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VOYAGER MISSION DESCRIPTION*

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Abstract. The Voyager Project, managed by the Jet Propulsion Laboratory, involves the launching of two advanced spacecraft to explore the Jovian and Saturnian systems, as well as interplanetary space. The one-month launch period opens on August 20, 1977, with arrivals at Jupiter in March and July of 1979, and at Saturn in November of 1980 and August of 1981. Gravity-assist swingbys of Jupiter are utilized in order to reduce the launch energy demands needed to reach Saturn. In addition, a gravity-assist targeting option at Saturn will be maintained on the second-arriving Voyager for a possible continuation on to Uranus, with arrival in January of 1986. Flight through the Jovian and Saturnian systems will achieve close to moderate flyby encounters with several of the natural satellites, including special flyby geometry conditions for Io and Titan, as well as an Earth occultation of the spacecraft's radio signal by the rings of Saturn. The purpose of this paper is to describe the Voyager mission characteristics in order to establish a framework upon which to better understand the objectives and goals of the eleven scientific investigations which are described in subsequent papers.

1. Introduction

During the late 1970's, alignment of the outer planets affords a variety of multi-planet launch opportunities. From the standpoint of Jupiter flyby distance, the 1977 opportunity (Bourke *et al.*, 1972; Schurmeier, 1974) is the most favorable for reaching Saturn via a gravity-assist swingby of Jupiter. Two advanced spacecraft will be launched during a one-month launch period which opens on August 20, 1977. Each spacecraft will be launched by a Titan IIIE/Centaur D-IT from Launch Complex 41 at the Air Force Eastern Test Range. Final Earth-departure injection velocity will be delivered by a solid rocket portion of each spacecraft. After solid rocket burnout and jettison, the remainder of each spacecraft, having a mass of approximately 825 kg, begins its cruise to Jupiter.

As shown in Figure 1, each spacecraft will perform a flyby mission through the Jovian and Saturnian systems, including close to moderate flybys of several satellites. Among the satellite encounters, Titan, Io, and Ganymede command the highest priority. Planetary observations and environmental measurements with the Voyager scientific instruments are productive over extended time periods, starting two to three months before planetary encounter and ending about one month after encounter. Measurement sequences are particularly intense during the last day containing planetary encounter, when satellite observations are possible at reduced ranges and when the rapidly changing planetary viewing geometry and greater fields-and-particles effects occur. A variety of science data rates are available during the mission, and range from several hundred bits/sec at S-band frequency during cruise

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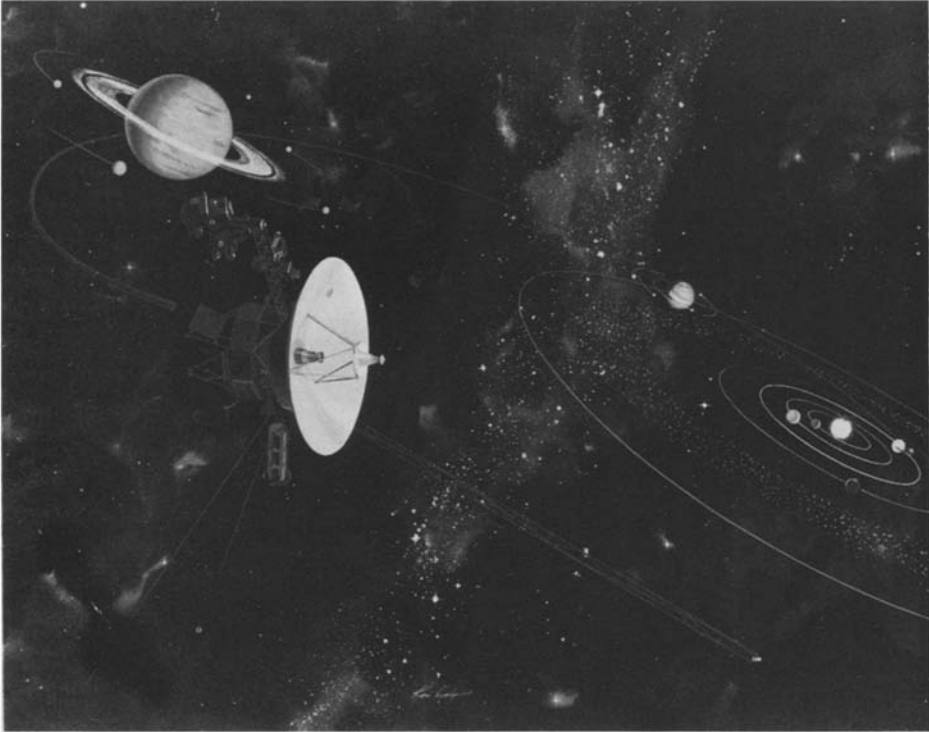


Fig. 1. Voyager journey to the giant planets. An artist's rendering depicts one of two Voyager spacecraft pointing at Earth for data return following the Saturn flyby. The use of Jupiter gravity assist has reduced the launch energy requirements needed to reach Saturn. Four trajectory correction maneuvers are planned on each planet-to-planet leg of the journey.

to 115.2 kilobits/sec at X-band frequency during most of the Jupiter encounter periods.

The remainder of this paper describes the overall mission and science objectives, the spacecraft capabilities, the trajectory design characteristics, the navigation performance, and selected features of the science observations and measurement sequences. Numerous mission design tradeoffs (Kohlhase, 1977) were necessary to enable selection of a preferred pair of trajectories out of the huge number of possible candidates (Beerer *et al.*, 1973; Penzo, 1974). A discussion of this selection process will not be presented in this paper in order to allow more time to describe the characteristics of the nominal mission that resulted from the selection process.

