TOPS SPACECRAFT AND THE MISSIONS

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The Thermoelectric Outer Planet Spacecraft (TOPS) is being designed to meet the challenges and hazards expected on outer-planet missions starting in the late 1970s—missions made possible by the rare, and now much discussed, planetary alignment of the next two decades.

The attention to the field of astrodynamics brought the necessary awareness to these missions by the mid-1960s. But the concept of using the gravity of a planet to change the trajectory of a space vehicle was initially advanced by Hohmann in his analysis of an Earth-Mars-Venus-Earth trajectory.[1]

In 1963 Minovitch presented the detailed trajectory analysis for "gravity assisted" trajectories and demonstrated the reduced launch-energy requirements for missions to the inner planets (Venus-Mercury).[2]

By 1964 Hunter had suggested using Jupiter's gravitational field to reduce flight time to the outer planets.[3] Flandro then discovered the rare late-1970s alignment of Jupiter, Saturn, Uranus, and Neptune that makes an encounter with all four planets in one mission practical, in a remarkably short flight time.[4-5] A direct flight to Neptune using a ballistic trajectory requires a 30-year flight period, but Flandro's proposed "Grand Tour" mission takes only about nine years.

Kingsland performed a detailed trajectory analysis of the four-planet Grand Tour mission, investigating two trajectories with a 1977 launch date: one that passes inside the inner ring of Saturn and the other just outside Saturn's rings.[6] The launch energy (defined as twice the energy per unit mass of the spacecraft at Earth escape and commonly designated as C_3) was about 120 km^2/sec^2.

Wallace also investigated numerous outer-planet missions using gravity-assisted trajectories.[7] He brought out the advantages of using two- or three-planet missions (rather than four) in the late '70s, particularly in light of the uncertainties concerning Saturn's rings, which make it desirable to bypass Saturn in some of these missions. The Grand Tour mission that does not fly by Saturn (the Jupiter, Uranus, Neptune, or J-U-N mission) was further investigated by Wallace, for 1978 and 1979 launches.[8] Further investigation of three-planet missions led to the detailed analysis of a Jupiter-Saturn-Pluto (J-S-P) mission with a 1977 launch. Wallace documents the trajectory considerations for this mission.[9] Last year in *A/A*, Long discussed these missions from a system and spacecraft-design point of view.[10]

Basic mission constraints that led to the selection of a multiple-planet trajectory have been discussed by Kingsland for the Grand Tour mission[6] and by Wallace for the J-U-N and J-S-P missions.[8-9]

In order to select a mission mode for TOPS, the project guidelines and definition, including the purpose and objectives of TOPS, have to be considered. To satisfy these objectives the 1977 Grand Tour inner-ring trajectory was chosen for analysis. Lifetime considerations, however, were based on a longer flight time (the 12 years required for the 1977 Grand Tour, outer-ring mission). Recent interest in three-planet missions has motivated the inclusion of both the 1977 J-S-P and the 1979 J-U-N missions in TOPS spacecraft-design considerations.

The table on page 48 summarizes encounter dates, altitudes, and hyperbolic approach velocity for these three missions. Charts on pages 46 and 47 show the heliocentric trajectories of the missions. The launch vehicle must supply an injection energy of some 120 km^2/sec^2 for the anticipated spacecraft weight. A 21-day period is required for two launches from the same pad with the proposed launch vehicle.

With this background, we can now consider the launch vehicle, the flight environment, and system design.

Launch Vehicle: Project leaders chose the Titan IIID/Centaur with a Burner-II upper stage as the basic launch vehicle for the TOPS missions because of its comparatively low cost. The exact performance of this launch vehicle, shown on page 51, will naturally change with development of improved or new versions. Improved or larger versions would slightly shorten trip times or increase payload weight. The graph on page 49 gives the current estimate of the launch-vehicle's performance, based on the following assumptions, including parking-orbit ascent:

Shroud weight, lb.	5600
Burner-II-to-Centaur adapter weight, lb.	215
Burner-II propellant loading, lb.	2300
Launch-vehicle contingency, lb.	150
Launch azimuth, deg	115

Environments: The environments, natural and self-induced, that the spacecraft will experience, from launch throughout cruise to encounter phases of the mission, include radiation fields, solid-particle fields, magnetic and electromagnetic fields, various temperatures, vacuum, and dynamic effects. The tables on page 50 describe some of these environments.

Because solar-cell performance decreases below acceptable levels beyond the asteroid belt, Radioisotope Thermoelectric Generators (RTGs) were chosen as the TOPS power source. These RTGs produce neutron and gamma radiation spectra in the range of a few MeV, as summarized in the table on page 50. Separating the RTGs from the science and electronic assemblies, shielding instruments to the level of damage thresholds, and hardening components wherever possible increases the tolerance to this and other radiation. The spacecraft subsystems are being designed to tolerate the 12-year integrated dose from the RTGs measured at a separation distance of 5 ft from the surface of the RTGs. This approach gives flexibility for future design changes.

Most scientific data on the magnetically trapped radiation of the outer planets concerns Jupiter, and indicate it has major sources of trapped primary radiation (electrons).[11] Both plasma theory and Earth analogy suggest protons are trapped in its magnetic field as well. The TOPS design criteria are based on travel through the peak of the Jovian radiation belts, thereby gaining flexibility for future mission design.

In addition, solar and interplanetary radiation has been reasonably well defined from past missions. It consists primarily of solar-event protons, solar wind, solar thermal radiation, and galactic cosmic rays. The table on page 50 summarizes the levels used as design constraints.

