pioneer 8	Pioneer 9	Pioneer E
Delta popular name		TAID	TAID	TAID	TAID	Long-tank Delta
Delta model number		E	E	E	E	L
Delta launch number		35	40	55	60	73
First stage	Model	DSV-2C	DSV-2C	DSV-2C	DSV-2C	DSV-2L-1B
	Height (ft) (with adapter)	60.4	60.4	60.4	60.4	70.3
	Diameter (ft)	8	8	8	8	8
	Weight (lb)					186 000
	Sealevel thrust (lb)	175 600	175 600	175 600	175 600	172 000
First stage augmentation	Model	Castor I	Castor I	Castor I	Castor II	Castor II
	Height (ft) (with nozzle)	24.3	24.3	24.3	24.3	24.3
	Diameter (ft)	2.6	2.6	2.6	2.6	2.6
	Weight (lb)	27 600	27 600	27 600	29 600	29 600
	Sealevel thrust (lb)	161 700	161 700	161 700	156 450	156 450
Second stage	Height (ft)	13	13	13	13	13
	Diameter (ft)	5.8	5.8	5.8	5.8	5.8
	Weight (lb)	14 000	14 000	14 000	14 000	14 000
	Sealevel thrust (lb)	7 400	7 400	7 400	7 400	7 400
Third stage	Model	X-258	FW-4D	FW-4D	FW-4D	FW-4D
	Height (ft)	5	5	5	5	5
	Diameter (ft)	1.7	1.7	1.7	1.7	1.7
	Weight (lb)	735	663	663	663	663
	Vacuum thrust (lb)	6 200	5 600	5 600	5 600	5 600
Total launch vehicle	Height (ft) (with shroud)	92	92	92	92	106
	Weight (lb)	150 000	150 000	150 000	150 000	200 000
	Date	12-16-65	8-17-66	12-13-67	11-8-68	8-27-69
Spacecraft	Weight (lb)	140	140	145	148	148

[a] Thrust and weight figures are approximate.

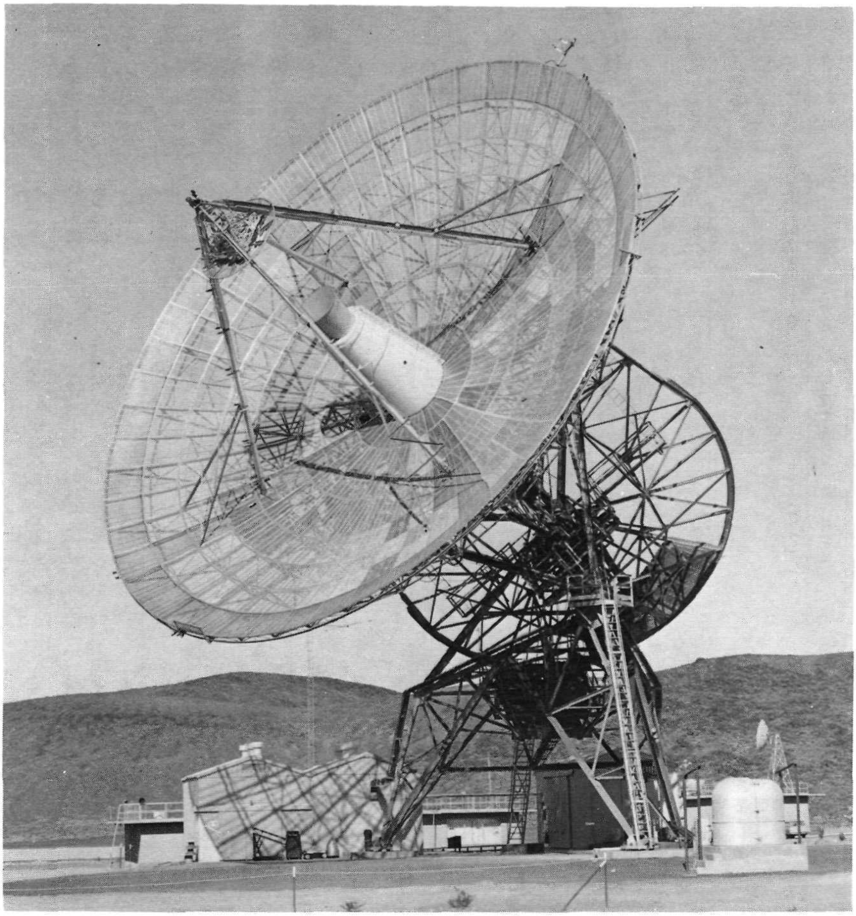

FIGURE 2–26.—The first 85-ft paraboloidal antenna installed at Goldstone (Pioneer site).

Manned Space Flight Network (MSFN) for its unified S-Band tracking during the Apollo Program (The phase-lock-loop concept is fundamental to the detection of signals by the DSN.)

In general terms, the DSN carries out the tracking, data acquisition, and command functions listed above using three distinct facilities:

(1) The Deep Space Instrumentation Facility (DSIF), which consists of the DSN tracking and data acquisition stations shown in table 2–8.

(2) The Space Flight Operations Facility (SFOF), located at

TABLE 2–8.—*The DSN Stations*

Station number	Location	Dish size	Primary during Pioneer flights: 6	7	8	9	E
11	Goldstone, Calif. (Pioneer) [a]	85 ft			X	X	
12	Goldstone, Calif. (Echo)	85 ft	X	X	X	X	
13	Goldstone, Calif. (Venus) [b]	85 ft					
14	Goldstone, Calif. (Mars) [c]	210 ft	X	X	X	X	
41	Woomera, Australia	85 ft			X		
42	Canberra, Australia [ad]	85 ft	X	X		X	
51	Johannesburg, South Africa	85 ft	X	X	X	X	
61	Madrid, Spain (Robledo) [a]	85 ft			X	X	
62	Madrid, Spain (Cebreros)	85 ft			X	X	
71	Cape Kennedy, Florida	4 ft	X	X	X	X	X

[a] MSFN Apollo Wing located here; used during some Pioneer flights.
[b] Used primarily for research and development.
[c] Used on extended Pioneer missions.
[d] Also called Tidbinbilla.

JPL, in Pasadena, California, which monitors all spacecraft data, issues commands, and performs all necessary mission calculations

(3) The Ground Communication Facility (GCF), which ties all DSIF stations to the SFOF with high-speed, real-time communications (The bulk of DSN communication traffic is carried via NASCOM, which contributes circuits to the GCF.)

Despite the size and capabilities of the DSN, NASA had to pool the following facilities to fully cover the Pioneer flights:

(1) The DSN, which included the DSIF, GCF, and SFOF

(2) The MSFN, which provided 85-ft dish support on occasion

(3) NASCOM, which contributed many circuits to the DSN's GCF

(4) The Air Force Eastern Test Range (AFETR), which supplied much of the ground environment from the launch pad downrange 5000 miles to Ascension Island; i.e., the Near-Earth Phase Network

The Pioneer flights were divided logically into two main phases: near-Earth and deep-space. The successful injection of the spacecraft into a heliocentric orbit was the event that separated the two phases (fig. 2–27). At this point, somewhere over the Indian Ocean, the spacecraft would be handed over completely to the DSN and cooperating MSFN stations. Each phase of tracking required a different configuration of tracking, data acquisition, command, and ground communication equipment.

The equipment committed to the Pioneer Program during the near-Earth phase varied slightly from flight to flight, as detailed in table 2–9. The stations along the AFETR had the primary responsibility for tracking (or metric data) during the launch and Earth-

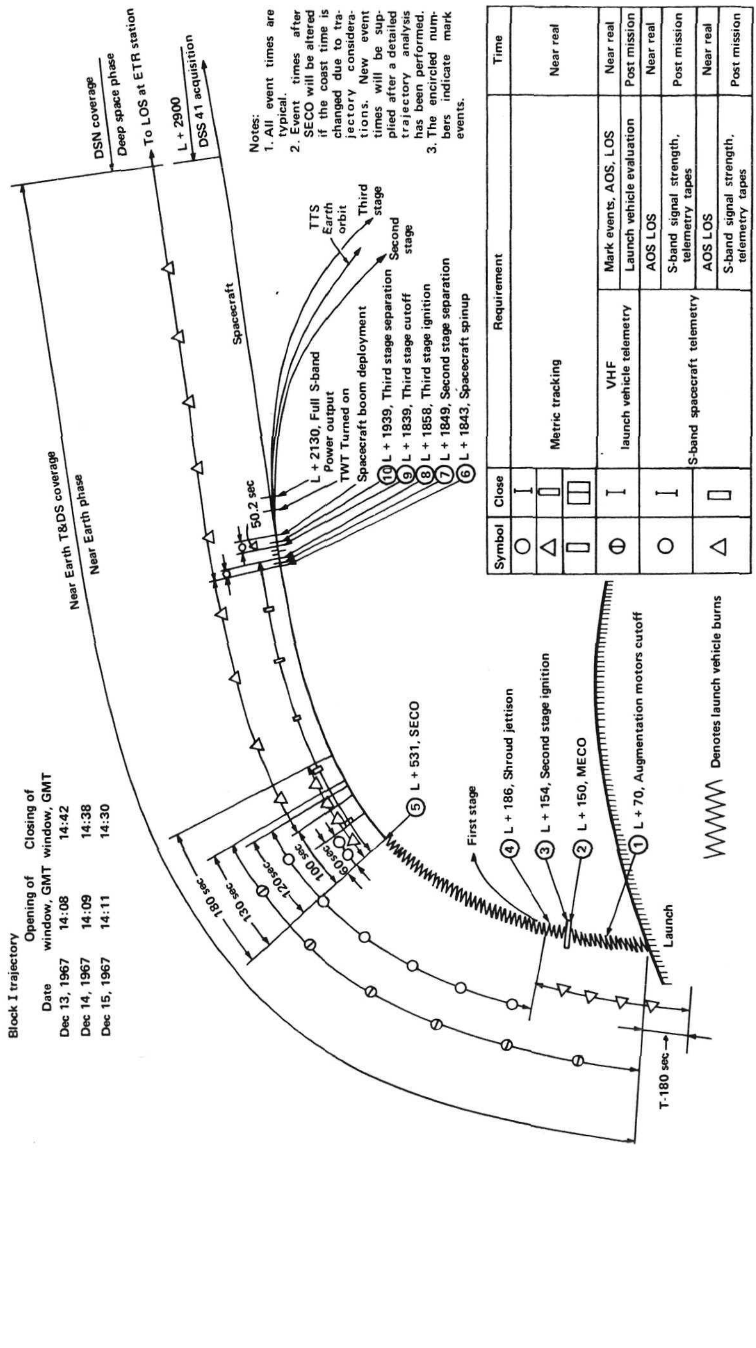

FIGURE 2-27.—Near-Earth tracking and telemetry requirements for the Pioneer 8 flight.

TABLE 2–9.—*Configuration of Tracking and Data Acquisition Stations during Near-Earth Phases*

Station number		Location	Tracking radars	Telemetry	Used during Pioneer flights			
					6	7	8	9
AFETR	1	Cape Kennedy	FPQ–6 FPS–16, TPQ–18	VHF, S-band	X	X	X	X
	3	Grand Bahama	FPS–16, TPQ–18	VHF	X	X	X	X
	7	Grand Turk	TPQ–18	VHF	X	X	X	X
	91	Antigua	FPQ–6	VHF, S-band	X	X	X	X
	12	Ascension	FPQ–18, FPS–16	VHF, S-band	X	X	X	X
	13	Pretoria	MPS–25	VHF, S-band	X	X	X	X
		Twin Falls (ship)	FPS–16		X	X	X	X
		Coastal Crusader (ship)			X	X	X	X
MSFN	1	Bermuda	FPS–16, FPQ–6	VHF	X	X	X	X
	2	Ascension			X	X	X	X
	3	Tananarive, Malagasy	Capri	VHF	X	X	X	X
	4	Carnarvon, Australia	FPQ–6	VHF	X	X	X	X
	5	Goddard Space Flight Center, Greenbelt, Md.			X	X	X	X
	6	Guam				X	X	X
	7	Hawaii				X	X	X
DSN	71	Cape Kennedy			X	X	X	X
	72	Ascension			X	X	X	X
	51	Johannesburg			X	X	X	X
		SFOF, Pasadena			X	X	X	X
		Building AO, Cape Kennedy			X	X	X	X

orbit portions of the flights. The Cape itself is well-equipped with radars, radio interferometers, and a great variety of optical tracking equipment. AFETR and MSFN downrange stations and Range Instrumentation Ships (RIS) also possess full complements of tracking radars and telemetry receiving equipment. Data are fed back to the Cape via submarine cables and radio links.

The DSN station at the Cape (DSS 71) provided prelaunch support to assure spacecraft compatibility with DSN configurations supporting Pioneer flights. JPL also maintains a field station at Cape Kennedy that provides an operational tracking interface between the SFOF, in Pasadena, and the Kennedy Space Center and Goddard Space Flight Center groups. Considering the manifold operations at the Cape, their complex interactions, and the immense detail required for effective coordination, such interface groups are essential. The JPL Field Station also contained an Operations Center with displays to help JPL personnel monitor the status of range instrumentation during Pioneer launches. Critical tracking and telemetry data were also routed to the SFOF through the field station.

All launches at Cape Kennedy are under the direct control of the Air Force until the spacecraft leaves Eastern Test Range (ETR) jurisdiction somewhere beyond Ascension. Because it is responsible for range safety, the Air Force monitors launch vehicle status data and tracking information. Commands to terminate the mission through the destruction of the launch vehicle are also an Air Force prerogative–one that was exercised during the launch of Pioneer E on August 27, 1969.

After leaving Earth orbit, the Pioneer spacecraft quickly ascended beyond the 500 to 1000 mile ranges of the AFETR and MSFN tracking radars. From here on they were tracked, communicated with, and commanded by the primary DSN stations listed in table 2–8. MSFN and other DSN stations worked the Pioneer spacecraft on an as-needed basis (fig. 2–28).