2. Mission Objectives

The Voyager mission objectives are to conduct exploratory investigations of the Jupiter and Saturn planetary systems and of the interplanetary medium from Earth to Saturn. Primary emphasis will be placed on comparative studies of the two

systems, including their environments, atmospheres, and body characteristics. Special trajectory targeting will allow detailed investigations of one or more satellites of each planet, including Io and Titan, and of the rings of Saturn. In addition, a Uranus option possibility is being maintained on the second-arriving spacecraft at Saturn, but would only be considered if the first-arriving spacecraft had first secured the key Saturn-related science objectives and if the second-arriving spacecraft was judged to have adequate expendables and operational health to undertake the additional four years of flight from Saturn to Uranus. The large complement of scientific instruments aboard each Voyager allows the investigation of particles and fields as well as broad coverage of the electromagnetic spectrum. Table I lists the instrument teams together with their Principal Investigator and major experiment objectives. The teams themselves directly involve nearly 100 science investigators.

Jupiter, with 13 known satellites, and Saturn, with 10 known satellites and unique rings, provide many targets of interest (Table II); certainly too many to investigate at close range for the two Jupiter and two Saturn planetary flybys available with this mission. Thus, very early in the mission design, the Science Steering Group (SSG, composed of the Principle Investigators and chaired by E. C. Stone of Caltech) decided that, in addition to the planets themselves, emphasis should be given to the Galilean satellites, particularly Io and Ganymede, and to Titan and Saturn's rings. In summary, the major objectives (not prioritized) are to investigate:

- (a) The Jupiter and Saturn gravitational fields and satellite masses,
- (b) the dynamics of the Jupiter and Saturn atmospheres,
- (c) the Jupiter and Saturn magnetospheres, i.e., the magnetic fields and charged particle environments and wave particle interactions,
- (d) the interaction of the satellites with these media, particularly Io,
- (e) the energy balance of Jupiter and Saturn,
- (f) the atmospheres, surface composition and features of Titan, the Galilean satellites, and other satellites, as available,
- (g) Jupiter's Great Red Spot,
- (h) Saturn's rings,
- (i) the interplanetary and interstellar media, and
- (j) the Uranus planetary system, should conditions allow the option to be exercised.

It is primarily these objectives that determine the nature of the planetary flybys. Several of these objectives are related to the planets and to the planetary and interplanetary media and can be met simply by achieving a moderately close flyby of the planets, say 5–10 planetary radii, and are independent of the time of arrival at the planet, the approach distance, and the trajectory inclination. Other objectives, particularly those for the satellites and the rings, are quite dependent upon the arrival time, distance, and orbit inclination. Based upon these science objectives, and the ability to shape the flybys of Jupiter and Saturn, it is possible to provide the following characteristics for the Voyager trajectories:

- (a) Earth and Sun occultations of Jupiter and Saturn on both trajectories,

TABLE I
Scientific investigations for the Voyager mission

EXPERIMENT (PRINCIPAL INVESTIGATOR)	ABBREVIATION	PRIMARY EXPERIMENT OBJECTIVES
IMAGING SCIENCE (B.A. Smith, Arizona)	ISS	IMAGING OF PLANETS AND SATELLITES AT RESOLUTIONS AND PHASE ANGLES NOT POSSIBLE FROM EARTH. ATMOSPHERIC DYNAMICS AND SURFACE STRUCTURE
INFRARED RADIATION (R.A. Hanel, GSFC)	IRIS	ENERGY BALANCE OF PLANETS. ATMOSPHERIC COMPOSITION AND TEMPERATURE FIELDS. COMPOSITION AND PHYSICAL CHARACTERISTICS OF SATELLITE SURFACES AND SATURN RINGS
PHOTOPOLARIMETRY (C.F. Lillie, Colorado)	PPS	METHANE, AMMONIA, MOLECULAR HYDROGEN, AND AEROSOLS IN ATMOSPHERES. COMPOSITION AND PHYSICAL CHARACTERISTICS OF SATELLITE SURFACES AND SATURN RINGS
ULTRAVIOLET SPECTROSCOPY (A.L. Broadfoot, KPNO)	UVS	ATMOSPHERIC COMPOSITION INCLUDING THE HYDROGEN TO HELIUM RATIO. THERMAL STRUCTURE OF UPPER ATMOSPHERES. HYDROGEN AND HELIUM IN INTERPLANETARY AND INTERSTELLAR SPACE
RADIO SCIENCE (V.R. Eshleman, STANFORD)	RSS	PHYSICAL PROPERTIES OF ATMOSPHERES AND IONOSPHERES, PLANET AND SATELLITE MASSES, DENSITIES, AND GRAVITY FIELDS. STRUCTURE OF SATURN RINGS
COSMIC RAY PARTICLES (R.E. Vogt, CALTECH)	CRS	ENERGY SPECTRA AND ISOTOPIC COMPOSITION OF COSMIC RAY PARTICLES AND TRAPPED PLANETARY ENERGETIC PARTICLES
LOW ENERGY CHARGED PARTICLES (S.M. Krimigis, JHU/APL)	LECP	ENERGY SPECTRA AND ISOTROPIC COMPOSITION OF LOW ENERGY CHARGED PARTICLES IN PLANETARY MAGNETOSPHERES AND INTERPLANETARY SPACE
MAGNETIC FIELDS (N.F. Ness, GSFC)	MAG	PLANETARY AND INTERPLANETARY FIELDS
PLANETARY RADIO ASTRONOMY (J.W. Warwick, Colorado)	PRA	PLANETARY RADIO EMISSIONS AND PLASMA RESONANCES IN PLANETARY MAGNETOSPHERES
PLASMA PARTICLES (H.S. Bridge, MIT)	PLS	ENERGY SPECTRA OF SOLAR-WIND ELECTRONS AND IONS, LOW ENERGY CHARGED PARTICLES IN PLANETARY ENVIRONMENTS, AND IONIZED INTERSTELLAR HYDROGEN
PLASMA WAVES (F.L. Scarf, TRW)	PWS	ELECTRON DENSITIES AND LOCAL PLASMA WAVE-CHARGED PARTICLE INTERACTIONS IN PLANETARY MAGNETOSPHERES