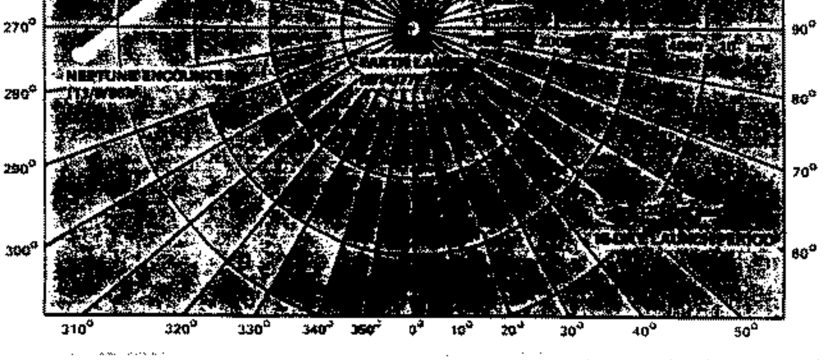
Solid particles in space include micrometeoroids, asteroids, and material trapped in planetary orbit (e.g., Saturn's rings). Through appropriate shielding and wrapping, the spacecraft will be designed to withstand the impacts described by a table on page 50. This chiefly protects the spacecraft from particles with a mass less than 10^{-3} grams. It provides a high probability of surviving passage through the asteroid belt.

Saturn's rings, however, pose another problem for close planetary encounter. Engineering models indicate potential hazards to spacecraft passing closer than three Saturn radii from planetary center. But the spacecraft and subsystem designs are not at this time restrained by the fluxes of solid particles in Saturn's rings. Instead the design requirements imposed by the asteroidal and micrometeoroidal debris will be assumed to control the altitude and latitude of closest approach to Saturn. Current ring models indicate either large ring thickness (15 km) and large particles ($\cong$50 cm) or small ring thickness (tens of centimeters) and small particles ($\cong$500 μ out to three Saturn radii.

The TOPS design has a magnetometer experiment. In order to detect the boundary between the solar and intergalactic fields, the spacecraft-caused field must be less than 0.01 gamma at the magnetometer sensor, which is on a boom not less than 25 ft from the closest spacecraft subassembly. The following design guidelines will be followed to achieve the 0.01-gamma limit: small use of soft magnetic materials; compensation or shielding of hard magnetic materials that cannot be replaced with nonmagnetic materials: degaussing loops or compensation on unavoidable current loops (particularly applicable to power sources); and detailed speci-

1977 INNER-RING GRAND TOUR OF JUPITER, SATURN, URANUS, AND NEPTUNE

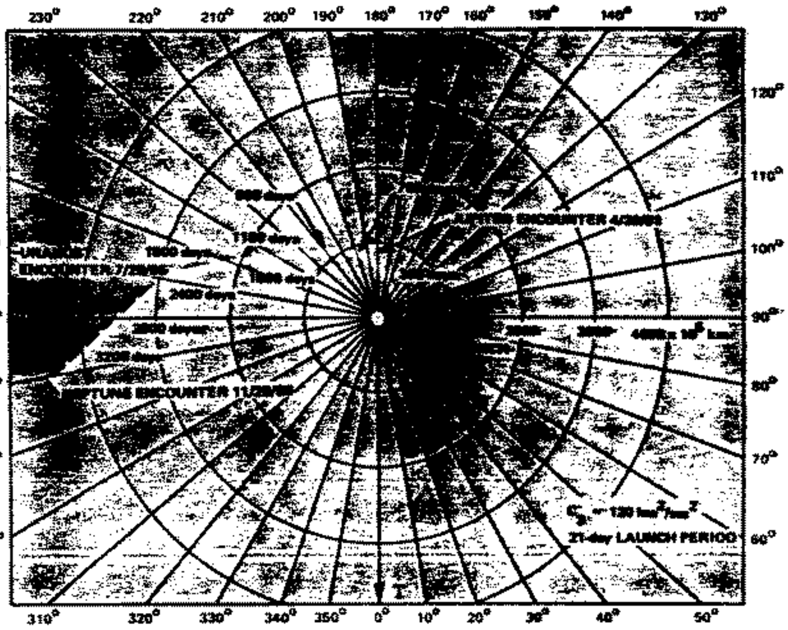
Ecliptic-plane heliocentric geometry.



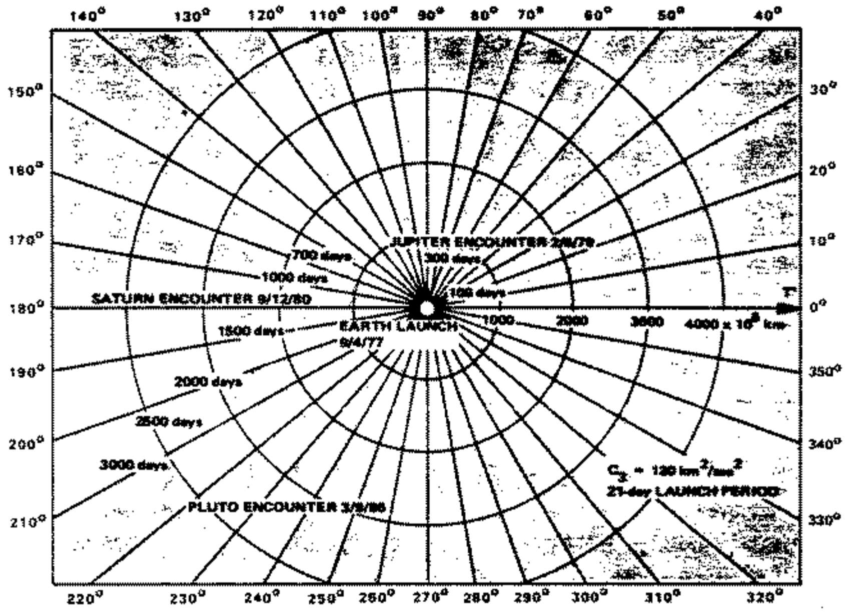
fication and measurement of piecepart and breadboard-level equipment to insure design compatibility.