Each of the primary DSN stations was outfitted with mission-dependent equipment that accommodated general-purpose DSIF machinery to specific Pioneer requirements. The DSN gear was called Ground Operational Equipment (GOE). No special equipment was installed at the SFOF, although a general-purpose mission-support area was reconfigured for the Pioneer missions. Additional mission-dependent equipment was installed at Ames.

PIONEER DATA PROCESSING EQUIPMENT

Pioneer spacecraft radioed back to Earth two kinds of data: scientific data for the experimenters and engineering data for mis-

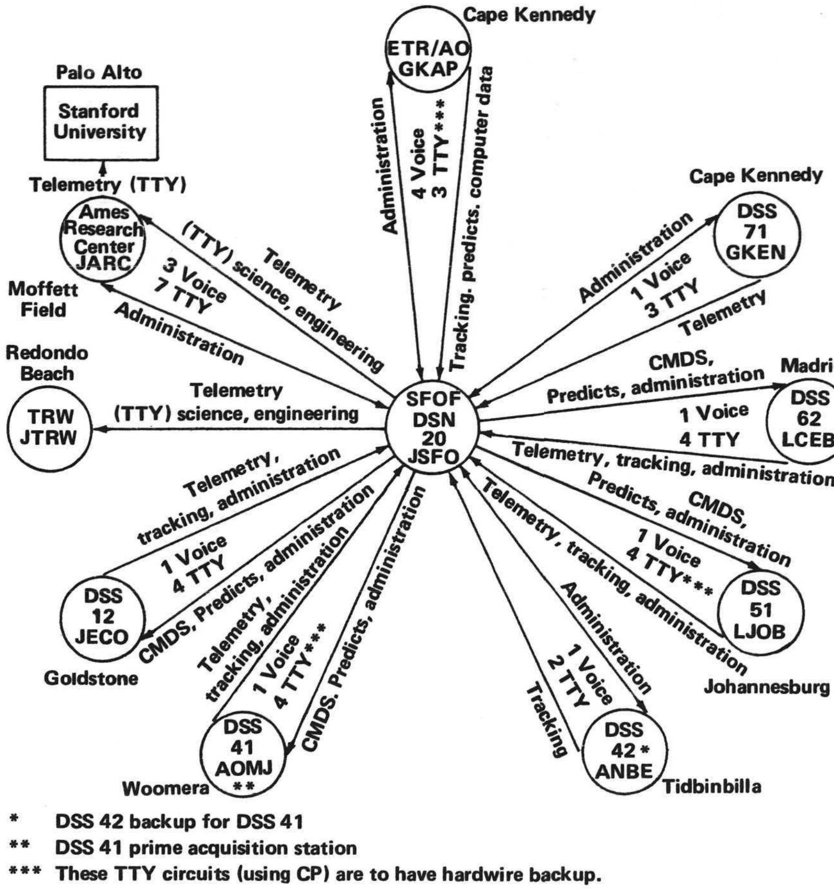

FIGURE 2–28.—GCF channels established for Pioneer 8.

sion controllers to use in assessing the "health" of the spacecraft. The telemetry data follow two separate paths between the DSN stations (which receive it directly from the spacecraft) to the experimenters and Pioneer project personnel. As they arrive from deep space, Pioneer telemetry data are recorded directly on magnetic tape at the DSN stations and airmailed to JPL for verification and then to Ames Research Center. This is the first route, and all data follow it. At Ames, they are processed on the Pioneer Off-Line Data-Processing System (POLDPS) for subsequent transmission to the experimenters on digital magnetic tapes in formats compatible with their computer facilities. Some of the telemetry data also follow a second route. These are dispatched immediately from the DSN to Ames Research Center via teletype through JPL's SFOF. These

FIGURE 2–29.—Pioneer Off-Line Data Processing System (POLDPS) at Ames Research Center.

are called "quick look" data; they are used for checking the scientific instruments and for retransmission (after some processing) to the Environmental Science Services Administration (ESSA) to help forecast solar activity. Data from the Stanford radio propagation experiment are handled differently. Proper operation of this experiment requires the near-real-time feedback to Stanford of information on the Stanford receiver status. This information is relayed by teletype from Ames Research Center to Stanford a few miles away. In addition, engineering data flow via teletype from the DSN to the SFOF and from there to both Ames and TRW Systems for analysis. At Ames, these engineering data are used to assess the health of the spacecraft and guide operational decisions.

Originally JPL had been assigned the task of processing Pioneer scientific data, but in 1964 JPL computers were heavily loaded, and it was decided to construct the processing line at Ames Research Center. Magnetic tape represented the only practical way to transmit the bulk of data from Pioneer spacecraft—teletype facilities could not handle the volume. At each DSN station, two Ampex FR–1400 tape recorders operating in parallel prepare analog tapes of the transmissions received from the Pioneers. Tape loading times for each machine are staggered to avoid the loss of data. One set of tapes containing all recorded data is selected and shipped first to JPL where it is examined (verified) to ensure the quality of reproduction. The tapes are then sent to POLDPS at Ames Research Center.

During 1969, Pioneer tape shipments averaged four hundred 9200-ft tapes per month, each containing 4 hr of data with half-hour overlaps. POLDPS processed and sorted out these data, preparing an average of four hundred 2400-ft tapes per month for the experimenters. The preparation of over 15 experimenter tapes per working day indicated that POLDPS was extremely active during 1969, when four Pioneers were transmitting data back to Earth (fig. 2–29).

POLDPS processes these tapes in a two-level system. The first level, called the Tape Processing Station (TPS), produces a multifile digital tape that serves as the input to the second level of processing, which consists of the Pioneer Off-Line Direct Coupled System (POLDCS). POLDCS generates separate experimenter tapes that are IBM-compatible and in the formats and densities desired by the individual Pioneer experimenters.

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CHAPTER 3

Pioneer Flight Operations

PRELAUNCH ACTIVITIES

THE SUCCESSFUL COMPLETION of the spacecraft's Preship Review at the TRW Systems plant in Redondo Beach, California, signals the beginning of prelaunch activities. The spacecraft is carefully packed and shipped to Cape Kennedy by air. Its arrival at the Cape initiates a 6 to 10 week series of additional tests and checkout procedures designed to assure both the readiness of the spacecraft and its compatibility with the Delta launch vehicle, the DSN, and the ETR. If all goes well and the pieces fit together, the spacecraft is launched.

More people and facilities participate during the Pioneer prelaunch and launch activities than at any other time. Although the Cape Kennedy and ETR downrange stations are the focal points during this phase of operations, the Deep Space Network, JPL's Space Flight Operations Facility, and Ames Research Center's Pioneer Mission Operations Center are all involved. As the moment of launch approaches, more and more of the NASA and Air Force general-purpose facilities "come on the line" for the launch. During the minutes after liftoff, radars, optical instrumentation, and telemetry antennas at the Cape and downrange are all waiting for the Delta and its Pioneer payload. Likewise, critical antennas at some of the DSN's Deep Space Stations break off from tracking Mariners and Pioneers already out in space and swing toward the points where the new Pioneer is expected to come over the horizon.

The functions of the major facilities concerned with a Pioneer launch are:

(1) Cape Kennedy provides facilities for spacecraft tests, checkout, and integration and facilities for mating of spacecraft with launch vehicle and for launch vehicle assembly and launch. The Pioneer Electrical Ground Support Equipment (EGSE) provides an interface between the spacecraft and the launch pad environment.

(2) Eastern Test Range (ETR) provides tracking and data acquisition services from launch through DSN acquisition at Johannesburg.

(3) The Deep Space Network (DSN) provides tracking, data acquisition, and transmission of command signals to the spacecraft. The

Pioneer Ground Operational Equipment (GOE) at selected DSN stations provides an interface between the spacecraft and the generalized DSN equipment.

The prelaunch phase of activities consists of so many hundreds of separate items and events that the checkout and countdown lists are often printed by computers. Three groups of processes and events stand out as particularly important:

(1) Training in operational procedures
(2) Integrated systems tests (ISTs)
(3) Operational readiness tests

Training in operational procedures was most important during the preparations for the launch of Pioneer A in 1965, when the Pioneer Program was new to ETR and DSN personnel. The Delta was already familiar, and the ETR and of course DSN had handled more complex spacecraft. The different aspects of the Pioneer launches were:

(1) The unusual orientation maneuvers following launch
(2) The narrow launch window associated with injecting the spacecraft into an orbit roughly parallel to the plane of the ecliptic
(3) The ejection of the TTS satellites from the Block–II Pioneers
(4) The occultations and flights through the Earth's magnetic tail.

The orientation maneuvers, especially, required careful training at the Goldstone DSS site and, in the case of Pioneers 6 and 9, at Johannesburg and Goldstone, respectively, where partial Type–II orientation maneuvers were carried out.

Pioneer-A Prelaunch Narrative

Both the prototype and flight models were sent to the Cape. The prototype arrived October 1, 1965, for use in practicing prelaunch operations.

The Pioneer-A flight model arrived on December 5. During preliminary alignment checkout a Total Indicator Runout (TIR) of 0.25 in. was noted, indicating a physical mismatch. The attach fitting was modified to bring the alignment within tolerance. Tests and checkouts proceeded normally through F −1 day, with only minor, easily corrected problems.

December 15, F −0 Day, was relatively calm with visibility of only 0.125 to 2 miles. Countdown commenced 30 min early at 1630. Everything went smoothly until T −90 min when the second-stage umbilical plug was inadvertently pulled, causing loss of power to the Delta second stage and the spacecraft itself. No one could be sure exactly what would happen if the plug were reinserted. Conceivably, some unforeseen signal could cause serious damage by firing some of the ordnance. The spacecraft and the Delta were therefore revalidated. The built-in 60-min hold and ultimately the launch window had to be extended while further checks were made. The terminal count resumed at 0145, December 16, at T −35 min.

At T −2 min an abnormality in the radio guidance equipment caused another hold. The situation seemed to correct itself, and the count was recycled to T −8 min. Liftoff occurred at 0231:20 EST, December 16, 1965 (fig. 3–1).

FIGURE 3–1.—The launch of Pioneer A on Delta 35.

Pioneer-B Prelaunch Narrative

The prelaunch operations for Pioneer B were comparatively uneventful. The flight spacecraft arrived at Building AM on July 17, 1966. On August 9, it was discovered that a connection opened when the Chicago cosmic-ray experiment warmed up, signalling a nonexistent low radiation level at all times. The experiment flew in this condition.

F −0 day, August 17, had superb weather, with 5-knot winds and a visibility of 10 miles. The countdown proceeded normally to T −3 min, when a hold was called due to the loss of communications downrange on the ETR. Communications were restored after 2 min and liftoff occurred at 1020:17 EST.

Pioneer-C Prelaunch Narrative

Pioneer C was the first of the Block–II spacecraft. In addition, this flight was the first to carry a Test and Training Satellite mounted in the Delta second stage. The Pioneer-C flight model was received at Building AM on Nov. 11, 1967. The IST of November 15 identified a faulty decoder, which was replaced. On November 22, the Ames plasma probe was removed to correct a wiring error.

F −2 day, December 11, was plagued by bad weather, twice forcing personnel to clear the pad. At 1520, electrical power was lost for 25 min, causing some concern because the spacecraft air conditioning was also lost. On F −1 day, the fairing had to be removed to repair the wiring to the third-stage velocity meter. Terminal count began at 0543, December 13, and Pioneer C was launched successfully at 0908:00 on December 13, 1967.

Pioneer-D Prelaunch Narrative

This spacecraft was the first to incorporate the convolutional coder experiment and the Ames magnetometer. Pioneer D arrived at Building AM on October 6, 1968. The beginning of the countdown was delayed for two days while tests and adjustments were made to the second-stage programmer. The countdown then proceeded smoothly to 0900 EST, when anomalies appeared in the experimental data and experiment performance. Holds were called to investigate these problems, which were found to be due to radio and electrical interference from the launch vehicle. No troubles were encountered during F −1 day countdown activities. At 1850 EST, November 7, 1968, F −0 day checks began. Spacecraft power was turned on at 1920. Spacecraft systems checks ran ahead of schedule and a 20-

min hold was called at 2015 to give the spacecraft receiver additional time to warm up. The terminal count began at 0050, November 8. Following a hold of 9.5 min due to high sheer winds aloft, the Delta lifted off at 0446:29.

Pioneer-E Prelaunch Narrative

On July 18, 1969, the Pioneer-E spacecraft was received at Cape Kennedy. There were no unusual prelaunch events. A study of the launch vehicle test summary indicates a normal sequence of prelaunch events. Although a number of minor problems arose, nothing unusual occurred. Nothing in the prelaunch tests and checkout presaged the failure of the launch vehicle after lift-off.

Spacecraft and radio frequency checks, Task VII, began at 0835 EDT on F −0 day, August 27, 1969. Except for a thunderstorm that temporarily delayed work, weather was excellent with a visibility of 8 miles and light winds. The terminal countdown was uneventful. Lift-off was at 1759:00 EDT, August 27, 1969.

LAUNCH TO DSS ACQUISITION

The phase of operations stretching from launch to DSS acquisition lasts less than 1 hr, but it is the only time when all four Pioneer systems are in operation together. Even then, the spacecraft systems and scientific instruments are essentially passive during powered flight and coast. Only housekeeping data are telemetered and all scientific instruments are off. The spacecraft comes to life when the TWTs are switched on, the booms deploy, and the Type–I orientation maneuver begins automatically. By this time, the spacecraft has been spun up and has separated from the Delta third stage. The ground-based Pioneer system, the DSN, is involved through the Near-Earth-Phase Network, which also incorporates some facilities from the Air Force Eastern Test Range and the Manned Space Flight Network. Figure 3–2 illustrates the chronology and terminology involved in the near-Earth phase of the mission.

It is best to view Pioneer operations from several vantage points so that the operations of all four systems can be appreciated. First, the sequence of events is portrayed schematically in figure 3–3. The nominal time frames for all of the launches are added to the picture in table 3–1. Of course, the timing of the critical events varies from mission to mission because the burn and coast times changed with each launch and the Delta rocket was upgraded during the Program. The nominal time frame, with its critical events, provides a yardstick against which to measure the success of the launch.