(b) passage through the Io flux tube (defined in Figure 2) at a distance of about 20 000 km,

(c) close to moderate encounters with Europa, Ganymede, and Callisto (50 000–250 000 km),

TABLE II

Target Body Selected Physical Characteristics. Values in this table have been taken from a single reference source, Newburn and Gulkis (1975), and may not reflect more recent data such as that shown in parentheses for selected parameters. These physical data are provided only as a convenient reference of the major parameters for the bodies of primary interest. No values are given for the temperatures of the Galilean satellites because of the uncertainties quoted in the reference. The rotational periods of the satellites assume synchronous rotation about the primary.

	DISTANCE FROM PRIMARY (AU or PLANET RADIUS)	EQUATORIAL RADIUS (km)	MASS (EARTH = 1)	MEAN DENSITY (gm cm ⁻³)	TEMPERATURE (°K)		ROTATION PERIOD (hr)
					EQUILIBRIUM	MEASURED	
JUPITER	5.20 AU	71,600	318	1.31	105	134	9.9
Io	5.95 R _J	1,820	0.015	3.54	-	-	42.4
EUROPA	9.48 R _J	1,490	0.008	3.51	-	-	85.2
GANYMEDE	15.12 R _J	2,635	0.025	1.94	-	-	171.7
CALLISTO	26.59 R _J	2,500	0.018	1.63	-	-	400.5
SATURN	9.54 AU	60,000	95	0.70	71	97	10.2
TITAN	20.38 R _S	(2,900)	0.023	2.34	101	132	382.7
URANUS	19.18 AU	25,900	14.6	1.21	55	55	(15-25)

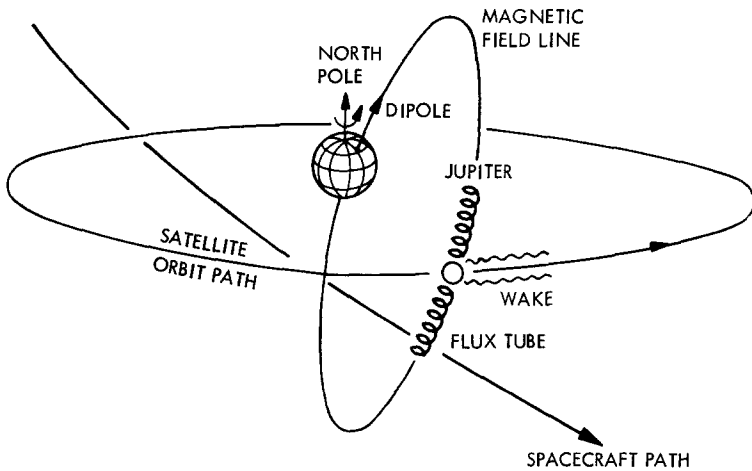


Fig. 2. Jupiter flux tube and wake diagram. The motion of a Galilean satellite through the Jovian environment can produce such interesting geometrical regions as a 'flux tube', where the satellite interrupts the flow of charged particles along the magnetic field lines, and a 'wake' region, which arises from the satellite interference with the co-rotating planetary plasma.

(d) passage through the Callisto Earth and Sun occultation regions on selected launch days,

(e) close encounter with Titan (5000–15 000 km) including Earth and Sun occultations and wake passage,

- (f) close to moderate encounters with several of Saturn's satellites,
- (g) occultation of the Earth by all of Saturn's rings.

At Jupiter, it is not possible to provide all of these characteristics with a single flyby. Therefore, the trajectories for each Voyager have been designed to be complementary. For example, an Io flux tube passage is planned for the first-arriving spacecraft, and a Ganymede close encounter or a Callisto Earth and Sun occultation is planned for the second-arriving spacecraft. The two nominal trajectories are also well designed in the event that one spacecraft should not reach Jupiter, since each trajectory has good encounters with three of the four Galilean satellites. At Saturn, a close Titan encounter with Earth and Sun occultations is possible on both trajectories, with the Titan encounter occurring three-quarters of a day prior to Saturn periapsis passage. The capability also exists on both trajectories to achieve acceptable ring occultations by the Earth. There are two reasons for this redundancy. The first is that, if Voyager 1 fails prior to arriving at Saturn, then Voyager 2 can still realize the best overall science of the Saturnian system. The second reason is that, in the event that Voyager 1 successfully completes its planned objectives, then Voyager 2 can be flown past Saturn through a gravity-assist corridor so that it may continue on to the planet Uranus. It should be noted that, if the Uranus option is selected, the Saturn flyby cannot provide a close encounter with Titan, nor a ring occultation by the Earth. But the Uranus option would only be exercised if these key objectives had already been secured by Voyager 1.