Electromagnetic interference (EMI) is expected on hard-line wiring between spacecraft subsystems, between the operational support equipment (OSE) and the spacecraft (umbilical and direct access), and between spacecraft and the launch vehicle. Specifying allowable levels for generated and conducted electromagnetic interference will enable the designer to evaluate compatibility problems and take corrective action or make special tests.

1979 JUPITER, URANUS, NEPTUNE Ecliptic-plane heliocentric geometry.



1977 JUPITER, SATURN, PLUTO Ecliptic-plane heliocentric geometry.



Temperature environments originate from thermal radiation from the Sun, planetary reflected sunlight, planetary radiation, and heat generated within the spacecraft. Control of the spacecraft's thermal environment requires both active and passive techniques.

The spacecraft dynamic environments—shock, vibration, acoustic noise, and static acceleration—occur primarily during launch. Normal design practice covers these.

Spacecraft System Design: The drawings on page 52 show the spacecraft configuration evolved to meet TOPS scientific objectives, trajectory requirements, and environmental constraints.

In many respects, its organization resembles earlier interplanetary spacecraft, at least in terms of subsystem function, but the TOPS configuration really differs markedly from the earlier spacecraft. Some of its important features have been summarized with the drawings.

Trajectory characteristics, science objectives, reliability, and launch-energy constraints all call for the application of new technologies.

In particular, reliability must be designed into any system requiring such longevity as TOPS'. From the earliest design phases, the TOPS project assigned reliability paramount importance. The designers attempted to anticipate every environment and to design subsystems with margin. They had the spacecraft and its subsystems quantitatively analyzed to determine failure modes and remove them wherever possible, and to develop techniques for working around a failed part or for operating in a degraded mode.

The TOPS design aims at achieving reliability largely by *eliminating* known design problems, by using extensive redundancy to eliminate the effects of single-point failures, and by including *self-test and repair* techniques to identify and compensate for any failures.

TOPS TRAJECTORY DATA

Mission	Launch date	Launch energy,* km²/sec²	Launch period, days	Flight time, years	Planet-encounter dates	Altitude at closest approach, 10³ km	Hyperbolic approach velocity, km/sec
1977 Grand Tour inner-ring trajectory	9/4/77	120	18	9.2	Jupiter: Jan 29, 1979 Saturn: Sept 3, 1980 Uranus: Feb 1, 1984 Neptune: Nov 8, 1986	217.9 (3.0 radii) 6.4 (0.1 radius) 21.3 (0.9 radius)	11.97 16.56 21.07 23.57
1977 J-S-P	9/4/77	120	21	8.5	Jupiter: Feb 6, 1979 Saturn: Sept 12, 1980 Pluto: Mar 9, 1986	230 (3.2 radii) 452 (7.5 radii)	11.8 16.3 18.5
1979 J-U-N	11/6/79	120	21	9.1	Jupiter: Apr 30, 1981 Uranus: Jul 28, 1985 Neptune: Nov 28, 1988	413 (5.8 radii) 25 (1.1 radii)	12.2 16.3 17.3

*_Vis viva_ energy, or injection energy of the escape hyperbola, or twice the total energy per unit mass, commonly designated as C_3.

The radio subsystem represents a good example of the use of redundancy: five S-band and two X-band transmitters can send spacecraft data to Earth. This is not simple block redundancy, but rather complete *functional* redundancy, since three of the S-band transmitters use TWT amplifiers and two use solid-state amplifiers.

The control computer represents a good example of self-test and repair techniques. All control and data words incorporate error-detecting codes. This permits the assigning of standby processors to replace faulty units.

Science Instruments: The outer-planet mission opportunities of the late 1970s present the first chance to observe closely all the major planets, the far reaches of the interplanetary medium, and possibly, the intergalactic medium. Consequently, TOPS carries an ambitious complement of representative scientific instruments.

The preceding article by Newburn et al. outlines both interplanetary and planetary science experiments. The instrument requirements influence spacecraft design primarily through structural constraints imposed by viewing angles, power demands for operations, telemetry bandwidth for data return, control-signal demands to cover proper sequencing, onboard data processing to increase telemetry-channel efficiency, attitude stability for proper pointing, temperature control, need for navigational accuracy, and data storage.

Structure: The TOPS structural design reflects the desire to gain separation between the RTGs and the critical electronics and science subsystems, as well as some self-shielding against damaging gamma radiation through the selected mounting of the RTGs. The plasma-wave experiment and the vector helium magnetometer must be remote from any spacecraft component that generates an electromagnetic field that can be sensed by these instruments. Booms were set at a length that was possible to achieve and would provide the needed isolation from the spacecraft. The booms must withstand the accelerations of trajectory-correction maneuvers and must not cause the spacecraft to become dynamically unstable.