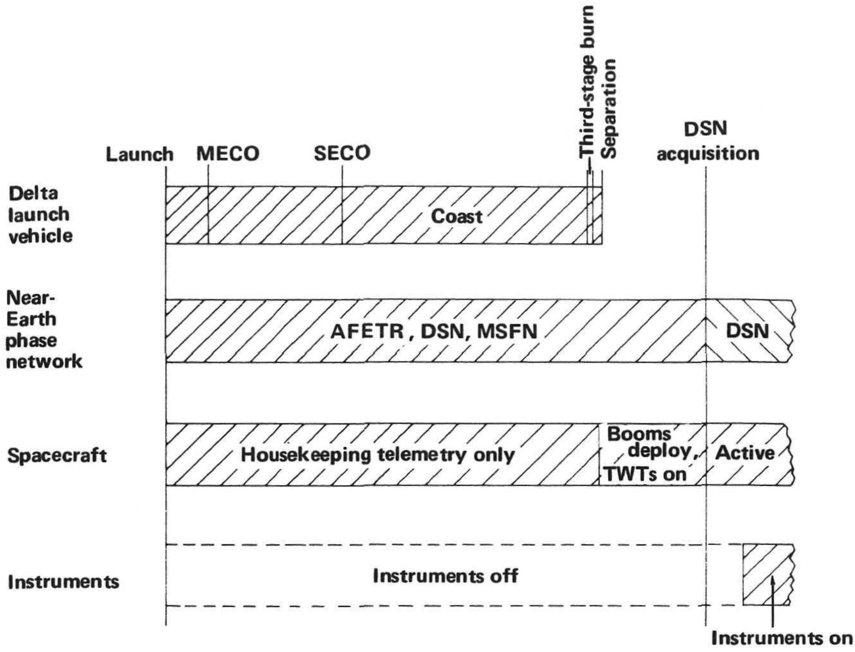

FIGURE 3–2.—Status of the four Pioneer systems from launch through DSS acquisition.

Performance of the Delta Launch Vehicle

The Delta launch vehicle performed superbly during the first four Pioneer launches. The fifth mission, Pioneer E, had to be aborted by the Range Safety Officer when the vehicle began to stray off course.

Tracking and Data Acquisition

As a spacecraft and its launch vehicle rise from the launch pad at Cape Kennedy, they are viewed downrange by a variety of radio and optical tracking devices. Until the spacecraft is handed over to the Johannesburg Deep Space Station, the pooled radars, optical trackers, guidance equipment, and telemetry receivers of the Air Force Eastern Test Range and some stations of NASA's Deep Space Network and Manned Space Flight Network are crucial to mission success.

The facilities assigned to each of the Pioneer missions from launch through DSS acquisition are listed in table 3–2. The AFETR was the primary agency responsible for providing metric (tracking) data during this phase. The MSFN stations in table 3–2 provided redundant radar support. Metric requirements were met by tracking

C-2

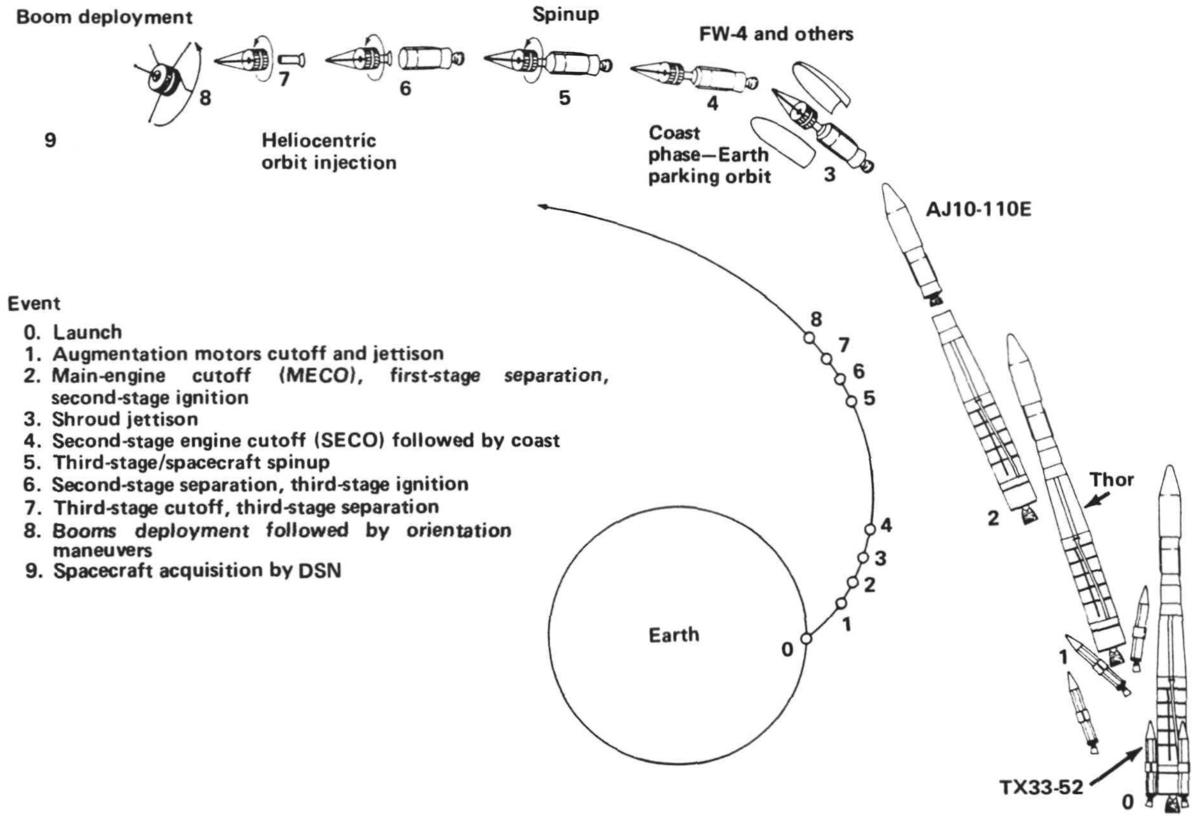

FIGURE 3–3.—A typical Pioneer launch sequence.

TABLE 3-1.—*Summary of Critical Nominal and Actual Launch Events*

	Pioneer 6		Pioneer 7		Pioneer 8		Pioneer 9		Pioneer E[a]	
	Nominal	Actual	Nominal	Actual	Nominal	Actual	Nominal	Actual	Nominal	Actual
Liftoff (sec)	0	0	0	0	0	0	0	0	0	0
Solid motor burnout	43.00	42.23	42.65	41.60	41.90	42.25	38.19	39.4		
Solid motors jettisoned	70.00	69.97	70.00	70.79	70.00	70.3	70.00	[b]69.94	70.00	69.8
Main-engine cutoff	149.21	148.01	149.52	148.10	149.75	149.45	150.53	151.35	220.0	215.4
Second-stage ignition	153.21	152.03	153.52	152.13	153.75	153.50	154.53	155.42	224	224
Fairing jettisoned	------	178.84	175.52	174.74	185.75	186.16	169.53	171.01	229	229.1
Second-stage engine cutoff command	551.13	531.44	529.32	527.89	530.93	536.73	534.35	539.01		
Third-stage spinup	1486.21	1485.03	1475.52	1474.12	1842.75	1842.42	1201.53	1202.40		
Second-stage jettisoned	1488.21	1487.03	1477.52	1476.12	1844.75	1844.43	1203.53	1204.37		
Third-stage ignition	1501.21	1496.94	1490.52	1488.98	1857.75	1857.98	1216.53	1218.54	------	------
Third-stage burnout	1523.71	1520.74	1521.34	1519.80	1888.55	1888.78	1247.33	1249.34	------	------
TTS separation	------	------	------	------	1904.75	1904.25	1263.53	1264.4	------	------
Actual launch date	Dec. 16, 1965		Aug. 17, 1966		Dec. 13, 1967		Nov. 8, 1968		Aug. 27, 1969	
Actual launch time	0231:20 EST		1020:17 EST		0908:00 EST		0946:29 GMT		1759 EDT	

[a] First stage hydraulic pressure lost at 214 sec. Destruction by Range Safety Officer at 483.9 sec.
[b] For one motor; the other two augmentation motors were jettisoned at 69.992 sec.

the C-band beacon aboard the Delta and the S-band telemetry signal from the spacecraft. From liftoff to 5000 ft altitude, AFETR optical equipment provided additional metric data.

Spacecraft Performance

The spacecraft were nearly dormant during powered-flight stages. About 5 min before launch, each spacecraft was put on internal power. The spacecraft low-gain antenna 2 was connected to the transmitter-driver rather than to one of the TWTs, to conserve battery power. Consequently, only about 40 mW of signal power were broadcast until the TWT was switched on. Housekeeping telemetry during launch was set at 64 bps—a relatively low rate—to increase the likelihood of obtaining good diagnostic data at the low power level should the TWT fail to turn on.

As soon as the spacecraft separated from the Delta third stage, the booms and Stanford antenna automatically deployed and locked

TABLE 3-2.—*Tracking and Data Acquisition Support Stations through DSS Acquisition*

Range/ network	Station	Used during Pioneer flights				
		6	7	8	9	E
AFETR	1 Cape Kennedy and Patrick AFB	X	X	X	X	X
	3 Grand Bahama I	X	X	X	X	X
	7 Grand Turk I	X	X	X	X	X
	91 Antigua I	X	X	X	X	X
	12 Ascension I	X	X	X	X	X
	13 Pretoria, S.A.	X	X	X	X	X
	Twin Falls (ship)	X	X	X	X	
	Coastal Crusader (ship)	X	X	X	X	
	Sword Knot (ship)		X			
MSFN	Merritt I.					X
	Bermuda	X	X	X	X	X
	Grand Bahama					X
	Antigua					X
	Ascension I	X	X	X	X	X
	Tananarive, Malagasy Rep.	X	X	X	X	X
	Vanguard (ship)					X
DSN	DSS-71, Cape Kennedy	X	X	X	X	
	DSS-72, Ascension I.	X	X	X		
	DSS-51, Johannesburg, S.A.	X[a]	X	X	X	X[b]
	DSS-41, Woomera, Australia[c]			X		

[a] Commanded partial Type-II orientation This maneuver was commanded from Goldstone on Pioneer 9.

[b] Scheduled, but not actually used due to abort.

[c] The primary DSN acquisition station for Pioneer 8.

into position. Power was applied to the TWT and the orientation subsystem, again automatically. The Type–I orientation maneuver then began and proceeded in the manner described in Chapter 2. When the low-gain antenna was switched from the transmitter driver to the TWT, the telemetry signal from the spacecraft faded for about a minute while the TWT warmed up. By the time Johannesburg rose, the spacecraft was transmitting at about 7 W. It was fully operational and had completed one Type–I orientation maneuver. Upon acquisition the first commands generally sent were:

(1) Switch to 512 bps
(2) Repeat the Type–I orientation maneuver.

FROM DSS ACQUISITION TO THE BEGINNING OF THE CRUISE PHASE

The period of several hours stretching between the initial acquisition of the spacecraft by one of the DSN stations and the beginning of the cruise phase encompasses several events crucial to the success of the mission:

(1) Two types of orientation maneuvers
(2) Experiment turn-ons
(3) The first thorough assessment of spacecraft health in flight
(4) The first passes over all participating DSN stations

Prior to DSS acquisition, the spacecraft automatically went through the Type–I orientation maneuver. This event was started by switches triggered when the deploying appendages locked into position. By the time the spacecraft was acquired by DSN, spacecraft power was on and the transmitter was sending telemetry. In addition, the spin axis was almost perpendicular to the sunline by virtue of the automatic Type–I orientation maneuver.

The first command dispatched after a two-way lock had been established was usually that which changed the telemetry bit rate from Format C, 64 bps, to Format C, 512 bps. Next, a command initiating the Type–I orientation manuever was sent to refine the alignment made automatically prior to acquisition and, more important, to preclude the possibility that the automatic orientation sequence may have terminated prematurely. The third in the series of preparatory commands was "Undervoltage Protection On," but this was sent only if analysis by the Spacecraft Analysis and Command (SPAC) Group (located at the SFOF during launch) was confident that the spacecraft power level was normal and that the spacecraft was operating properly. Following the spacecraft's execution of Undervoltage Protection On, the Pioneer was ready for experiment turn-on and the all important Type–II orientation maneuvers.

The purpose of the Type–II maneuver was the rotation of the spacecraft spin axis about the Sunline until the spin axis was perpendicular to the plane of the ecliptic. As explained more fully in Chapter 2, this maneuver was normally controlled from Goldstone where Operations Orientation Director (OOD) maximized the telemetry signal received from the Pioneer's high-gain telemetry antenna. Generally, hundreds of Type–II orientation commands were relayed to the spacecraft, each giving rise to a pulse of gas from the orientation subsystem. There was some jockeying back and forth across the peak in the signal-strength reception curve. On occasion, the normal Type–II orientation process was interrupted for another Type–I maneuver to remove any spin-axis misalignment inadvertently introduced by cross coupling during Type–II maneuvers.

Preliminary trajectory analysis in the cases of Pioneers 6 and 9 indicated that partial Type–II orientation would be desirable early in the flight to preclude an unfavorable spacecraft orientation later in the flight. This special maneuver was necessary because the low-gain omnidirectional antenna used for communication early in the flight had a very low gain within about 10° aft of the spin axis. During the partial Type–II orientation maneuver the gas pulses torqued the spin axis sufficiently so that Goldstone antennas would not be looking up this cone at the spacecraft during the final Type–II orientation maneuver. The final Type–II orientation maneuvers were always directed from Goldstone. Special equipment for this task, as well as the OOD and his team, were located there.

SPACECRAFT PERFORMANCE DURING THE CRUISE PHASE

The Pioneer spacecraft were designed for a minimum life of 6 months each. Each greatly exceeded this goal. In fact, each spacecraft functioned well for several years, their longevity confirming the design decisions made by Ames and TRW Systems in the early 1960's. This section is concerned with spacecraft performance in orbit around the Sun.