3. Spacecraft Description

The use of a Voyager spacecraft (Draper *et al.*, 1975), with its greater amount of power, onboard computer capability, and precision pointing, permits the use of remote sensing instrumentation which is more sophisticated than that of the Pioneer spin-stabilized spacecraft (Fimmel *et al.*, 1976). As shown in Figures 3 and 4, instruments to support eleven scientific investigations will be carried aboard each spacecraft. The science payload mass is approximately 105 kg and consumes 90 W for electronics and 10 W for heating. Included are medium and high resolution television cameras, spectrometers and photometric instruments for atmospheric and other analyses, radio receivers to measure planetary radio emissions and plasma waves, numerous sensors to measure fields and charge particles, and a high precision Earth/spacecraft radio link for communication, navigation, and science purposes. Visual surveys, spectral scans, temperature measurements, mass and size determinations, and radio probing of possible ionospheres and atmospheres will be performed. The narrow-angle television camera will also be used for extremely precise navigation (Duxbury *et al.*, 1974) during planetary approach by permitting calculation of the spacecraft trajectory based upon pictures of the planetary satellites against a star background.

In order to remain functional for the nearly four-year journey to Saturn, the Voyager subsystems have been designed with high reliability components and

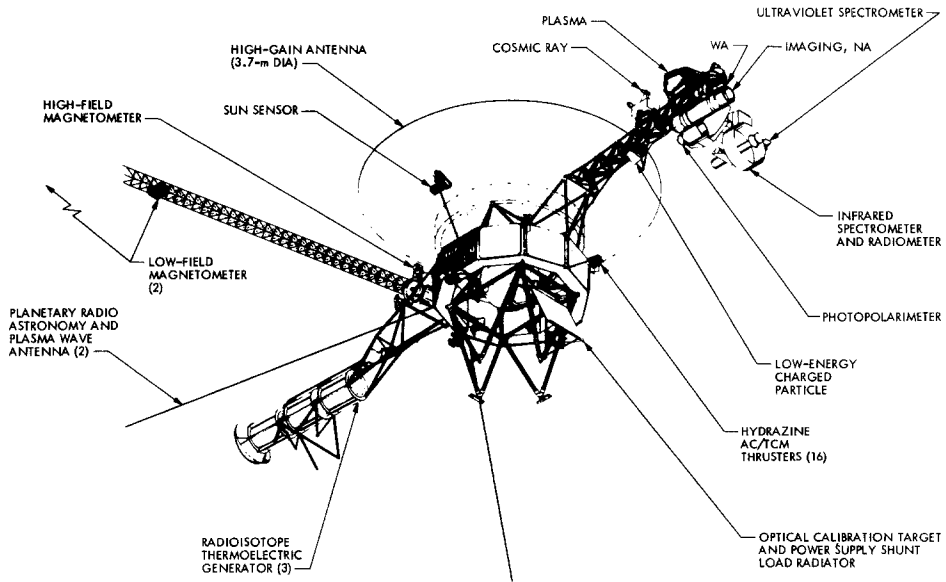
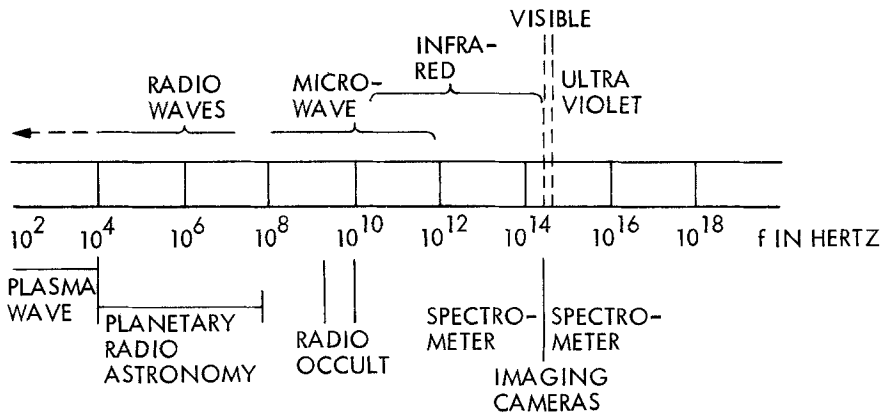


Fig. 3. Voyager spacecraft. An advanced three-axis attitude stabilized spacecraft for exploration of the outer planets. Key features include: radioisotope power sources, subsystem redundancy, onboard computer control and fault detection, 3.7 m high-gain antenna with S-band and X-band telecommunications, accurate scan platform pointing for remote-sensing, and instruments for conducting eleven different scientific investigations. Total spacecraft mass is approximately 825 kg, with total power available of approximately 400 W.

extensive redundancy. In addition, an onboard computer provides for selected fault detection and corrective action to place the spacecraft in a safe state for ground-based follow-up. As a result of the severe Jupiter radiation environment measured by the Pioneer 10 and 11 spacecraft (Fimmel *et al.*, 1976), appropriate radiation hardening, parts selection, circuit design evaluation, and shielding actions were taken to strengthen the Voyager resistance to radiation effects.

Because of the great distance of Saturn from the Sun, it is no longer practical to use solar cells. Instead, plutonium-oxide-fueled radioisotope thermoelectric generators are used to convert 7200 W of heat to the nearly 390 W of electrical power needed during Saturn encounter. During cruise, attitude control electronics utilize Sun and star tracker error signals to maintain three-axis orientation by firing small thrusters. An integrated hot gas (monopropellant hydrazine) propulsion subsystem with sixteen small thrusters is used for both attitude control and trajectory correction maneuvers. Precision pointing of the scan platform is possible under both celestial and inertial attitude control modes.