The thrust axis of the trajectory-correction motor must point through the spacecraft's CG, and its propellant should be close to the electronics to gain warmth from their waste heat.

The unfurlable high-gain antenna must point at Earth constantly, except during maneuvers, and must be rigid after unfurlment to maintain its high-gain characteristics.

These requirements taken together resulted in the structure shown on page 52. The central bus contains adjacent electronics and propellant compartments. The RTGs ride a boom extending from the bus on the side opposite from the boom supporting the sensitive science instruments. The vector helium magnetometer and the plasma-wave experiment ride long booms, remote from all other subsystems and from each other. The hinged, but rigid, ribs supporting the high-gain antenna mesh join the main bus directly, and the entire spacecraft is kept pointed toward Earth.

Electronic components are more densely packaged than on previous spacecraft to reduce bus volume and to minimize structural supports. Similarly, improved cabling and interconnections using miniature connectors reduce spacecraft weight. The electronic and propellant compartments are arranged for easy assembly and disassembly and for quick access during system-level testing.

Because TOPS must be a versatile spacecraft, to carry out several types of missions to the outer planets, it has been made readily modifiable to accept an atmospheric probe or take the configuration of a planetary orbiter.

Communications: Communicating from the vicinity of an outer planet will be particularly difficult because of the great distances involved and the large amount of data to be transmitted. X-band was chosen to augment the S-band downlink because of the potential for a 7.8-db improvement in data rate if the ground tracking stations have clear, dry weather without winds. TOPS sends telemetry with programmable data-rates varying in powers of 2. This allows the X-band downlink to be compatible with the weather at the tracking station and yet exploit the full potential of the X-band channel.

During the cruise between planetary-encounters, all science and engineering data are stored and played back at weekly intervals, rather than continuously. This keeps down Deep Space Network (DSN) costs and operational complexities. This mode holds throughout the mission—except during transit of the asteroid belt, when tracking is continuous to favor safety and reliability.

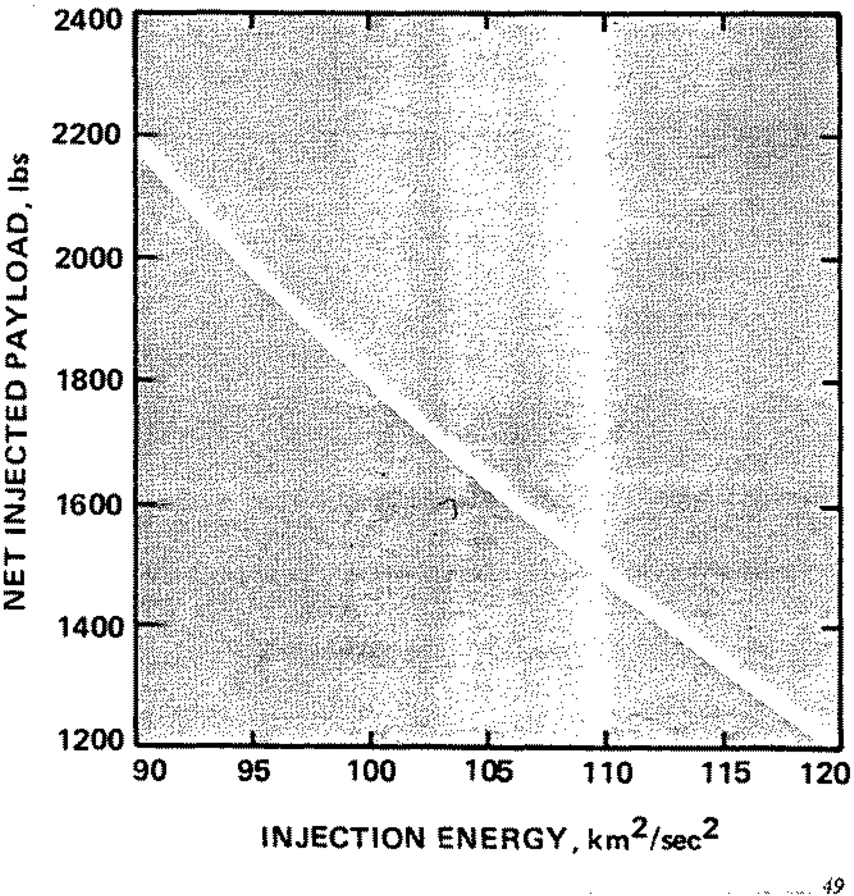
Reasons of reliability and cost motivated comparatively high data-rates. A rate of 2048 bps from Neptune allows 400 pictures of 5-million bits each to be returned to Earth in some 11 days—not an unreasonable amount of time to tie up tracking stations.

This rate from Neptune sets the scale for data-rates from the other planets. Because the spacecraft encounters Neptune seven times farther from Earth than it does Jupiter, and because channel capability varies inversely as the square of the communication distance, this 2048 bps from Neptune translates into about 100,000 bps at Jupiter. The power of 2 closest to 100,000 is 131,072 bps. This rate being the one at which a vidicon is scanned in real time eliminates the need for a tape recorder or other large-volume storage device at Jupiter.

The TOPS telecommunication subsystem comprises redundant S-band receivers, redundant S- and X-band transmitters, four antennas, and associated logic, switches, waveguides, transmission lines, oscillators, exciters, amplifiers, mixers, modulators, demodulators, and power-conversion equipment.