Pioneer–6 Performance

The nominal Pioneer–6 mission extended from December 16, 1965, to June 13, 1966—a total of 180 days. However, because spacecraft performance at the end of 180 days continued to be good and the 210-ft dish at DSS–14 became available for long-distance tracking, the mission was extended.

Although each Pioneer surpassed the goals set for it, each spacecraft had its share of minor problems. On Pioneer 6, for example, a gas leak in the orientation control subsystem caused some concern. And the degradation of the Sun sensors plagued every Pioneer until Pioneer 9's ultraviolet filters finally solved the problem.

Pioneer–7 Performance

As the spacecraft began the long cruise phase, all spacecraft subsystems appeared to be operating normally. On August 25, 1966, however, TWT 1 began to display anomalous performance in the noncoherent mode of operation, although operation was normal in the coherent mode. The helix current jumped to 10.2 mA as compared to the normal 6.1 mA, and the temperature rose to 180° F from the normal 101° F. On August 31, 1966, Ames personnel decided to switch in TWT 2. This TWT behaved normally in every respect. Except for this difficulty, which was overcome by design redundancy, spacecraft performance during the basic 180-day mission was excellent.

Pioneer–8 Performance

The Earth-escape hyperbola for Pioneer 8 was less energetic than planned. Instead of occurring at roughly 500 Earth radii, syzygy took place at 463 Earth radii. The heliocentric orbit is less eccentric and more inclined than the planned orbit, but the differences are not significant. The spacecraft has performed normally except for the deviations noted below.

Early in the mission, trouble was experienced with the Ames plasma probe and it was subsequently turned off. However, the difficulty was ultimately traced to a corona discharge resulting from outgassing. Later, the Ames experiment was switched back on and it operated without further trouble.

During an orientation maneuver in March 1968, Sun sensor D was found to be inoperative. On another orientation attempt in June 1968, Sun sensors A, B, and C were also found to be out of commission. The heavier Sun-sensor covers installed on Pioneer 8 had obviously not solved the degradation problem.

Pioneer–9 Performance

Pioneer 9, an inbound flight, was subjected to increasing solar radiation, higher solar-array temperatures, and, consequently, falling bus voltages. To prevent the discharge of the battery, it was switched off on January 14, 1969.

To check the effects of the newly installed ultraviolet filters on the Sun sensors, a special test was conducted on February 5, 1969, the 89th day of flight. Telemetry indicated that Type–I and Type–II commands were executed properly. The ultraviolet filters had apparently solved the Sun-sensor degradation problem.

The spacecraft reached perihelion at 0.754 AU on April 8, 1969. The spacecraft was designed to penetrate to only 0.8 AU, but it reached 0.754 AU without overheating, although the cosmic-ray experiment reached its upper temperature limit.

All spacecraft systems operated normally throughout the 180-day mission. During the extended mission, in May 1969, the communication range reached 130 million km (78 million miles) using only the 85-ft DSN antennas. This extension of the communication range can be attributed to three factors:

(1) Use of linear polarizers at some DSN stations

(2) Improvement of noise temperatures at the DSN stations

(3) Use of the Convolutional Coder Unit on Pioneer 9 (See below.)

The CCU, described in Chapter 2, was added to Pioneers D and E as an engineering experiment. It can be switched in or out of the telemetry stream. CCU performance has been good, contributing about 3 dB to the communication power budget. In effect, the CCU increased the maximum communication range for Pioneer 9 at each bit rate by 40 percent.

Between the launch date on November 6, 1968, and December 10, 1968, the spacecraft operated in the uncoded mode at 512 bps, except for CCU functional checks. Since December 10, the CCU has been in almost constant use except when the spacecraft was being worked by a DSN without Pioneer Ground Operational Equipment (GOE).

About January 7, 1969, Pioneer 9 was far enough away from the CCU to provide a "coding gain" for DSN stations configured for receiving circularly polarized waves.[13] Up to March 6, 1969, GOE-equipped DSN stations tracked Pioneer 9 for about 1000 hr with the CCU in operation; 680 hr were in the coding gain region. As a result of the CCU's coding gain, 4.43×10^8 additional bits were received during this period. The 3 dB gain at 512 bps was verified by direct comparison with uncoded data at 256 bps. The CCU experiment has been so successful on Pioneer 9 that convolutional coding is being applied to other spacecraft.

[13] The Pioneers transmit linearly polarized signals. A 3 dB loss is incurred when a DSN receiving circularly polarized signals is used.

CHAPTER 4

Pioneer Scientific Results

THE SCIENTIFIC LEGACY of the Pioneer Program will not be complete for many years. Scientific papers based upon the data telemetered back from deep space are still being published in abundance. Meanwhile, all four successfully launched spacecraft at this writing continue to operate successfully. The Pioneer scientific record, though incomplete, is impressive—some 150 contributions to the literature as of early 1971. Some of these papers and their implications are summarized in the following pages.

THE GODDARD MAGNETIC FIELD EXPERIMENT

By December 1965, when Pioneer 6 was launched, satellites had confirmed the theoretical prediction of a basically spiral solar magnetic field imbedded or "frozen" in the streaming solar plasma. The Sun's rotation about its axis imposed the "water sprinkler" pattern on the outwardly rushing plasma (fig. 4–1).

Pioneer–6 data confirmed that the interplanetary magnetic field often changes direction abruptly without changing magnitude. This phenomenon was interpreted at that time in terms of intertwined filamentary or tube-like structures in interplanetary space which, on a large scale, display the classical spiral structure but which, on a small scale, create a twisted microstructure.

Generally early Pioneer magnetometer data tended to confirm the Earth shock structure, the magnetopause, and the spiral sector structure of the interplanetary field inferred from previous spacecraft flights.

Outward-bound Pioneers carried Goddard magnetometers through the region where the geomagnetic tail was expected to exist. This region was crossed by Pioneer 7 between September 23 and October 3, 1966, at distances ranging from 900 to 1050 Earth radii. A coherent, well-ordered geomagnetic tail with an imbedded neutral sheet was not observed by Pioneer 7. However, the rapid field reversals recorded are characteristic of the neutral sheet region observed closer to Earth. The conclusion at Goddard was that the geometry of the tail changes to a complex set of intermingled filamentary

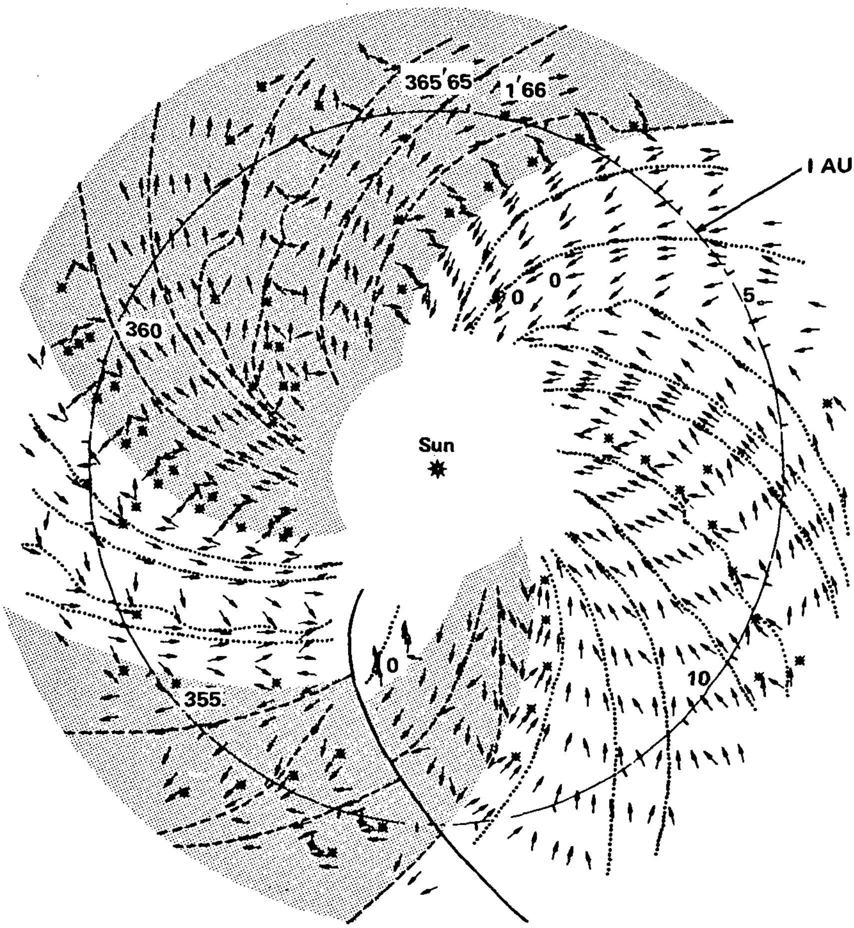

FIGURE 4–1.—Sector structure of the interplanetary magnetic field from Pioneer 6 data telemetered between Dec. 18, 1965, and Jan. 14, 1966. Each arrow represents an equivalent flux of 5γ for 6 hr. Shaded regions are those where the field is directed away from the Sun; field was antisolar elsewhere. From: Schatten, Ness, and Wilcox: Solar Physics, vol. 5, p. 250, fig. 8, 1968.

flux tubes at several hundred Earth radii. Later analysis led to a "discontinuous" model.

The new model recognizes the fact that field discontinuities on the mesoscale and microscale—in both magnitude and direction—are more prevalent than previously suspected, and that their character does not always imply the existence of filaments.

Pioneer magnetometer results have also helped provide insight into what happens in interplanetary space when a major solar event, such as a large flare, occurs. The following observations based on

Pioneer–8 telemetry represent about what one would expect from the general model of a solar disturbance propagating through space.

(1) A rather steady field of 4 to 6γ was observed during the early hours of February 25.

(2) The field increased rapidly to near 10γ between 2000 and 2022, then it rose slowly to about 14γ.

(3) Long-period variations were observed between 0200 and 0500, February 26.

(4) A very quiet field of about 6γ occurred between 2000 and 0500, February 27.

(5) The next group of telemetered data at 2149, February 27, again revealed a high field (over 10γ). Large variations were noticed.

(6) In the last time interval telemetered, between 0200, February 28, and 0500, February 29, the field had dropped to normal values.

THE MIT PLASMA PROBE

The preliminary MIT data indicated first, that sharp changes in the plasma density preceded the dramatic changes in the magnetic field recorded by the Goddard magnetometer, and second, that the peaks in number density were followed by periods of increased bulk velocity.

The MIT group later published additional correlations between their plasma-probe and magnetometer data. The simultaneous changes in plasma and magnetic parameters were consistent with what one would expect from tangential discontinuities. High-velocity shears were observed across these discontinuities; the largest was about 80 km/sec. The discontinuities observed by the MIT plasma probe were undoubtedly due to the same filament boundaries or discontinuities discussed in the papers published by the Goddard group.

The MIT plasma-probe and Goddard magnetometer data also showed that these discontinuities have preferred directions in space, with a tendency for the solar wind to be fast from the west and slow from the east. This east-west asymmetry in solar-wind velocity is a natural result of the rotation of the Sun—the water sprinkler effect again.

Pioneer 6 carried the MIT plasma probe through the magnetosheath in the dusk meridian on December 16, 1965. While the data confirmed some portions of the various theories developed to describe the magnetosheath, the proton distribution measured was bi-Maxwellian rather than the classical single-peaked curve. Roughly 10 percent of the total number density was estimated to reside in the high-energy tail (fig. 4–2). Apparently the high-energy tail was

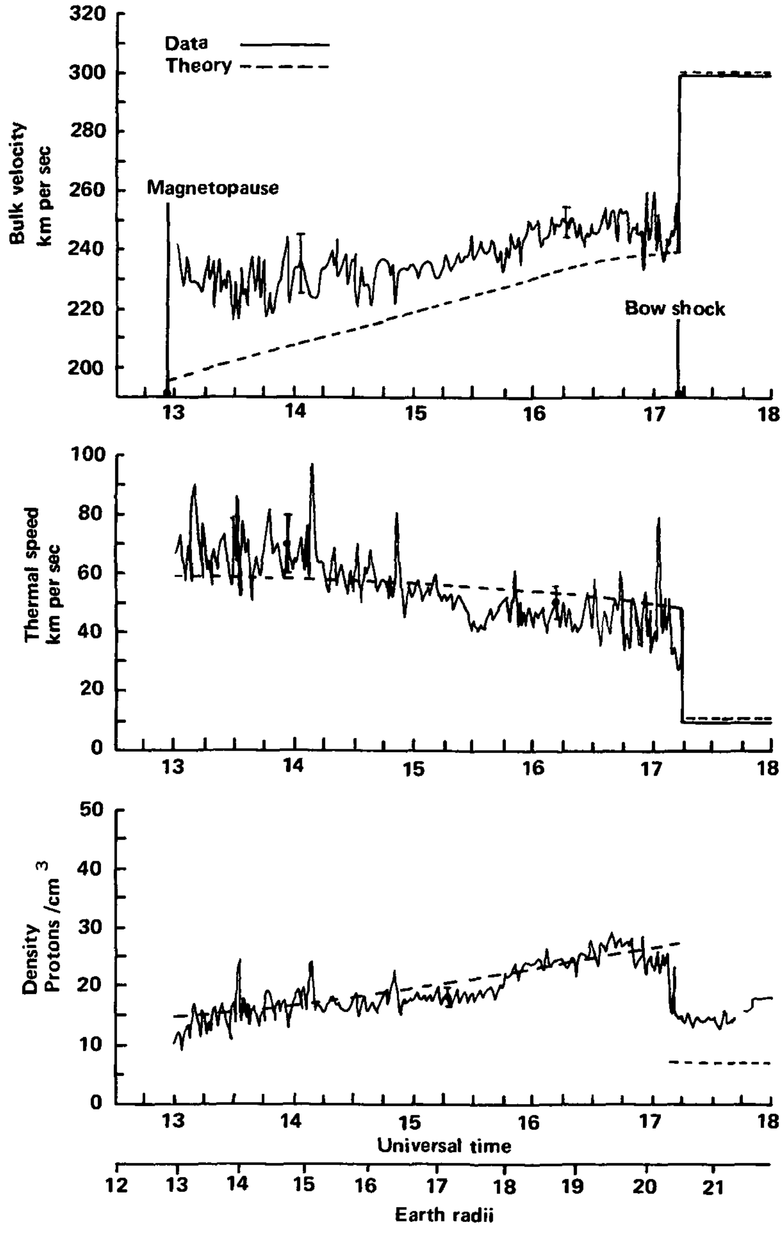

FIGURE 4–2.—Pioneer 6 magnetosheath proton observations showing velocity, thermal speed, and number density. From: Howe: J. Geophys. Res., vol. 75, p. 2434, fig. 4, May 1, 1970.

composed of solar plasma particles penetrating through the magnetosheath and eventually swerving to travel in the direction of the bulk flow within the magnetosheath.