The science boom provides mounting for the science scan platform and, inboard of the platform, the Low Energy Charged Particle, Cosmic Ray, and Plasma instruments. The two-degree-of-freedom scan platform supports the Ultraviolet Spectrometer, Infrared Interferometer Spectrometer and Radiometer, Photopolarimeter, and the wide and narrow-angle cameras and control electronics of the Imaging



THE STABLE ORIENTATION, ACCURATE INSTRUMENT POINTING CAPABILITY AND FLEXIBLE DATA MANAGEMENT PERMIT:

- LONG EXPOSURE TO INTEGRATE LOW LEVEL RADIATION
- HIGH SPATIAL/SPECTRAL RESOLUTION
- SELECTIVE VIEWING OF PLANET AND SATELLITE REGIONS
- SIMULTANEOUS MEASUREMENT SEQUENCES
- HIGH DATA RATE, LARGE CAPACITY DATA STORAGE



Fig. 4. Remote sensing capability of Voyager science instruments. Insert shows scan platform optical instruments and thermal blankets.

Science Subsystem. A Brewster plate is mounted on the bus for polarimetric calibration of the Photopolarimeter, and a diffuse calibration target for scan platform instruments is positioned on the back side of the shunt radiator assembly of the power subsystem.

Uplink communications use an S-band link at 2115 MHz and can be received over the spacecraft LGA or HGA. Downlink communications can be at 2295 MHz S-band over the LGA or HGA, or at 8415 MHz X-band over the HGA. Telemetry is collected by the Flight Data Subsystem (FDS), formatted, and routed to the Modulation Demodulation Subsystem (MDS) for impression on the rf carrier, or to the Digital Tape Recorder (DTR) for later playback. The four basic types of telemetry data consist of engineering only, cruise science plus engineering, encounter general science plus engineering (GS & E), and imaging plus GS & E. Table III summarizes the FDS data modes, contents, and data rates. In general, data rates of 2560 bps or less are returned at S-band frequency, and data rates from 7.2 to 115.2 Kbps are returned at X-band frequency. Science data are digitized within each instrument subsystem and presented to the FDS for formatting.

TABLE III
Voyager data modes summary

DATA TYPE	NUMBER OF FORMATS	FORMAT CONTENTS	DATA RATES, bps
ENGINEERING ONLY	11	LAUNCH DATA	1200 (40 bps SUBSET OVER CENTAUR TELEMETRY LINK)
		CRUISE	40
		TCM ENGINEERING	1200 RECORDED BY DTR
		ENCOUNTER	40
		LOW RATE MEMORY READOUTS (CCS, FDS, AACS)	40
		HIGH RATE MEMORY READOUTS (CCS, FDS, AACS)	1200
		HIGH RATE ENGINEERING	1200
CRUISE SCIENCE PLUS ENGINEERING	9	CRUISE SCIENCE DATA FROM ALL INSTRUMENTS EXCEPT ISS, IRIS, PLUS HOUSEKEEPING ENGINEERING	2560, 1280, 640, 320, 160, 80 (FORMATS FOR 40, 20, 10 bps RATES WILL BE DEVELOPED AFTER POST-SATURN MISSION APPROVAL IS OBTAINED)
ENCOUNTER GENERAL SCIENCE PLUS ENGINEERING	9	STANDARD ENCOUNTER GENERAL SCIENCE PLUS ENGINEERING	7200 REAL TIME OR REAL TIME PLUS RECORDED (ACTUAL DATA RATE IS 3600 bps WHICH IS GOLAY CODED TO 7200 bps)
		SPECIAL FORMATS	
		PLASMA WAVE	115,200
		PLANETARY RADIO	115,200
		ASTRONOMY	
		OCCULTATION	7,200
		PLAYBACK FORMATS	
		PLAYBACK PLUS STANDARD	67,200
		ENCOUNTER	44,800
		PLAYBACK ONLY	29,866 2/3
			21,600
			7,200
ENCOUNTER IMAGING, GENERAL SCIENCE, AND ENGINEERING	13	ENCOUNTER GENERAL SCIENCE PLUS ENGINEERING WITH FULL RESOLUTION IMAGING	115,200 REAL TIME OR 115,200 OR 7,200 WITH 115,200 DATA RECORDED BY DTR
		FULL RESOLUTION EDITED	
		3/4 FRAME	89,600
		1/2 FRAME	67,200
		1/3 FRAME	44,800
		1/5 FRAME	29,866 2/3
		1/10 FRAME (SKIP SLIDE)	19,200
		SLOW SCAN IMAGING	
		2:1 SLOW SCAN	67,200
		3:1 SLOW SCAN	44,800
		5:1 SLOW SCAN	29,866 2/3
		10:1 SLOW SCAN	19,200
		SLOW SCAN EDITED	
		5:1 SLOW SCAN, 1/2 FRAME	19,200

Science data return rates can range from a maximum of 115.2 Kbps down to as little as a few tens of bits/sec, depending upon the configuration of the telecommunications system. Link performance is governed by such configuration parameters as S-band vs X-band frequency, 26 m vs 64 m Deep Space Station (DSS) receiving antenna diameter, spacecraft transmitter low vs high-power mode (from 6 to 28 W), and Earth-to-spacecraft range. In addition, performance at X-band is particularly sensitive to the amount of moisture in the path of the radio signal. Since weather is probabilistic in nature, even given the seasonal and diurnal conditions, it is not possible to state deterministically the performance at X-band. As a general rule, however, the poorest X-band performance is expected to occur during the low elevation angle overlap between the DSS-43 (Australia) and DSS-63 (Spain)