A fixed data-rate from a certain point on the trajectory defines a fixed transmitter power-antenna gain product for the spacecraft telecommunications system. For TOPS, an optimum (minimum weight and cost) is reached at 20 w of X-band power transmitted over a 14 ft diameter, high-gain antenna.

Power: Beyond the asteroid belt solar-cell power sources fall below the performance (measured in watts per pound) of radioisotope thermoelectric generators; and for missions that go much beyond Jupiter, the spacecraft must derive its electrical power of 439 w from



LAUNCH-VEHICLE PERFORMANCE: TITAN IIID/CENTAUR/ BURNER II.

solar-independent sources. Since this power must be available at the most distant planetary encounter, it is referred to as an *end-of-mission* (E.O.M.) requirement. The end-of-mission designation is important because RTG power sources degrade with time due to the radioactive half-life of the plutonium source, the resulting reduction in thermal output, and the time-dependent degradation of the generator components.

The AEC and contractors estimate RTG efficiency at about 1.7 w/lb (E.O.M.), so meeting the 439-w end-of-mission requirement makes RTGs weigh 258 lb of the 308-lb power subsystem. The RTGs use plutonium 238 as the radioactive heat source, in a compound form of plutonium dioxide. The radioactivity from this source heats one junction of a silicon-germanium thermocouple, and the Seebeck effect generates electrical energy in the thermocouple circuit between the hot and cold junctions. The radioactivity of the plutonium 238 and therefore the hot-junction temperature and power output of the RTGs, decrease throughout the mission. To accommodate this shift, a shunt regulator in the power-conditioning equipment absorbs excess

ENVIRONMENTAL CONSTRAINTS UNIQUE TO TOPS

A. Radioisotope Thermoelectric Generator (RTG) Radiation

Maximum flux rates and 10-year mission integrated flux levels correspond to positions 5 ft from RTG (minimum separation distance between RTG and any electronic assembly).

Neutron energy, MeV	Peak flux rate in neutrons, cm²-sec	10-year integrated flux, neutrons, cm²
$E < 0.5$	3.7×10^2	1.1×10^{11}
$0.5 < E < 1.5$	8.7×10^2	2.5×10^{11}
$1.5 < E < 2.5$	1.2×10^3	3.5×10^{11}
$2.5 < E < 3.5$	8.7×10^2	2.5×10^{11}
$E > 3.5$	1.3×10^2	4.0×10^{11}
Total	3.5×10^3	1.4×10^{12}

Gamma energy, MeV	Peak rate, rad/hour	10-year integrated level, rads
$0.2 < E < 0.5$	7.0×10^{-3}	7.0×10^2
$0.5 < E < 1.0$	2.4×10^{-2}	2.4×10^3
$1.0 < E < 2.0$	1.7×10^{-2}	1.7×10^3
$2.0 < E < 3.0$	5.0×10^{-2}	5.0×10^3
$E > 3.0$	2.0×10^{-3}	2.0×10^2
Total	1.0×10^{-1}	1.0×10^4

C. Asteroidal and micrometeoroidal debris

Mass, gm	Average velocity, km/sec	Average density, gm/cm³	Total integrated impacts (per sq. meter from particles with mass greater than indicated)
1.0	20	3.5	2.8×10^{-5}
10^{-1}	20	3.5	1.9×10^{-4}
10^{-2}	20	3.5	1.3×10^{-3}
10^{-3}	20	3.5	9.1×10^{-3}
10^{-4}	20	3.5	6.3×10^{-2}
10^{-5}	20	3.5	4.4×10^{-1}
10^{-6}	20	3.5	3.0
10^{-7}	20	3.5	21.
10^{-8}	20	3.5	140.
10^{-9}	20	3.5	1000.

Note: Impact design value is for particles of less than 10^{-2} gram mass.

B. Solar and interplanetary radiation; planetary trapped radiation

Electron energy, MeV	Peak flux rate in electrons, cm²-sec	10-year integrated flux, electrons/cm²
$E < 0.25$	4.3×10^8	1.0×10^{12}
$E > 0.25$	2.7×10^7	
$E > 1.0$	6.5×10^7	
$E > 4.0$	6.4×10^7	
$E > 6.0$	6.3×10^7	8.2×10^{11}
$E > 12.$	5.7×10^7	6.6×10^{11}
$E > 24.$	4.1×10^7	3.6×10^{11}
$E > 70.$	7.3×10^6	3.6×10^{10}

Proton energy, MeV	Peak flux rate, protons/cm²-sec	10-year integrated flux, protons/cm²
$E \approx .003$	1.2×10^8	5.0×10^{15}
$E > 0.4$	$4. \times 10^8$	3.1
$E > 5.0$	1.4×10^8	1.4×10^{12}
$E > 30.$	1.4×10^8	1.4×10^{12}
$E > 120.$	1.3×10^8	1.3×10^{12}
$E > 250.$	1.1×10^8	1.1×10^{12}
$E > 500.$	7.7×10^7	7.7×10^{11}
$E > 1000.$	2.6×10^7	2.6×10^{11}
$E > 10{,}000.$	.44	9.9×10^7

High-energy alpha particle energy, MeV	Peak flux rate, particles/cm²-sec	10-year integrated flux, particles/cm²
$E > 100$	.55	1.2×10^8
$E > 500$	.39	9.0×10^7
$E > 1000$	.26	6.0×10^7
$E > 10{,}000$	.015	3.5×10^6

Heavy particles with energy greater than 100 MeV; these have same spectral shape as Alpha particles normalized at 100 MeV.