The electron flux was more complex, with three distinct regions being observed. The first region, from 9 to 11.5 Earth radii, was characterized by angularly isotropic fluxes in all four electron channels. The electron energy spectrum indicated that the electrons formed a plasma sheet in this region. The second region, 1.5 Earth radii thick, was bounded at the outer edge by the magnetopause. The electron distribution in this region could be explained by two models. Using a thermodynamic model, the distribution matched that of a Maxwellian having a pressure of about 300 ev/cu cm, with the temperature parallel to the local magnetic field about twice that perpendicular to the field. In the third region, the magnetosheath, itself, the following parameters were typical: thermal electron energy—40 eV; electron speed—2700 km/sec; electron temperature—100 000° K.

THE AMES PLASMA PROBE

The Block–I and Block–II plasma probes built by Ames Research Center record the energy spectra of electrons and positive ions in the solar plasma as functions of azimuth and elevation angles. For a more complete understanding of the interplanetary medium, it is essential to relate plasma probe results to the magnetometer data and, of course, the somewhat different perspectives apparent to the MIT Faraday-cup plasma probe and the TRW Systems electric field detector.

Figure 4–3 shows one type of data acquired by the Ames plasma probe: energy spectra and angular spectra. The energy spectrum indicates a proton peak at 1350 V, corresponding to a proton velocity of approximately 510 km/sec. The second peak in the curve was due to alpha particles. However, analysis of subsequent data revealed the possible presence of singly ionized helium in the solar wind—the first time this had been detected.

The early data also revealed an average solar wind electron temperature of about 100 000° K during quiet times when the solar wind was blowing at about 290 km/sec, with a maximum ion temperature of 50 000° K.

As Pioneer 6 passed through the Earth's magnetopause, the Ames plasma probe measured the temperature of solar electrons in the bow shock at 500 000° K. Here, ion temperatures were about the same as electron temperatures, but, in contrast, the ions did not cool off downstream from the Earth.

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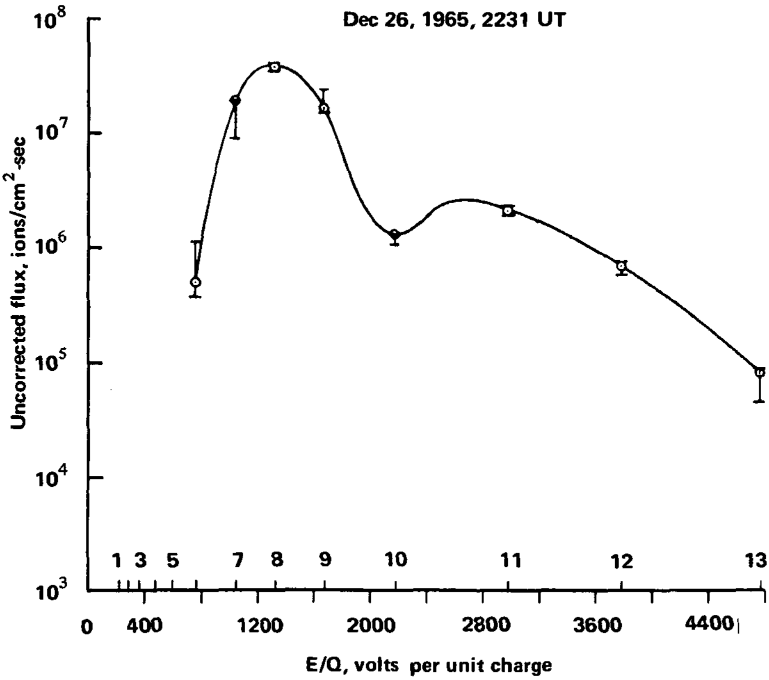

FIGURE 4–3.—Pioneer 6 Ames plasma probe E/Q spectrum, Dec. 26, 1965, 2231 UT, showing the hydrogen peak at approximately 1350 V, with the helium peak estimated at 2700 V. From Wolfe, et al.: J. Geophys. Res., vol. 71, p. 3330, fig. 2, July 1, 1966.

Pioneers 7 and 8 were outward missions and swept through the Earth's tail early in their flights. Instruments on both spacecraft detected evidence of the Earth's tail or "wake" with their magnetometers and plasma probes. The Ames plasma probes detected the wakes at about 1000 and 500 Earth radii for Pioneers 7 and 8, respectively.

The Ames investigators felt, on the basis of their data, that the following interpretations were possible:

(1) The observations could represent a turbulent downstream wake if the Earth's magnetosphere closed between 80 and 500 Earth radii.

(2) If the solar wind diffuses into the magnetic tail, the plasma probe measurements could be due to the tail "flapping" past the spacecraft.

(3) The tail might have a filamentary structure at these distances (500 and 1000 Earth radii) and the disturbed data could arise at filament boundaries.

(4) Possibly, the tail might have disintegrated into "bundles" at these distances.

(5) If magnetic merging occurred, subsequent acceleration of pinched-off gas may have caused the disturbed conditions that were measured.

Prior to Pioneer 6, few spacecraft were capable of making detailed measurements of the solar wind. Consequently, the collisionless interplanetary plasma was treated as a single magnetofluid. However, the Ames plasma probes have revealed that the solar proton distribution is definitely anisotropic, with the temperature parallel to the local magnetic field being larger than that perpendicular to the local magnetic field.

THE CHICAGO COSMIC-RAY EXPERIMENT

The Chicago cosmic-ray telescope on the Block–I Pioneers provided the opportunity for scientists to investigate the direction of arrival of cosmic-ray particles near the plane of the ecliptic. The experiment also had a short enough time resolution so that rapid fluctuations in cosmic-ray intensity could be recorded. The first test case came shortly after the launch of Pioneer 6, when solar-flare protons were detected on December 30, 1965.

The solar flare that erupted about 2 weeks after the launch of Pioneer 6 was given an importance rating of 2. The effects were noted for almost a week, as indicated in figure 4–4. Interplanetary conditions during most of this period were remarkable free of solar-flare blast effects capable of modulating the galactic cosmic-ray flux. Solar protons in the energy range 13 to 70 MeV first arrived at the spacecraft at about 0300 UT, December 30, 1965, with lower energy particles arriving later. The anisotropy of these protons was striking. The average direction of particle flow about halfway between the Sunline and the angle would be expected if the particles traveled along the water-sprinkler spiral lines. However, the detailed data reveal a more complex situation:

(1) The direction of the peak amplitude was highly variable, changing direction by as much as 90° within 10 min.

(2) Relative to the intensities in other directions, the peak intensive varies rapidly.

(3) Occasionally, the angular distribution was strongly peaked within a 45° sector.

(4) Rarely, two intensity peaks 180° apart were noted.

The strong collimation of solar protons with energies greater than 13 MeV suggests that there are few irregularities in the propagation path from the Sun that could scatter the protons. However, the

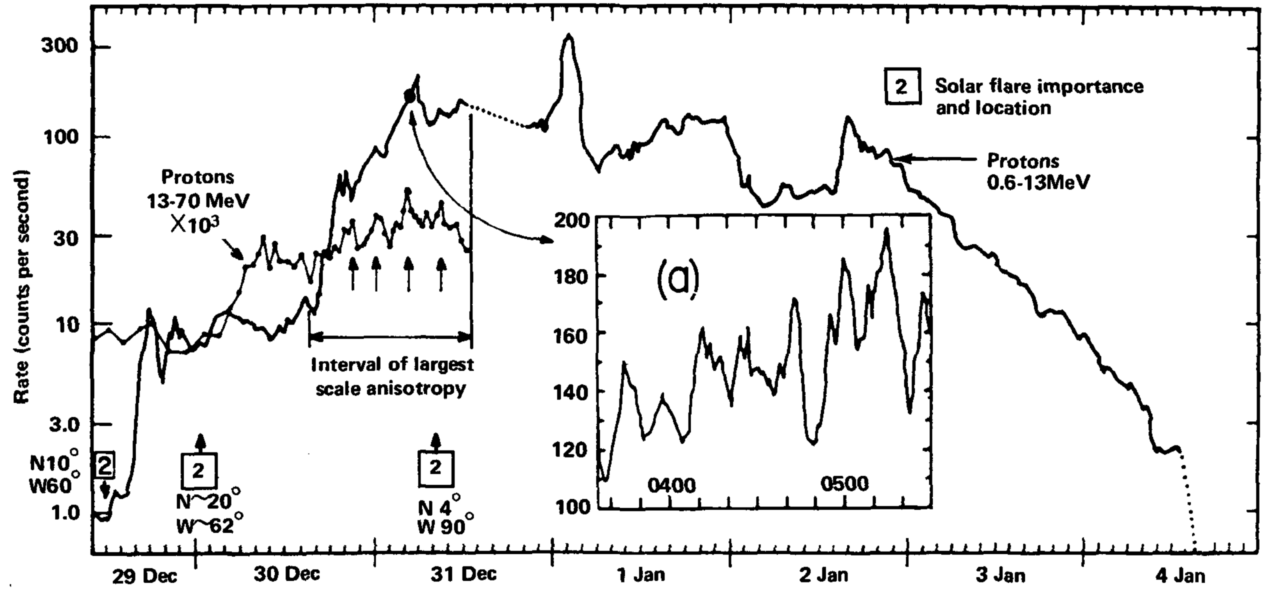

FIGURE 4-4.—The intensity-time distribution of protons of 0.6- to 13-MeV energy and protons of 13- to 70-MeV energy. Antisotropies were observed for a period of approximately 2 days after the flare of Dec. 30, 1965. The arrows refer to quasi-periodic bursts of period ~ 4 hr. Insert (a) is an expansion of the region shown within the circle. Data points are ~ 56 sec apart. Note the quasi-periodic oscillations of ~ 15 min. From: Fan et al.: J. Geophys. Res., vol. 71, p. 3291, fig. 3, July 1, 1966.

rapid changes in direction of the peak flux vector supports the conclusion from Goddard magnetometer and GRCSW cosmic-ray antisotropy data that there are many short-term, rather localized changes in the Earth's magnetic field.

Corotation effects were noted early in flight by the Chicago instrument, supporting the joint observations of several other Pioneer–6 instruments and similar instruments on spacecraft elsewhere in the solar system.

Proton flux increases over the period from December 1965 through September 1966 have been unambiguously associated with specific solar flares. Enhanced solar proton fluxes in the energy range of 0.6 to 13 MeV have been recorded from specific active regions from ranges as great as 180° in longitude. The enhanced fluxes were characterized by definite onsets when their associated active centers reached points from 60° to 70° east of the central solar meridian. Cutoffs occurred at from 100° to 130° west. Coupled with the detection of associated modulations of the galactic cosmic-ray flux, these observations again point to the existence of corotating magnetic regions associated with the active centers on the Sun. Observations seem to show that solar-flare protons propagate along the spiral interplanetary field from the Sun's western hemisphere. Present evidence supports the view that the solar protons arise from processes continually occurring in the solar active centers.

Further inferences from the Chicago data are:

(1) Most of the particles observed during the solar minimum are of galactic origins.

(2) Relativistic electrons were detected only in the neutral sheet of the geomagnetic tail, pointing to the possible acceleration of these electrons by the split magnetic field.

THE GRCSW COSMIC-RAY EXPERIMENT

The primary mission of the GRCSW experiment was the measurement of anisotropy in the distribution of cosmic rays within the solar system, but still far enough away from the Earth to avoid its perturbing magnetic field. The construction of a theoretical model describing how cosmic rays are propagated through the solar system depends upon the accurate measurement of cosmic rays with energies less than 1000 MeV. Because the weaker cosmic rays, especially those originating on the Sun, are affected by the solar magnetic field and the plasma in which it is imbedded, the GRCSW data must be examined in conjunction with the results of the Pioneer plasma and magnetometer experiments.

The extent of the anisotropy of low-energy solar protons during early flight was striking. Since scattering normally reduces anisotropy, these results imply that little scattering transpired since the cosmic rays were injected into the interplanetary field near the Sun. In contrast, the anisotropy of relativistic cosmic rays is known to be obliterated quickly.

From Pioneer anisotropy data collected during 1965 and 1966 for periods when solar flare effects were not seen and considering only cosmic rays in the vicinity of 10 MeV/nucleon, the conclusions were:

(1) The 10 MeV/nucleon cosmic rays possessed a density gradient directed toward the Sun; i.e., density increases sunward, as expected.

(2) These low-energy cosmic rays are predominantly of solar origin even during the sunspot minimum.

(3) The density gradient frequently reverses in the range $10<E<1000$ MeV.

(4) Cosmic radiation between 10 and 10^5 MeV corotates with the Sun.

Studies of the large-scale, steady-state structure of interplanetary space have also been made by comparing Pioneer data with those from other spacecraft. It was concluded that there exist numerous, long-lived regions of modulated cosmic-ray flux following the general spiral configuration of the interplanetary magnetic field as it corotates with the Sun.