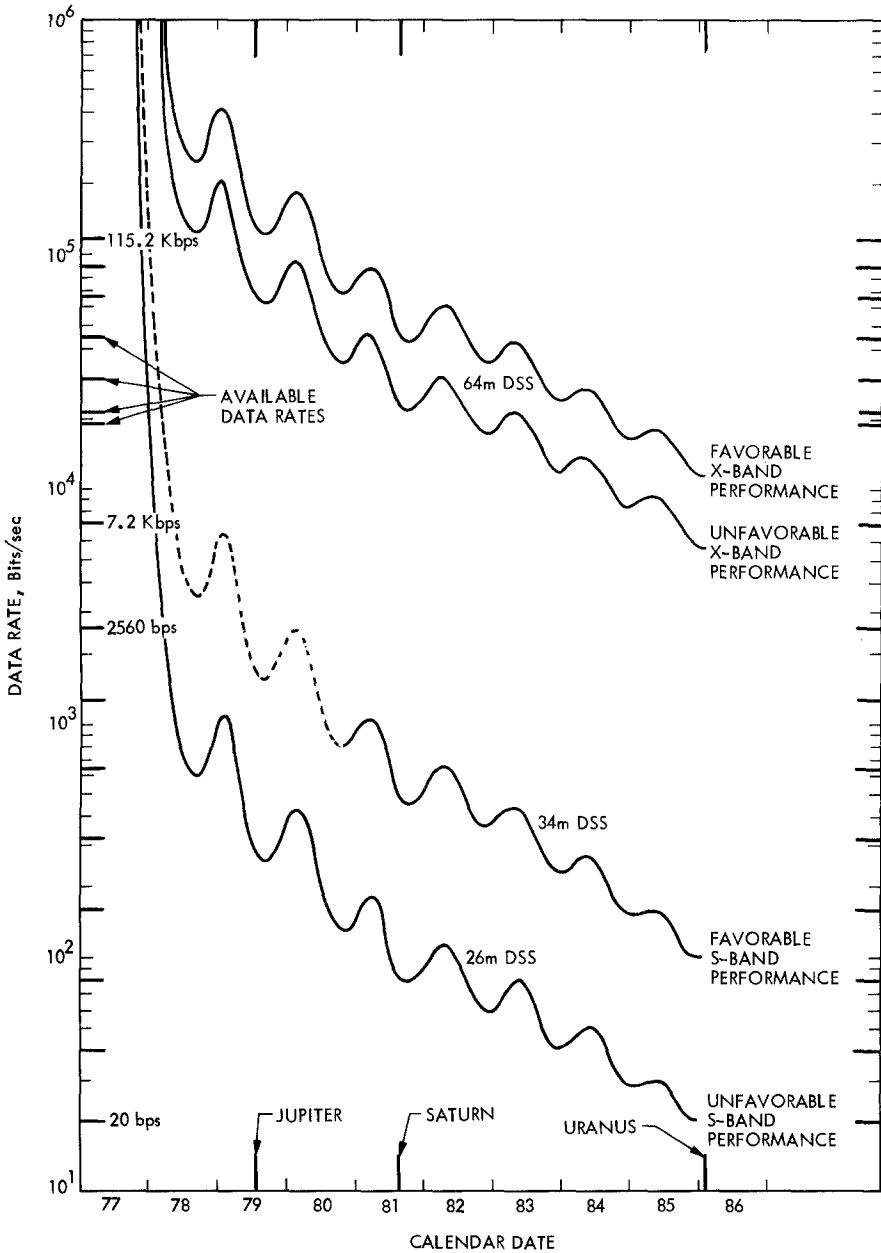


Fig. 5. Voyager data rate capability envelope for JSX trajectory. Several assumptions were employed in calculating the above data rate performance boundaries. All curves are based upon the appropriate Voyager transmitter at high power over the high-gain antenna. Unfavorable performance is at the -1.28σ level (0.9 probability of performance this good or better), and the dashed curve indicates conversion of one 26 m DSS subnet to 34 m by 10/1/1980. Performance oscillations are due to the yearly Earth orbit range effects, and performance for the JST trajectory (not shown) is comparable to or better than that for JSX, particularly at Jupiter encounter. Available spacecraft discrete data rates have been indicated on the ordinate.

tracking stations, while the best performance is expected near the center of the DSS-14 (California) tracking pass. In order to envelope the data rate performance anticipated through the mission, Figure 5 has been constructed to show both the conservative and the optimistic performance boundaries for the JSX trajectory. The actual operating point will fall inside the boundaries shown, but a more comprehensive assessment is beyond the scope of this paper. Data rate performance for the earlier arriving JST trajectory is considerably better at Jupiter encounter due to the reduced Earth Jupiter range.

Finally, the spacecraft Attitude and Articulation Control Subsystem (AACS) and the Computer Command Subsystem (CCS) each play a key role in determining the science pointing and instrument sequencing capabilities. In addition to providing three-axis attitude control, the AACS provides articulation of the science scan platform about azimuth and elevation axes. Available slewing rates about each axis are 0.096 mr/sec (very low rate), 1.45 mr/sec (terminal rate), 5.82 mr/sec (low rate), and 17.45 mr/sec (high rate). Settling times from the end of each slew until reaching an effective rate of $20 \mu\text{r}/\text{sec}$ can range from 30 sec (1.45 mr/sec slew) to 170 sec (17.45 mr/sec slew). Platform pointing control of 2.5 mr per axis, 3σ , is expected relative to celestial references, with a platform pointing knowledge from telemetry data of 1.5 mr per axis, 3σ . Control of the spacecraft is normally accomplished by onboard commands issued by the CCS in response to stored program instructions. The CCS contains two identical nonvolatile 4096 word by 18 bit memories within each of which about 2810 words are for fixed spacecraft routines, leaving about 1286 words for science sequencing functions. The total length of time for which one CCS sequencing memory load can continue to operate the science related functions obviously depends upon the science activity level. Time durations range from as long as 28 days cruise to slightly less than one day during the high-activity period near planetary closest approach.