Atomic Number (Z)	Peak flux rate, particles/cm²-sec	10-year integrated flux, particles/cm²
$3 \leqq Z \leqq 5$	.022	5.0×10^6
$6 \leqq Z \leqq 9$	.044	9.9×10^6
$Z \geqq 10$	.011	2.5×10^6

power in the early-mission phases.

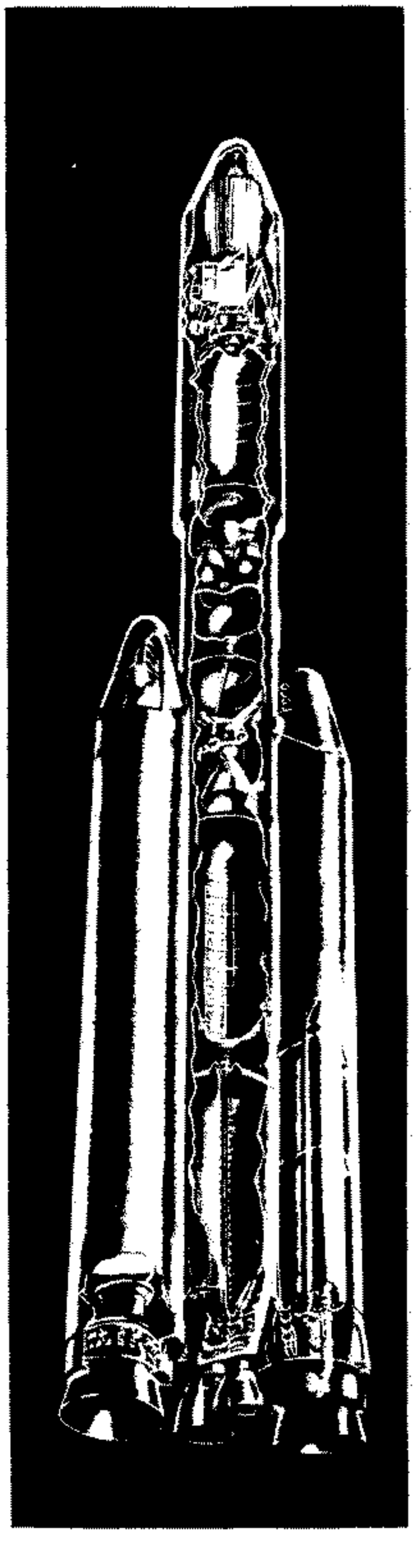
Control: In the past, Mariner spacecraft have been designed to be very autonomous, but they have all incorporated a ground-command override. The TOPS spacecraft must be even more autonomous, since it will operate for several days without monitoring from Earth. On the other hand, it will be able to accept complete reprogramming from ground command of the memory of its control computer subsystem (CCS)—the heart of the spacecraft's control concept.

A self-test-and-repair (STAR) general-purpose computer in the CCS controls the state of the spacecraft throughout its normal operating modes, detects subsystem failures, and initiates corrective action when failures are detected. In some cases, the CCS can take over the functions of inoperable subsystems.

The CCS comprises multiple-redundant processors. All data and control words are coded in error-detecting codes. Transient failures are detected and corrected by recycling the operation. Permanent failures are corrected by replacing the faulty processor. The CCS employs a logic unit built up predominantly from large-scale integrated circuits (LSIs) in multigate arrays with as many as 116 NAND gates on one silicon chip. Each gate consumes only 0.4 mw of power and has a propagation delay of 50 nsec, allowing a computer clock rate of 1 MHz. LSIs aid standardization and reliability, since 80% of the CCS logic can be built from them.

As backup to the CCS and for CCS reprogramming, TOPS will have a single-channel digital, multiple-bit-rate command subsystem.

Data Processing: In contrast to earlier Mariner interplanetary spacecraft, which had two separate subsystems for processing data (the flight telemetry subsystem for engineering data and the data automation subsystem for science data), TOPS will use a more flexible, programmable measurement processor subsystem (MPS) for both science and engineering data. This change increases reliability and cuts costs.