The GRCSW and Goddard groups introduced the filament concept. The main thrust of this concept was that the observed anisotropies of low-energy cosmic rays could be divided into two groups:

(1) Equilibrium anisotropies are most evident toward the end of a solar-flare event. The maximum cosmic-ray flux is always directed away from the Sun (fig. 4–5), and the anistropy amplitude is low (5 to 15 percent). Perhaps of most significance is the fact that the anisotropies are not dependent upon the detailed nature of the interplanetary magnetic field.

(2) Nonequilibrium anisotropies change direction in time and have amplitudes between 20 and 50 percent. These anisotropies are aligned—parallel or antiparallel—to the magnetic field.

These observations were interpreted as possible evidence of complex loops in the magnetic field.

The GRCSW group also related Pioneer cosmic-ray data to cosmic-ray flare effects and energetic-storm-particle events. The data used came from Pioneers 6 and 7 and covered 29 solar flares occurring between December 16, 1965, and October 31, 1966. Some of the more important conclusions expressed in the first paper on this subject were:

(1) Solar cosmic rays are normally extremely anisotropic with

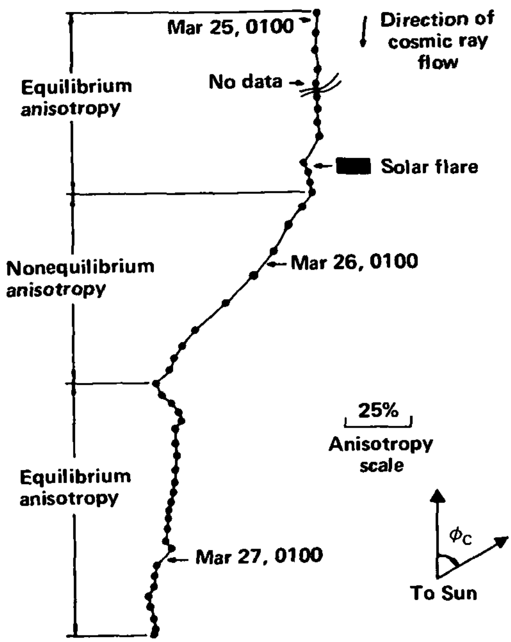

FIGURE 4-5.—The difference between the equilibrium and nonequilibrium classes of cosmic-ray anisotropy. The amplitudes and azimuths of the mean anisotropy for each hour are plotted as a vector addition diagram. Note definition of ϕ_c. From: McCracken, Rao, and Ness: J. Geophys. Res., vol. 73, p. 4160, July 1, 1968.

the direction of maximum flux aligned parallel to the magnetic field vector during the first part of the solar event.

(2) During the late portion of the flare, the cosmic rays are in diffusive equilibrium.

(3) Under some circumstances, the propagation of cosmic rays from the Sun to Earth is completely dominated by a "bulk motion" propagation mode. Here, the cosmic rays do not reach the spacecraft until the magnetic regime into which they were injected engulfs the Earth.

(4) In two cases, the anisotropy and cosmic-ray times of flight infer diffusion of the cosmic rays to a point on the western portion of the solar disk before injection into the magnetic field.

(5) Simultaneous observation by both Pioneers when separated by 54° of azimuth indicate density gradients of about two orders of magnitude per 60° sector during the initial stages of a solar flare.

(6) A study of cosmic-ray scattering within the solar system indicates a mean free path of about 1.0 AU for large-angle scattering.

A second paper dealt with the energetic-storm-particle event, which was defined as the very marked enhancement of cosmic rays in the 1 to 10 MeV range near the onset of a strong terrestrial magnetic storm. Data relating to seven such events were extracted from Pioneer–6 and Pioneer–7 telemetry. The data indicated a near 1-to-1 correspondence between the energetic-storm-particle events and the beginning of a Forbush decrease. It was shown further that the bulk of the energetic-storm particles are apparently not trapped in the magnetic regime associated wth the Forbush decrease. The Pioneer cosmic-ray data tend to support the Parker "blast wave" model, in which the charged particles are accelerated by the magnetic field within the shock front.

The GRCSW group also compared the characteristics of corotating the flare-induced Forbush decreases as derived from cosmic-ray data obtained from Pioneers 6 and 7. The results of this investigation are summarized in table 4–1.

Several solar-flare events have been examined in detail in the light of GRCSW cosmic-ray data and readings taken at several ground stations. By way of illustration, the results of the studies of the January 28, 1967, and March 30, 1969, events are summarized below. The salient features of the first event were:

(1) The probable location of the responsible solar flare was about 60° beyond the west limb of the Sun.

(2) Low-energy particles ($<$100 MeV) recorded by the Pioneers and the high-energy particles ($>$500 MeV) detected at Earth arrived after diffusion across the interplanetary magnetic field. Both groups of particles displayed remarkable isotropy.

(3) The flux that would be observed by a detector ideally located in azimuth would be greater than 2000 particles cm^{-2}-sec^{-1}-sr^{-1} above 7.5 MeV.

TABLE 4–1.—*Comparison of the Properties of Corotating and Flare-Initiated Forbush Decreases*

Corotating Forbush decrease	Flare-initiated Forbush decrease
Not accompanied by solar-generated cosmic rays	Accompaned by solar cosmic rays and an energetic-storm-particle event
Onset time difference due to corotation	Probably simultaneous onset up to ~100° off the axis of the Forbush decrease
No amplitude dependence over ~60° of solar azimuth	Amplitude varies by a factor of ~4.0 over ~60° of solar azimuth
The energy dependence of both classes of events is essentially the same	

(4) Pioneer observations indicated low-energy injection commencing several hours before the high-energy main event.

THE MINNESOTA COSMIC-RAY EXPERIMENT

The Minnesota cosmic-ray telescopes replaced the Chicago instruments on the Block–II Pioneer flights. The energy range of the Minnesota instrument was considerably higher (100 MeV/nucleon to over 22 BeV/nucleon) and, as intended, the research results are primarily concerned with galactic cosmic rays rather than the lower-energy particles originating on the Sun.

Although the carbon, nitrogen, oxygen, and "M" (for medium) nuclei are the most abundant nuclei in cosmic rays except for hydrogen and helium, their relative abundances have been in question until recently. New measurements of cosmic-ray nitrogen from balloons and Pioneer 8 have provided better estimates. The energy spectrum of nitrogen was found to be identical with those of the other M nuclei over the range from 100 MeV to over 22 BeV/nucleon. The ratio of nitrogen nuclei to all M nuclei was found to be about 0.125, constant to within 10 percent over the above energy range (fig. 4–6). Assuming that some of the nitrogen in the cosmic-ray flux originates in fragmentation reactions with interstellar matter and knowing the proper cross sections, one can compute a "source" N/M ratio less than about 0.03. However, the solar atmospheric value for the N/M ratio is about 0.10—a disturbingly higher value. The implication is that galactic and solar cosmic rays may originate in fundamentally different processes.

The Pioneer–8 instrument also identified and measured fluorine nuclei in the galactic cosmic rays. The fluorine abundance was 1 to 2 percent than that of oxygen for energies above 500 MeV/nucleon. These data on fluorine are consistent with the hypothesis that the fluorine is created by the fragmentation of heavier nuclei as they traverse roughly 4 g/sq cm of hydrogen in their flights through the galaxy.

Although Pioneer 8's orbit takes it only from 1.0 to 1.12 AU, the Minnesota instrument is sensitive enough to estimate cosmic-ray radial gradients within the solar system. First, the instrument measured differential energy spectra of protons and helium nuclei between 40 MeV/nucleon and 2 BeV/nucleon; the analysis in this range was two-dimensional, greatly reducing the background. Second, each event was assigned to one of four quadrants, permitting a study of the anisotropies associated with the gradients. The results of these measurements are presented in table 4–2. In general the cosmic-ray seems close to zero, however, it may be slightly positive in some

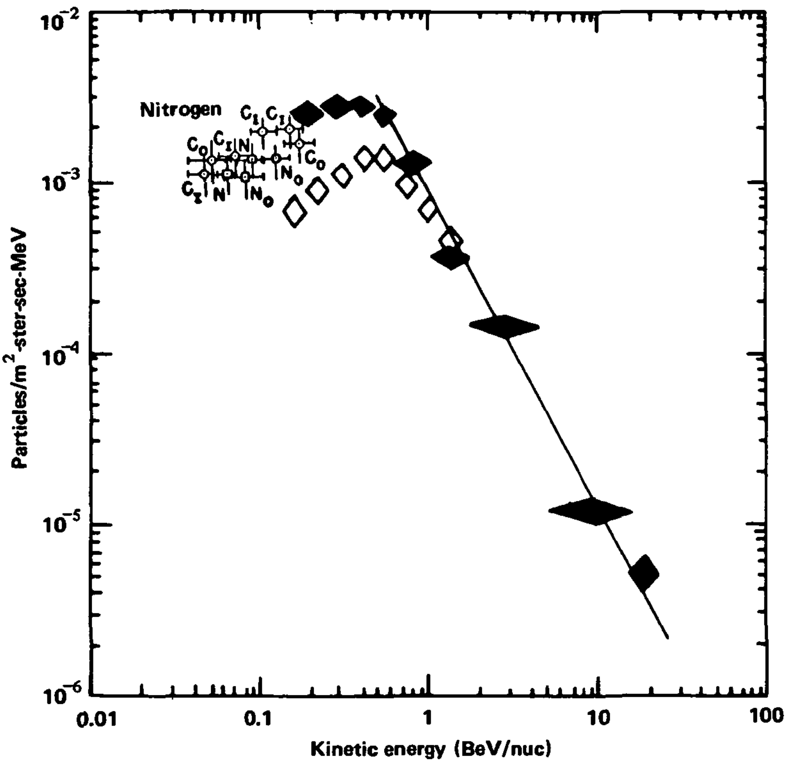

FIGURE 4–6.—Differential spectra of nitrogen nuclei measured by Pioneer 8 in 1968 (open diamonds) and from balloons in 1966 (solid diamonds). The low-energy points are from several satellites. From Lezniak et al.: Astrophys. and Space Sci., vol 5, p. 106, fig. 1, 1969.

energy ranges. The data indicate that there are no significant anisotropies above about 240 MeV.

THE STANFORD RADIO PROPAGATION EXPERIMENT

The Stanford radio propagation experiment operates in a closed loop which employs the 150-ft paraboloidal antenna and associated transmitting equipment at Stanford University, the spacecraft receiver and transmitter, and the facilities of NASA's Deep Space Network. Basically, the experiment measures the integrated electron content between the spacecraft and the Earth. Corrections for the Earth's ionosphere are made with the help of radio propagation measurements using Earth satellites, such as the Beacon Explorers.

Based upon Pioneer–6 data taken between February 2 and April

TABLE 4–2.—*Gradient and Anisostropy Proton Measurements on Pioneer 8*

Energy	Radial proton gradient, %	Radial proton anisotropy, %	Azimuthal proton anisotropy, %
>2 BeV	-1.5 ± 6	-0.31 ± 0.28	-0.13 ± 0.27
1.25 BeV–2 BeV	0 ± 7	$+0.26\pm0.45$	-0.38 ± 0.44
660 MeV–1.25 BeV	$+23\pm8$	$+0.57\pm0.35$	-0.55 ± 0.44
334 MeV–660 MeV	$+28\pm9$	$+0.36\pm0.38$	-0.80 ± 0.35
240 MeV–334 MeV	-7 ± 11	$+0.7\pm1.0$	-0.60 ± 1.0
63 MeV–107 MeV	$+20\pm15$		
>60 MeV	0 ± 5		
12 MeV–25 MeV	0 ± 25		

9, 1966, the average electron number density was 8.25 cm^{-3}, with an rms value of 4.43 cm^{-3}. As Pioneer 6 moved farther out into space, it soon became apparent that the first values reported were unusually high due to high solar activity. The spread in measured values of the total interplanetary electron content is shown for Pioneer 6 in figure 4–7. The electron number density can be computed from the slopes of the lines drawn through these scattered points. The data in the figure yield an electron number density of 5.74 ± 4.1 cm^{-3}. A similar procedure for Pioneer–7 data leads to the value of 8.02 ± 3.8 cm^{-3}.

The measurements plotted in figure 4–7 owe their variation primarily to changes in solar activity and, consequently, the quantity of electrons injected into interplanetary space. Some of these injections—called plasma pulses or clouds—are fairly well-defined and have been mapped by the Stanford radio propagation experiment.

The Stanford group made a detailed study of the plasma cloud ejected by the July 7, 1966, solar flare. Although the radio propagation experiment was being operated beyond its nominal maximum range, the description of the plasma cloud derived from the measurements is compatible with data from the MIT plasma probe, which also measured the passage of a plasma shock at the same time. The shape and extent of the passing plasma cloud was calculated from the integrated electron content measured from Pioneer 6. Three cloud shapes—each deduced from a different data channel—seemed to fit the data (fig. 4–8).