4. Trajectory Design

Two Voyager spacecraft will be launched during a one-month launch opportunity which opens on August 20, 1977. This opportunity, discussed by Bourke *et al.* (1972) and Schurmeier (1974), was originally identified with a special alignment of the outer planets allowing a spacecraft to use multiple gravity assists to go from Jupiter to Saturn, then to Uranus, and finally to Neptune, assuming that the appropriate inflight navigation trajectory corrections are applied. The unique Jupiter and Saturn alignment, which is being used in the 1977 mission, will not occur again until 1997. Although a 1978 launch is possible, launch in 1977 is optimum for investigation of Jupiter and the Galilean satellites.

The requirement for the trajectory to continue on to Saturn limits the design of the Jupiter encounter. Specifically, the trajectory must remain close to the ecliptic plane resulting in possible inclinations to Jupiter's equator of 6–10 deg. The arrival date at Jupiter can be varied, with the result that the distance of closest approach to each of

the Galilean satellites will vary. Thus, there will exist a unique arrival time for each satellite, and each orbit of that satellite. The Jupiter arrival times for these closest satellite approaches, in addition to the times for satellite flux tube passages, wake passages, and Sun and Earth occultations, have been computed for the available span of Jupiter arrival dates. The existence and characteristics of these events will also vary with the Earth launch date.

At Saturn, the flyby conditions will be unrestricted, unless the spacecraft is to continue on to Uranus, in which case the trajectory will be constrained to remain close to the ecliptic plane. Here the mission objectives of achieving an Earth and Sun occultation of the rings, and a close encounter with Titan, are the main considerations that shape the flyby trajectory. Concern that Saturn's rings may extend considerably beyond the A ring and impose a possible hazard to the spacecraft (Michaux, 1975), as well as the possibility of a non-negligible Saturn radiation environment, motivates the choice of encountering Titan before rather than after arriving at Saturn and the rings. In addition, the trajectory is designed to include occultations of the Earth and Sun by Titan and a passage through Titan's wake.

A final design consideration requires selecting a particular location of Titan in its orbit so that the post-Titan trajectory will achieve an acceptable occultation of the Earth by all of the rings of Saturn, as needed by the Ratio Science Team. Unlike the Jupiter trajectory design, the design at Saturn is essentially independent of the Earth launch date.

The accomplishment of these objectives at Saturn will require precise timing, on the order of tens of minutes. Thus, the planned arrival time at Saturn is nearly fixed, at least for each orbit of Titan. At Jupiter, satisfying the Galilean satellite objectives also requires precise timing. One property of ballistic gravity-assist trajectories is that fixing the launch date and the time of arrival at one other planet, say Saturn, will determine the arrival time at the intermediate planet, in this case Jupiter. Some variation in timing can be achieved with the use of propulsion, and significant propulsion is planned to be used after the Jupiter encounter to achieve the proper timing at Saturn. Thus, to a limited extent, favorable timing conditions at Jupiter can be matched with the desired Titan encounter timing at Saturn.

Satisfying the timing requirements at Jupiter and Saturn does not imply that all science objectives can be met on a single Voyager trajectory. In particular, early arrivals at Jupiter, no later than April 4, 1979, are required for close encounters with Io and passage through the Io flux tube. Later arrivals place Jupiter closest approach distances beyond Io's orbit. On the other hand, later arrivals at Saturn, and hence Jupiter (after June 15, 1979), are needed to maintain the Uranus option and remain outside the visible rings during the Saturn gravity-assist flyby. Earlier arrivals at Saturn would require passage through the visible rings to continue on to Uranus. Thus, the Voyager trajectory space divides into two distinct sets: that which can provide a close Io encounter, and that which can maintain the Uranus option without requiring a passage through the visible rings at Saturn. This latter set, since it requires more distance passages at Jupiter (greater than 8.6 Jupiter radii), may be considered

to be more conservative in the sense that the spacecraft would receive a lesser radiation dose during the Jovian flyby. The Io encounter set comes appreciably closer to Jupiter (4.5 to 6.0 Jupiter radii); however, the Voyager spacecraft have been designed to have a good probability of withstanding the higher radiation doses estimated for these closer Jovian flybys.

Each set contains several possible trajectories (10 to 20) for each launch date. For the Io encounter set, trajectory differences at Jupiter would involve how closely Io and other Galilean satellites are encountered. For the Uranus option set, with the primary Galilean satellite being Ganymede or Callisto, the differences would be in their flyby characteristics in addition to the encounter distances to the other Galilean satellites. At Saturn, with both sets providing the desired Titan characteristics, the differences would be the approach distances to the other Saturnian satellites, as well as the quality of the Earth occultation by the rings.

Presented with data describing the trajectory characteristics of these two sets, the SSG and the Project have chosen those candidates which became part of the overall launch strategy. This strategy identifies the trajectory which will be chosen for each launch day and, since there are two launches, the choice for the second will depend upon when the first is launched, and its success or failure. No attempt will be made here to describe the launch strategy and the trajectory choices on a day-by-day basis throughout the one-month launch opportunity. Instead, detailed descriptions will be given of the two nominal trajectories which have the highest probabilities of being flown. Thus, for the launch strategy developed, the first launch will be August 20 on a Uranus option trajectory. It has been designed JSX, where the X may be replaced by *U* if the Uranus option is exercised, or by *T* if a close Titan encounter is chosen. The second launch is planned for September 1 on an Io-intensive trajectory and is called JST, where the T stands for Titan. The JST trajectory, as discussed earlier, will arrive at Saturn first and will not have the option to go to Uranus. The Voyager 1 spacecraft will fly the JST trajectory, and Voyager 2 will fly the JSX trajectory.