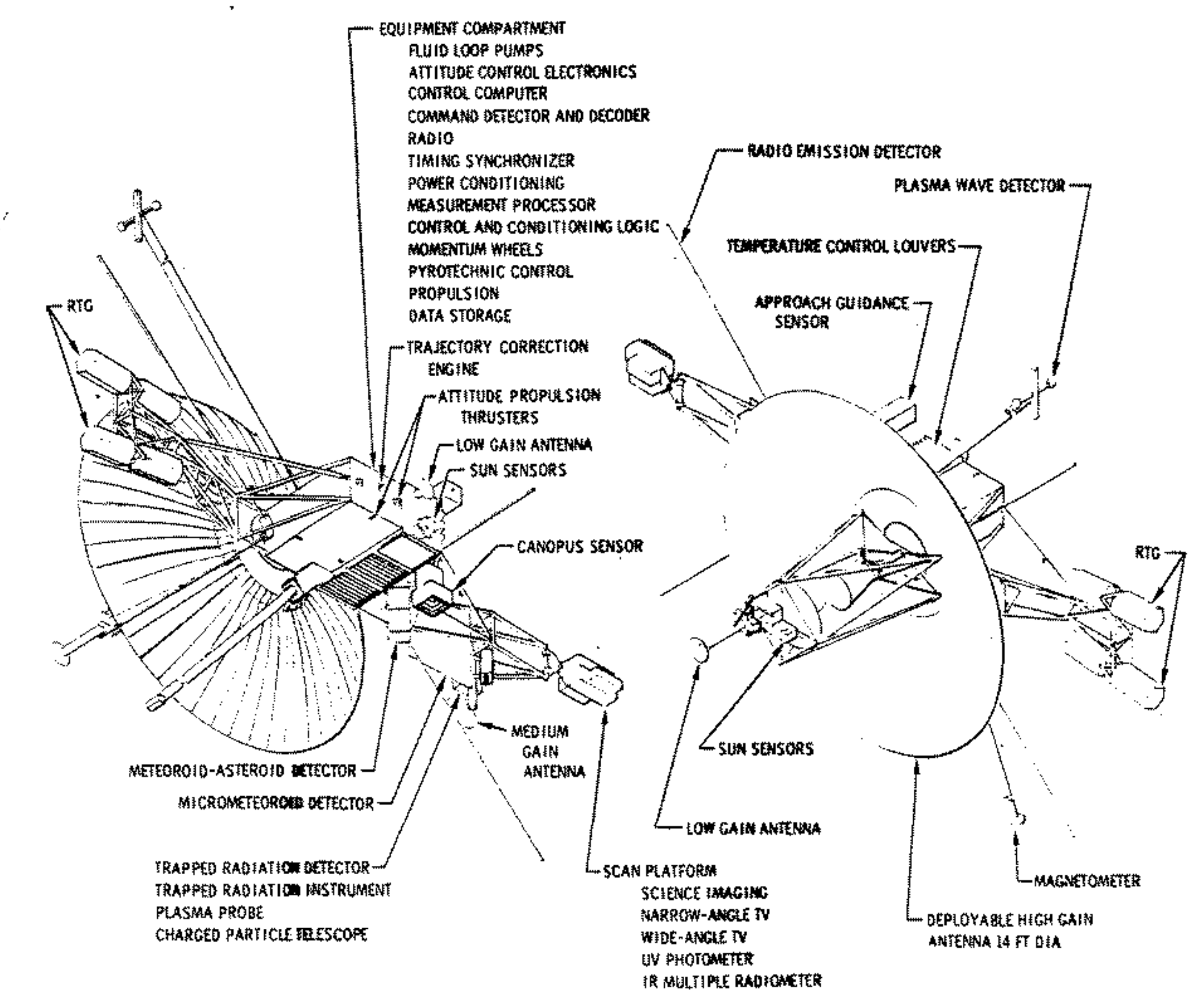
Cutaway view of proposed Titan IIID/
Centaur/Burner II launch vehicle.

The MPS works closely with the data-storage subsystem (DSS), which consists of two redundant 10^9-bit tape recorders and an 8×10^6-bit buffer based on LSI semiconductor or plated-wire technology. The MPS receives instructions from the CCS or from the command subsystem as to which of several data modes it should be in. The MPS, in turn, controls the logic and processing states of the control and conditioning logic (CCL) units, one of which is associated with each science instrument. The MPS also controls the state of a "tree switch," which accesses the analog measurement sensors. Data are then multiplexed, compressed, and routed to the appropriate unit for storage or transmission to Earth.

The central memory (buffer) was sized to allow enough volume for a full TV picture, output buffering, some cruise science storage, and TV data compression. If the tape recorders fail, the buffer still allows a significant imaging experiment and, if TV is not operated during solar occultation at any planet, the buffer can store much of the non-imaging encounter science data.

In data-processing studies, it was decided that a central clock would minimize synchronization problems; spacecraft subsystems should be monitored by the MPS and the data should then be sent to the CCS, rather than the CCS having its own sensors; and ground commands should be distributed to the subsystems independently of the CCS to insure parallel command paths.

Data-compression algorithms are included in the MPS or CCL software so that only significant data will be transmitted to Earth, even though sensors are sampled



TOPS SPACECRAFT IN MOST RECENT CONFIGURATION

Total spacecraft launch weight: 1445 lb.
Total spacecraft power required: 249-439 w, depending on mission phase.
Structure: Central bus; deployable antenna; deployable science and RTG booms.
Radio: Redundant receivers; five S-band transmitters; two X-band transmitters.
Antennas: Two low-gain; one steerable medium-gain; one deployable high-gain.
Data rates: Variable from 131,072 to 8 bps.
Command and control: Onboard decision-making with backup ground control; synchronous spacecraft timing.
Power source: Radioisotope thermoelectric generators (RTGs).
Measurement processing: Programmable sampling and data compression; 512 analog and digital engineering sensors; separate channel for multiplexed science data.
Attitude control: Stabilized in three axes by momentum wheels and hydrazine thrusters.
Propulsion: Hydrazine trajectory-correction engine.
Thermal control: Passive shields, fluid loop, and resistance heaters.
Navigation: Earthbased ranging and doppler tracking; onboard optical measurements for approach guidance.
Data storage: Mass storage (2×10^9 bits) and serial buffer storage (8×10^6 bits).

at a much higher rate. Real-time engineering data gets transmitted to Earth with a minimum of "series hardware" to improve reliability. Programming the data format permits easier mode switching, removing failed sensors from the format, and sampling sensors for interesting or critical data more frequently.