When the Moon occulted the Pioneer–7 spacecraft on January 20, 1967, radio signals sent from the 150-ft Stanford antenna were diffracted by the edge of the lunar disk and also refracted by the lunar ionosphere. If there is no lunar ionosphere at all, only the classical Fresnel diffraction pattern will be measured. If an ionosphere

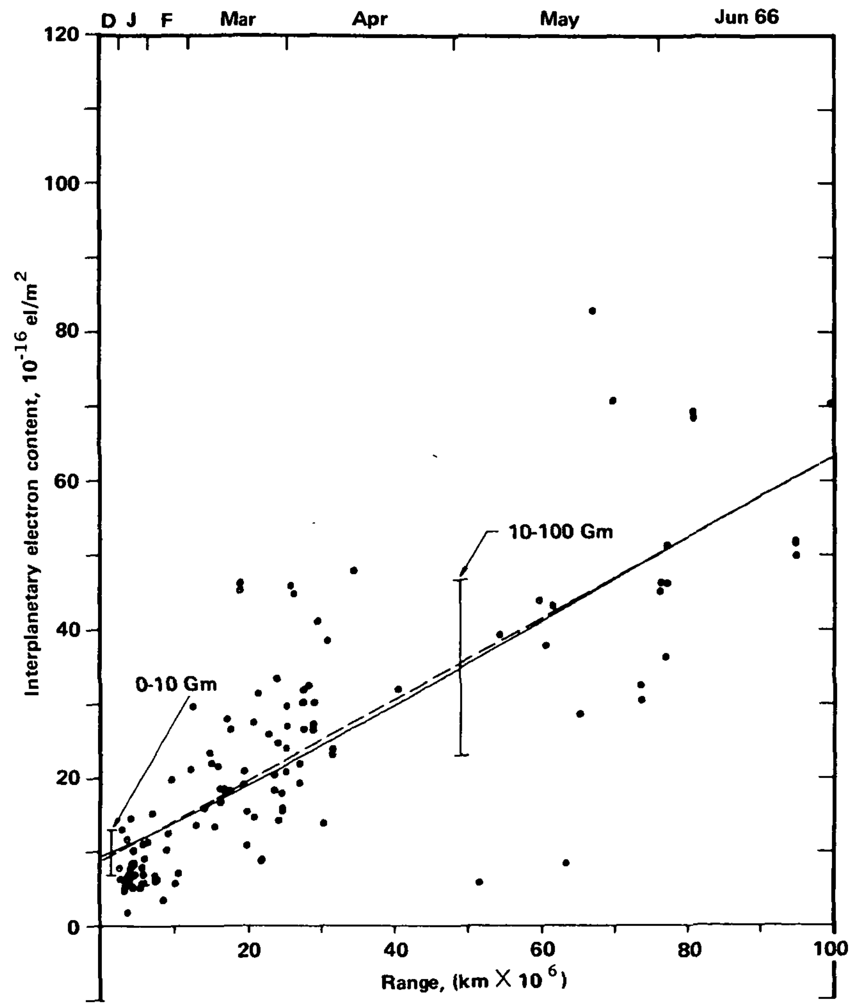

FIGURE 4-7.—Integrated electron content measured from Pioneer 6 to Earth as a function of spacecraft range. From: Koehler: SEL-67-051, p. 56. fig. 5-4, 1967.

is present, however, its refractive effects will displace the diffraction pattern in time. In this case, the difference in the angles of refraction for the 49.8- and 423.3-MHz signals was used to compute electron density.

The ray path from the Stanford antenna to Pioneer 7 was partially in the shadow of the Moon during immersion but was fully illuminated during emersion. The angles of refraction were −2.3 microradians and −5.7 microradians for immersion and emersion, respectively. The minus sign indicates that the electron density

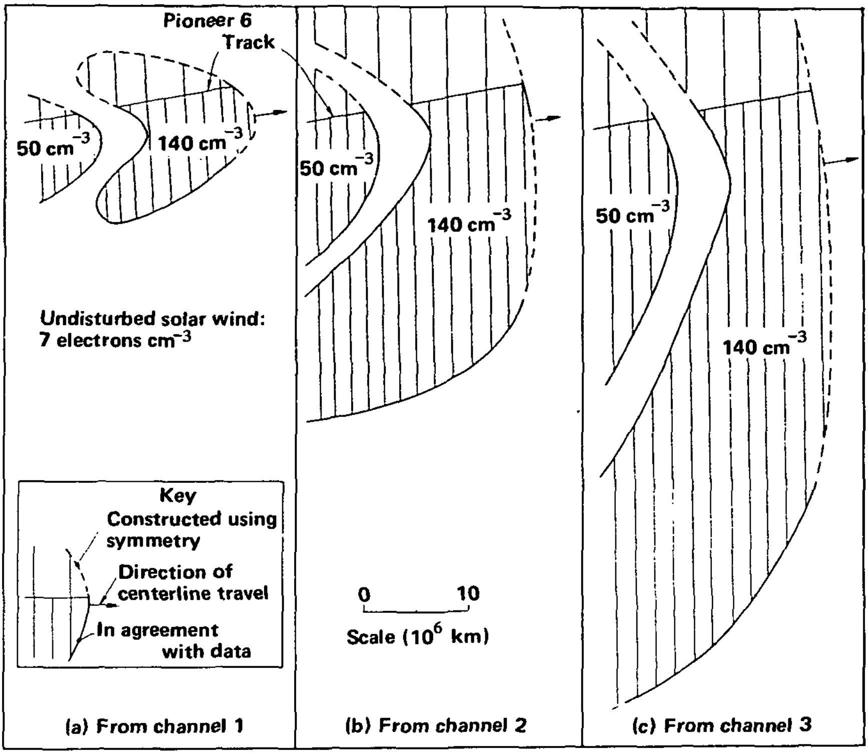

FIGURE 4–8.—Possible plasma cloud shapes. These shapes are consistent with measurements, but were restricted by simplifying assumptions and incorporate structural features based on prevailing theories about such cloud behavior. The configuration shown in (b) is considered the most likely. A gradient in density was actually measured along the Pioneer track and a lateral gradient also probably existed; consequently, the cloud must have been broader than the outlines shown. From: *Landt and Croft:* SU–SEL–70–001, 1970.

increases with height near the surface of the Moon, and that a tenuous ionosphere may be created—at least on the sunlit side—by the interaction of the solar wind with the lunar surface.

Useful scientific information can also be obtained concerning transient space phenomena by observing changes in the Faraday rotation of the signal from the spacecraft S-band transmitter. Levy and his associates at the California Institute of Technology and the University of Southern California have used the DSN 210-ft antenna at Goldstone to measure transient Faraday rotations during solar occultation of Pioneer 6. As the spacecraft line of sight approached the Sun, the S-band telemetry signal passed through increasingly dense regions of the solar corona. At three points between

6 and 11 solar radii, Faraday-rotation transients were recorded. The duration of each event was about 2 hours. The transients were poorly correlated with solar flares, but it was noted that bursts of radio noise in the dekameter range occurred prior to the observation of the Faraday rotation phenomena.

TRW SYSTEMS ELECTRIC FIELD EXPERIMENT

Near the Earth's orbit the solar wind is very dilute, and the plasma is truly collisionless. Individual electrons and positive ions are influenced only by dc electromagnetic fields or by fields due to the organized motion of plasma particles in the form of ac plasma waves. The Pioneer Electric Field Experiment was designed to detect these microscopic plasma phenomena. The overall size of the Pioneer spacecraft and its appendages is small compared to the Debye length in interplanetary space and also the minimum wavelength for any undamped plasma oscillation. Thus, the spacecraft actually represents a "microscopic" measuring platform immersed in plasma phenomena of much greater fundamental size. The 423-MHz antenna of the radio propagation experiment is a relatively insensitive, but adequate, capacitively coupled sensor that detects plasma waves sweeping past the Pioneers in interplanetary space.

While magnetometers have helped scientists understand microscopic electromagnetic phenomena in space, the Pioneer Electric Field Experiment is electrostatic in nature—it was the first low-frequency (under 100 Hz) electric field experiment to be flown in space. The Pioneer instruments detect density fluctuations within the plasma rather than the motions of current systems indicated by magnetometers.

The following conclusions were made on the basis of early Pioneer–8 data:

(1) Even when the Sun is quiet, low-frequency electric waves ($\geq$ 100Hz) can be detected in the solar wind.

(2) Wave amplitudes at the lowest frequencies vary markedly with changing conditions in interplanetary space. These electric field changes are correlated with local changes in the plasma environment, as registered on the Ames plasma probe.

(3) As Pioneer 8 moved away from the Earth, the effects of corotation and solar-wind travel times were evident when comparing disturbances recorded both on Earth and on the spacecraft.

(4) Large-amplitude, high-frequency waves, detected when the spacecraft was far from Earth, are apparently the result of bursts of interplanetary electron oscillations.

Data from Pioneers 8 and 9 and OGO 5 were used to demonstrate the several types of shock structures found in the high Mach-number solar plasma colliding with the Earth's magnetosphere. The most common structure reported was a large-amplitude magnetohydrodynamic pulse having a characteristic length equal to the initial gradient and a trailing wavetrain.

The plasma-probe and electric-field data, recorded as Pioneer 8 crossed the Earth's geomagnetic tail during January 1968, indicated disturbances near the tail boundaries between 500 and 800 Earth radii downstream. The major conclusion of this paper was that tail breakup and field-line-reconnection phenomena begin within 500 Earth radii.

The initial results from the Pioneer–8 electric field experiment showed clearly their close correlations with terrestrially detected magnetic activity. Because the other Pioneer instruments also record space events—although from a different perspective—on-board correlations should also be obvious in many instances. Scarf has presented a three-way correlation during a Forbush decrease. Figure 4–9 indicates how the Pioneer–8 magnetometer, electric-field experiment, and the Minnesota cosmic-ray experiments all recorded the same event. Similar correlations have been made with data from other spacecraft.

THE GODDARD COSMIC DUST MEASUREMENTS

During the early days of the Space Age, cosmic dust was thought to be a serious hazard to men and machines operating outside the Earth's protective atmosphere. More accurate measurements of cosmic dust particles have since shown these fears to have been unwarranted. Sensitive external surfaces on long-lived Earth satellites may suffer some degradation, but neither manned nor unmanned spacecraft have been compromised. Nevertheless, cosmic dust particles do exist and their presence in space demands a scientific explanation.

Are cosmic dust particles products of cometary disintegration or the debris from collisions within the asteroid belt? Most of our insight into this question at present comes from ground-based photographic and radar measurements of meteor trails. These data suggest that almost all cosmic dust trajectories are heliocentric with the orbital characteristics of comets rather than asteroids. Further, the particles seem "fluffy" and of low density. The Pioneer cosmic dust experiment, which flew on Pioneers 8 and 9, was designed to help answer this question of particle origin with *in situ* data from deep space.

During the first 390 days of continuous exposure of the Pioneer–8 sensors, numerous events (several per day) were recorded by the front sensor array *alone,* the rear sensor array *alone,* or the micro-

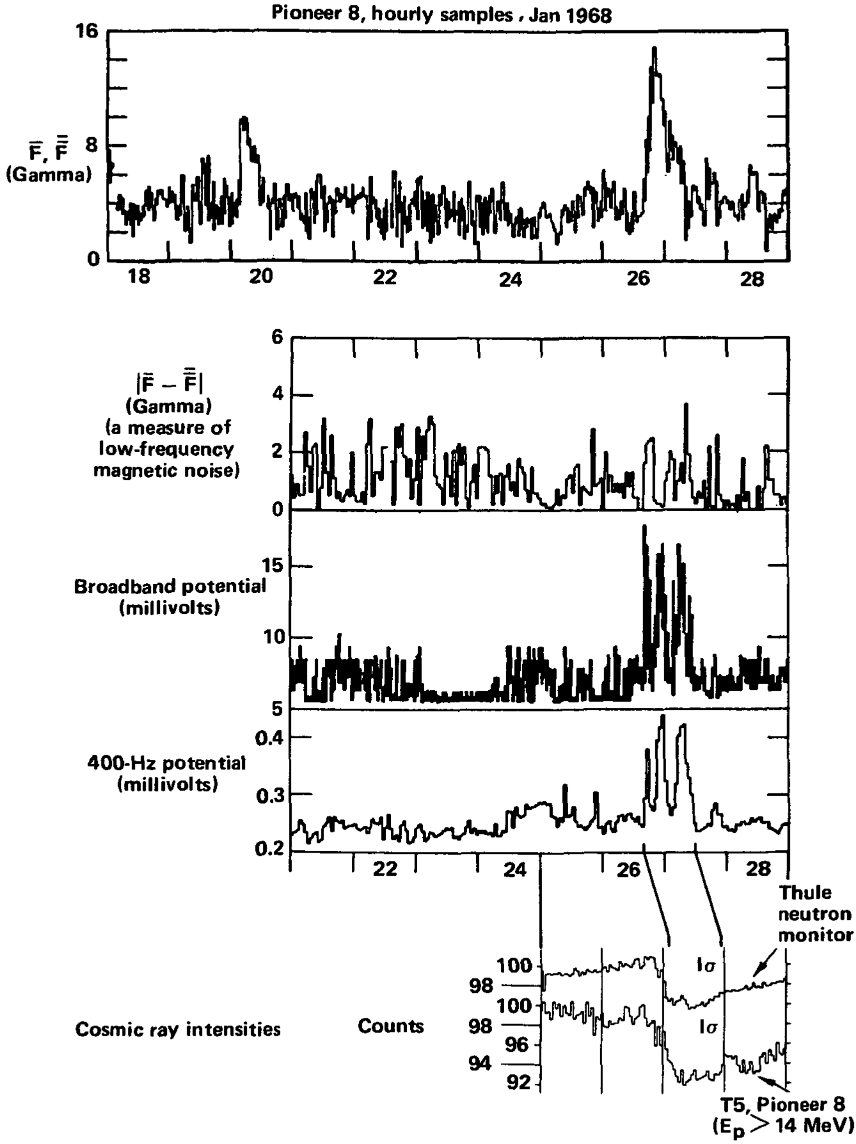

FIGURE 4–9.—Pioneer 8 magnetometer data (top) and electric-field data (middle) reveal interplanetary shock. Cosmic-ray readings (bottom) show attendant Forbush decrease.

phone sensor *alone*. Six time-of-flight events involving *both* front and rear sensor arrays were also registered. These are considered highly important to the question of cosmic dust origin because orbital information can be derived from the measurements.

The six time-of-flight events in a space of 390 days represent a rate 3.8×10^4 lower than the rate recorded by a time of flight experiment on OGO 1. It is surmised that the high OGO–1 rate was due to coincident noise pulses in that experiment. Noise was a serious problem with early scientific satellite cosmic dust experiments. In general, early Pioneer–8 results confirm expectations from zodiacal light measurements.

From a knowledge of the spacecraft trajectory and orientation at the instant of each event and the telemetered data indicating times of flight and the specific sensors activated in the front and back arrays it was possible to derive the particle orbits (fig. 4–10). These data indicate a cometary origin for the six particles, reinforcing the conclusions derived from ground-based observations.