Attitude Control: The three-axis attitude-control subsystem, using biased Sun sensors and a biased Canopus sensor, must point the spacecraft at the Earth and at the south ecliptic pole with a one-sigma accuracy of 0.05 deg. Then the radio-frequency closed-loop tracking system takes over and provides the error signals for fine pointing of the high-gain antenna (and the entire spacecraft) at the Earth to a three-sigma accuracy of 0.05 deg. The attitude-control subsystem must also control the pointing directions of the science scan-platform, the approach guidance sensor scan-platform, and the medium-gain antenna.

Attitude control is accomplished by reaction wheels, and monopropellant hydrazine thrusters are used to unload the reaction wheels periodically when they become saturated. From a system-level tradeoff, reaction wheels were chosen over mass expulsion for attitude control because they reduce the attitude-control-subsystem weight and decrease the number of thruster firings per axis from about 500,000 to 1000 over the duration of a Grand Tour mission. In a similar study, monopropellant hydrazine was chosen over cold nitrogen as a propellant. The hydrazine system proved simpler and lighter, and it uses the same fuel supply as the trajectory-correction motor. Gyros provide attitude control when the spacecraft does not point at the celestial or radio references.

Propulsion: Trajectory-correction maneuvers are planned for 5 to 25 days after launch (one or two, if required) and before and after each planet encounter (one maneuver between 4 and 40 days before and after each encounter). A 25-lb thrust monopropellant-hydrazine engine, restartable and gimbaled, provides a total velocity increment of 220 m/sec for trajectory correction. This is enough for the 9 or 10 corrections that could be required in a four-planet Grand Tour "inside-ring" mission. A 1445-lb spacecraft requires a total impulse of 31,000 lb-sec in this mission.

The propulsion subsystem accelerates the spacecraft a maximum of 0.025 *g*. This keeps bending moments and shear stress low in the long, deployed magnetometer booms. The propulsion subsystem can provide velocity increments as low as 1 m/sec.

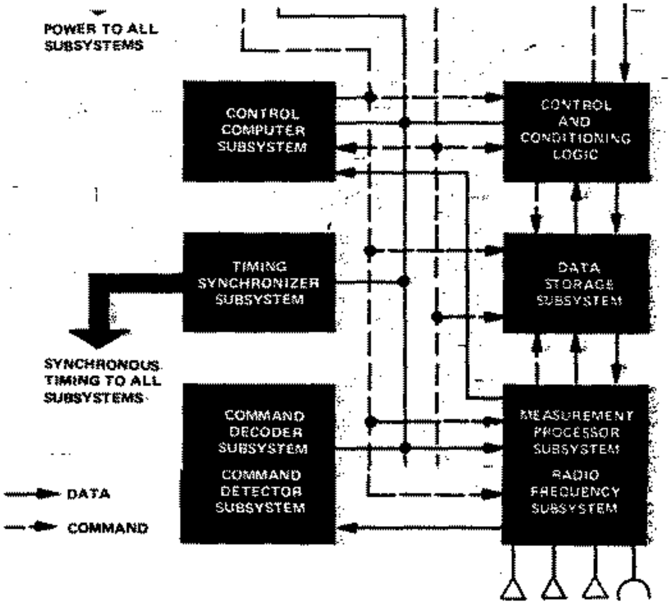
Temperature Control: Because the Sun delivers only 0.1% of the Earth's solar flux to Neptune, an infinitely conductive gray sphere reaches an equilibrium temperature of −370 F there; an infinitely conductive gray flat plate reaches −350 F. (Comparable gray-body equilibrium temperatures at Earth: 40 F for the sphere and 140 F for the flat plate.) The TOPS components obviously must not reach these low temperatures. Being only about 6% efficient in converting thermal to electrical watts, the RTGs offer some 6.8 kw for heating purposes at end of mission. Similarly, most of the electrical power used in the electronic subsystems must be dissipated as heat.

TOPS uses passive thermal control wherever possible. Typical schemes involve thermally actuated louvers to control the heat rejection from the electronic compartment, thermal shields, thermal blankets, and surface finishes. Waste RTG energy in a fluid loop heats the science instruments, which ride the end of a boom. Electrical-resistance heaters handle situations inconvenient for either passive control or rejected RTG heat.

Navigation: Outer-planet mission navigation by the classical techniques of ranging and doppler tracking will be difficult because of the extreme accuracy required, degradation of the usual techniques caused by the long communication distances and signal travel times, and the uncertainties in the ephemerides of the planets. Communication distances up to 4.6-billion km at Neptune mean round-trip signal times of about 8 hr. In addition, accurate control of the flyby trajectory is required because an error of a few kilometers at one planet translates into an error of thousands of kilometers at the next. Consequently, TOPS employs conventional doppler tracking and ranging and an onboard optical sensor for precise navigation in the vicinity of the target planet. The approach-guidance sensor images the target planets' natural satellites and certain stars. This data, combined with conventional tracking information, allows trajectory-correction maneuvers to be computed and executed before and after each planet encounter. This sensor in effect reduces fuel demands for the trajectory correction motor, since better accuracy means fewer and smaller maneuvers. On a four-planet Grand Tour mission inside Saturn's rings, the required total velocity increment drops from 410 to 220 m/sec through the use of an approach guidance sensor.

Concluding Remarks: The TOPS design, although ambitious, is consistent with the technology that can be expected at the time of

BLOCK DIAGRAM



the outer-planet launch opportunities. *In fact, any less-advanced and ambitious spacecraft design would have difficulty meeting the severe mission and environmental constraints.*

The Grand Tour presents a rare opportunity to increase our knowledge of the solar system. The TOPS system aims at maximizing the data to be returned from the outer-planet missions.

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