The most interesting of the six events reported occurred on April 13, 1968. Apparently, one front sensor segment and two rear sensors responded, inferring that the particle partially disintegrated upon first impact, showering the rear array with a conical spray of debris. No such fragmentation was observed during laboratory tests with particles fired from an electrostatic accelerator. In view of the possible friable nature of cosmic dust material, this type of event was not unexpected.

The April 13, 1968, event was notable in two other aspects: (1) its impact energy exceeded 80 ergs, more than any other particle recorded; and (2) it was the only particle that activated the acoustical sensor. Thus, independent measurements of the particle's mass were possible from the energy and momentum equations. These were 2.3×10^{-11} and 1.6×10^{-11} g–relatively good agreement for this kind of experiment. From this information, an orbit for the particle was computed.

THE PIONEER CELESTIAL MECHANICS EXPERIMENT

All spacecraft launched out of the Earth's gravitational "well" provide opportunities for improving solar system constants and ephemerides. Although the Pioneer spacecraft did not pass close to any other solar system planets, their trajectories were affected by the Moon. Further, the launch of four similar spacecraft, of known mass, all equipped with tracking aids, into heliocentric orbits, made possible more accurate determinations of the Astronomical Unit (AU) as well as the Earth's ephemeris. The three formal objectives of the experiment were:

(1) To obtain primary determinations of the masses of the Moon and Earth and of the AU

(2) To improve the ephemeris of the Earth

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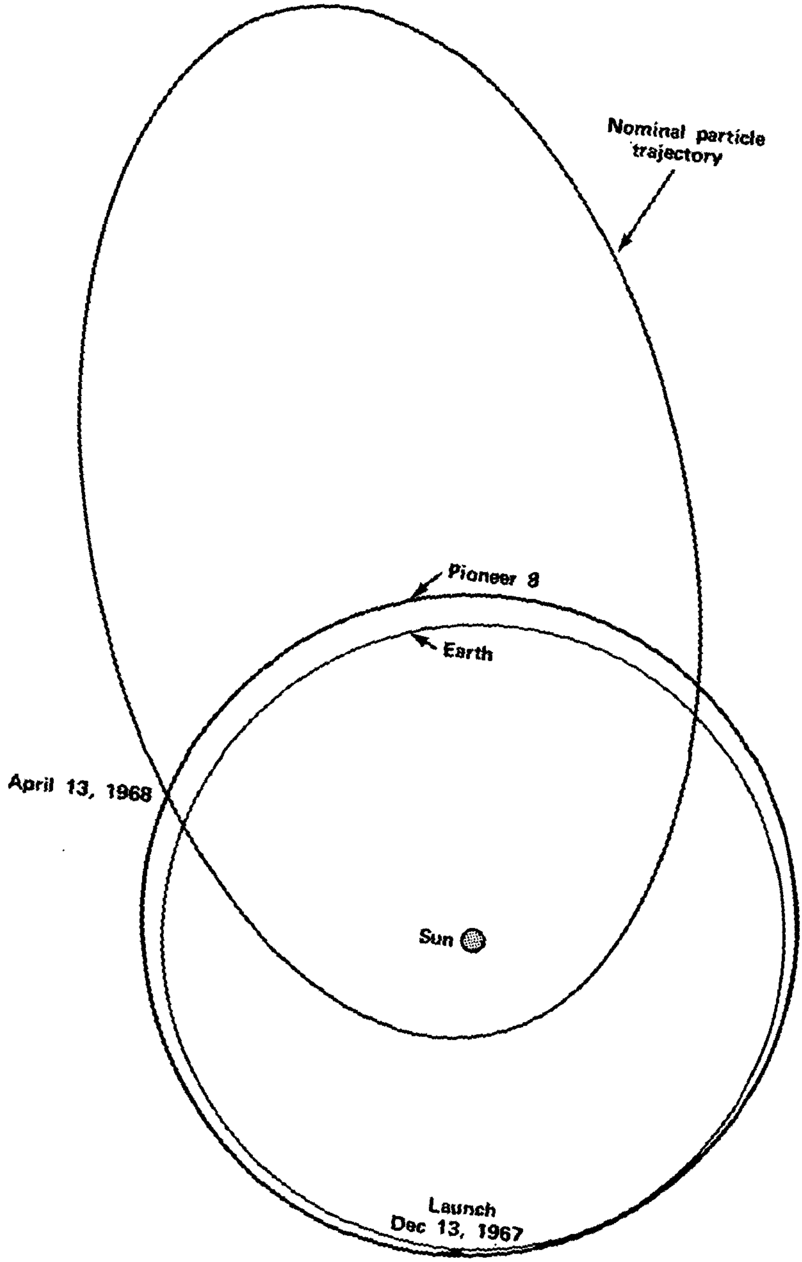

FIGURE 4–10.—Postulated orbit for the particle recorded on April 13, 1968. This was a time-of-flight event. From: Berg, 1969.

(3) To investigate the possibility of a General Relativity test, using Pioneer orbits and data

The following preliminary Earth-Moon data have been reported from this experiment:

Geocentric gravitational constant = GE = 398 601.5 ± 04 km^3/sec^2

Lunar gravitational constant = GM = 4902.75 ± 0.12 km^3/sec^2

Earth-Moon mass ratio = μ^{-1} = 81.3016 ± 0.0020

SOLAR WEATHER MONITORING

Because of these terrestrial effects of solar activity, several groups are interested in "solar weather"; i.e., the status of the interplanetary magnetic field, plasma fluxes, and cosmic radiation levels. The interest transcends pure science. NASA, for example, is concerned with solar events that might compromise manned space missions, particularly those that leave the shelter of the Earth's magnetosphere. The Environmental Science Services Administration (ESSA) desires advance information on magnetic storms and the injection of new, charged particles into the Earth's belt of trapped radiation. These are the events that sometimes upset terrestrial communications and have some not-so-well-understood effects on the planet's weather. The Department of Defense (DOD) has similar interests for military reasons.

Pioneer Solar Weather reports began in January 1967. Usually they are sent once a day to ESSA's Space Disturbance Forecast Center at Boulder, Colorado; to DOD's NORAD; and to other agencies. However, when manned flights are imminent, reports are sent hourly to NASA's Apollo Mission Control Center at Houston, Texas. The reports include:

(1) The corotation delay, i.e., the expected time in days between the measurement of a disturbance at the spacecraft and its arrival at Earth

(2) Solar wind velocity, density, and temperature

(3) Cosmic-ray intensities in several energy bands

(4) The general condition of the interplanetary magnetic field.

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Bibliography

ANDERSON, J.D.; AND HILT, D.E.: Improvement of Astronomical Constants and Ephemerides from Pioneer Radio Tracking Data. Am. Astronaut. Soc. Paper, pp. *68–130, 1968.*

ANON.: TRW Systems, Pioneer Spacecraft Project Final Project Report. Rep. no. 8830-28, 1969.

BARON, W.R.: The Solar Array for the Pioneer Deep Space Probe. Electronics and Power, vol. 14, March 1968, p. 261.

BARTLEY, W.C.; MCCRACKEN, K.G.; AND RAO, U.R.: Pioneer VI Detector to Measure Degree of Antisotropy of Cosmic Radiation in Energy Range 7.5–90 MeV/Nucleon. Rev. Sci. Instr., vol. 38, Feb. 1967, p. 266.

BERG, O.E.: The Pioneer 8 Cosmic Dust Experiment. NASA TN D-5267, 1969. (Also Rev. Sci. Inst., vol. 40, Oct. 1969.)

BERG, O.E.; KRISHNA SWAMY, K.S.; AND SECRETAN, L.: Cosmic Dust Radiants and Velocities from Pioneer 8. Goddard Space Flight Center, X-616-69-145 and X-616-69-233, 1969.

BURLAGA, L.F.: Microscale Structures in the Interplanetary Medium. Solar Phys., vol. 4, May 1968, p. 67.

CANTARANO, S.C., ET AL.: Magnetic Field Experiment, Pioneers 6, 7, and 8. NASA TM-X-63395, 1968.

FAN, C.Y. ET AL.: Differential Energy Spectra and Intensity Variation of 1-20 MeV/Nucleon Protons and Helium Nuclei in Interplanetary Space (1964–1966). Can. J. Phys., vol. 46, May 15, 1968, p. S498.

HALL, C.F.; AND MICKELWAIT, A.B.: Development and Management of the Interplanetary Pioneer Spacecraft. NASA TM-X-60564, 1967. (Also in Proc., 18th International Astron. Congress, vol. 2, M. Lunc, ed., Pergamon Press, Oxford, 1968.)

INTRILIGATOR, D.S. ET AL.: Preliminary Comparison of Solar Wind Plasma Observations in the Geomagnetic Wake at 1000 and 500 Earth Radii. Planetary and Space Sci., vol. 17, March 1969, p. 321.

LAZARUS, A.J.; SISCOE, G.L.; AND NESS, N.F.: Plasma and Magnetic Field Observations during the Magnetosphere Passage of Pioneer 7. J. Geophys. Res., vol. 73, April 1968, p. 2399.

LEZNIAK, J.A. ET AL.: Observations on the Abundance of Nitrogen in the Primary Cosmic Radiation. Astrophys. and Space Sci., vol. 5, Sept. 1969, p. 103.

LUMB, D.R.: Test and Preliminary Flight Results on the Sequential Decoding of Convolutional Encoded Data from Pioneer IX. IEEE ICC Conference Publications, vol. 5, IEEE, New York, 1969, pp. 39-1 to 39-8.

LUMB, D.R.; AND HOFFMAN, L.B.: An Efficient Coding System for Deep Space Probes with Specific Application to Pioneer Missions. NASA TN-D-4105, 1967.

MARIANI, F.; AND NESS, N.F.: Observations of the Geomagnetic Tail at 500 Earth Radii by Pioneer 8. J. Geophys. Res., vol. 74, Nov. 1, 1969, p. 5633.

McCRACKEN, K.G.; RAO, U.R.; AND NESS, N.F.: Interrelationship of Cosmic-Ray Antisotropies and the Interplanetary Magnetic Field. J. Geophys. Res., vol. 73, July 1, 1968, p. 4159.

NESS, N.F.: Interplanetary Sector Structure, 1962-1966. Solar Phys., vol. 2, Nov. 1967, p. 351.

NESS, N.F.: Direct Measurements of Interplanetary Magnetic Field and Plasma. Ann. of the IQSY, vol. 4, 1969, p. 88.

NUNAMAKER, R.R.; HALL, C.F.; AND FROSOLONE, A.: Solar Weather Monitoring—Pioneer Project. Am. Inst. Astronaut. Aeron. Paper 68-36, 1968.

RAO, U.R.; McCRACKEN, K.G.; AND BUKATA, R.P.: Cosmic-Ray Propagation Processes, 2. J. Geophys. Res., vol. 72, Sept. 1, 1967, p. 4325.

RAO, U.R.; McCRACKEN, K.G.; AND BUKATA, R.P.: The Energetic Storm Particle Event. J. Geophys. Res., vol. 72, Sept. 1, 1967, p. 4325.

REIFF, G.A.: Radio Propagation Experiments with Interplanetary Spacecraft. J. Spacecraft and Rockets, vol. 6, May 1969, p. 551.

REIFF, G.A.: The Pioneer Spacecraft Program. AAS Paper, 1969.

SCARF, F.L. ET AL.: Initial Results of the Pioneer 8 VLF Electric Field Experiment. J. Geophys. Res., vol. 73, Nov. 1, 1968, p. 6665.

SCARF, F.L. ET AL.: Pioneer 8 Electric Field Measurements in the Distant Geomagnetic Tail. J. Geophys. Res., vol. 75, June 1, 1970, p. 3167.

SHERGALIS, L.D.: A Magnetically Clean Pioneer. Electronics, vol. 38, Sept. 20, 1965, p. 131.

SISCOE, G.L.; GOLDSTEIN, B.; AND LAZARUS, A.J.: An East-West Asymmetry in the Solar Wind Velocity. J. Geophys. Res., vol. 74, April 1, 1969, p. 1759.

STAMBLER, I.: The New Pioneer Satellites. Space/Aeron., vol. 40, Nov. 1963, p. 58.

WOLFE, J.H. ET AL.: The Compositional, Anisotropic, and Non-radial Flow Characteristics of the Solar Wind. J. Geophys. Res., vol. 71, July 1, 1966, p. 3329.

APPENDIX

MEMORANDUM: ORGANIZATION OF AMES SOLAR PROBE TEAM

NASA–Ames
September 14, 1960

MEMORANDUM for Research Division Chiefs and Branch Chiefs

Subject: Organization of Ames Solar Probe Team

1. In the past few months a feasibility study of a solar probe has been made by members of the Ames staff. The purpose of such a vehicle would be to obtain valuable information on the spatial environment in the near vicinity of the sun which would permit a better understanding of the influence of the sun on weather and communication on earth and on the radiation hazard to manned flight in space. The results of this study have been compiled and a report entitled "A Preliminary Study of a Solar Probe" has been prepared and disseminated to interested personnel at Ames. The results of the study show that such a vehicle is feasible and have indicated a number of areas where research will be required in order to make the development of the solar probe practical.

2. In order to capitalize on the ideas and data that have resulted from this study the Ames Solar Probe Team is organized. It will be the responsibility of the team to consider the design problems of the vehicle, to recommend a practical system when it is judged feasible, and to recommend research programs that are desirable or necessary in this connection. Study of the vehicle system will be carried out by team members and their subordinates; recommendations of the team that require action by the Center should be brought to the attention of the Assistant Director's Office. This office will in turn organize a meeting of Branch Chiefs, Division Chiefs, and Team members for the required interchange and discussion so that decisions, approvals and assignment of responsibility can be accomplished expeditiously and with full backing of the Center Administration.

3. The following staff members are appointed to the Ames Solar Probe Team:

C. F. Hall	Chairman
John Dimeff	Instrumentation
C. F. Hansen	Experiments
W. A. Mersman	Trajectories
R. T. Jones	Theory
H. F. Matthews	Guidance, Stability and Control
H. Hornby	Boosters
W. J. Kerwin	Communication, Auxiliary Power
C. A. Hermach	Thermal Protection

Smith J. DeFrance
Director

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