Table IV summarizes the major characteristics of the JSX and JST nominal trajectories. Figure 6 shows the heliocentric view of the trajectories, and Figures 7–10 illustrate the Jovian and Saturnian encounters. At Jupiter, close to moderate encounters (22 000 to 201 000 km) with all the Galilean satellites will be obtained. For the narrow angle imaging system, this implies a resolution of 4 km or better. In addition, Table IV indicates that Ganymede and Callisto are encountered before Jupiter on JSX and after Jupiter on JST. Thus, assuming that the satellites are in synchronous rotation like Earth's moon, these satellites will present different faces to Voyager on each encounter. The closest Galilean encounters are for Io on JST (22 000 km) which includes a passage through the Io flux tube, and for Ganymede on JSX (55 000 km).

At Saturn, the JST trajectory will arrive first and encounter Titan 18 hr before Saturn. The Titan flyby has been shaped to have a close encounter distance of 7000 km followed by Earth and Sun occultations by Titan. This encounter distance has been chosen to allow the closest possible approach to Titan without causing the

TABLE IV

Voyager standard trajectory characteristics. This table provides the launch dates, planet encounter dates, and the major encounter characteristics for the nominal Voyager JST and JSX trajectories. Obvious abbreviations have been used for the satellites of Jupiter and Saturn. For each encounter, only the closest approach distances (from target center) and times for those satellites are listed for which the closest approach distance is within 10^6 km. Note that, for JSX, the Jupiter encounter characteristics are identical for both the Titan and Uranus options. This implies that the option choice need not be made until after Jupiter encounter. The symbols R_J and R_S indicate that the distance units are in terms of the Jupiter and Saturn radii, respectively (see Table II). The superscript cross attached to some Saturn satellite abbreviations indicates that the satellite and/or spacecraft is in Earth or Sun occultation by the planet at the satellite closest approach time. For JSX (to Uranus), the Uranus encounter date is January 30, 1986.

TRAJECTORY	JSX (TO TITAN)	JSX (TO URANUS)	JST
LAUNCH DATE	AUGUST 20, 1977	AUGUST 20, 1977	SEPTEMBER 1, 1977
JUPITER ARRIVAL DATE	JULY 9, 1979	JULY 9, 1979	MARCH 5, 1979
CLOSEST APPROACH TIME	22:30 GMT	22:30 GMT	12:04 GMT
CLOSEST APPROACH RADIUS	$10.0 R_J$	$10.0 R_J$	$4.9 R_S$
SATELLITE ENCOUNTERS	C, G, E, A (AMALTHEA)	C, G, E, A	A, I, E, G, C
CLOSEST APPROACH TIME (E + hrs)	-34.2, -15.3, -4.8, -2.56,	-34.2, -15.3, -4.8, -2.56	-5.7, 3.1, 5.3, 14.2, 29.1
CLOSEST APPROACH RADIUS (10^3 km)	220, 55, 201, 550	220, 55, 201, 550	415, 22, 733, 115, 124
JUPITER COMMUNICATION DISTANCE AND ONE WAY COMMUNICATION TIME	6.2 AU, 52 min.	6.2 AU, 52 min.	4.6 AU, 38 min.
OCCULTATIONS BY JUPITER	EARTH, SUN	EARTH, SUN	EARTH, SUN
POST JUPITER Δv (NON-STATISTICAL)	60 m/s	60 m/s	100 m/s
SATURN ARRIVAL DATE	AUGUST 27, 1981	AUGUST 27, 1981	NOVEMBER 13, 1980
CLOSEST APPROACH TIME	11:50 GMT	11:50 GMT	0:16 GMT
CLOSEST APPROACH RADIUS	$3.4 R_S$	$2.7 R_S$	$3.3 R_S$
SATELLITE ENCOUNTERS	H, T, R, Te, M [†] , E [†] , D	T, R, Te, E, M [†] , D [†]	T, Te, M [†] , E, D [†] , R, H
CLOSEST APPROACH TIME (E + hrs)	-24.5, -22.7, -8.2, -4.1, 1.8, 2.1, 4.9	-22.9, -7.8, -3.7, 0, 1.2, 1.7	-18.1, -1.6, 1.9, 2.0, 4.1, 6.7, 17.0
CLOSEST APPROACH RADIUS (10^3 km)	869, 15, 199, 150, 116, 102, 91	353, 254, 159, 94, 33, 196	7, 414, 96, 229, 139, 59, 889
SATURN RADIUS AT RING PLANE CROSSING	$5.7 R_S$	$2.9 R_S$	$7.0 R_S$
OCCULTATIONS BY SATURN	EARTH, SUN	EARTH, SUN	EARTH, SUN
OCCULTATIONS BY RINGS	EARTH (A, B, C, D), SUN (A, B)	NONE	EARTH (A, B, C, Q), SUN (A, B)
OCCULTATIONS BY SATELLITES	EARTH, SUN (BY TITAN)	NONE	EARTH, SUN (BY TITAN)
SATURN COMMUNICATION DISTANCE AND ONE WAY COMMUNICATION TIME	10.4 AU, 87 min.	10.4 AU, 87 min.	10.2 AU, 85 min.

navigation errors and Titan perturbation uncertainties to jeopardize subsequent satellite viewing from pre-stored pointing sequences. Other satellites encountered within 200 000 km are Mimas, Dione, and Rhea. Finally, Figure 11 illustrates the JST trajectory as seen from Earth, showing entry and exit occultations of Saturn's atmosphere, as well as an outbound occultation of Saturn's rings following a brief planet-ring gap passage period.

The JSX trajectory, which will arrive at Saturn nine months after JST, can continue on to Uranus, assuming a successful JST encounter at Saturn. This JSX option will not encounter Titan closely nor provide an Earth occultation by the rings. It will provide, however, encounters of less than 200 000 km with Tethys, Enceladus, Mimas, and Dione. If the Uranus option is not chosen, then the Titan encounter will

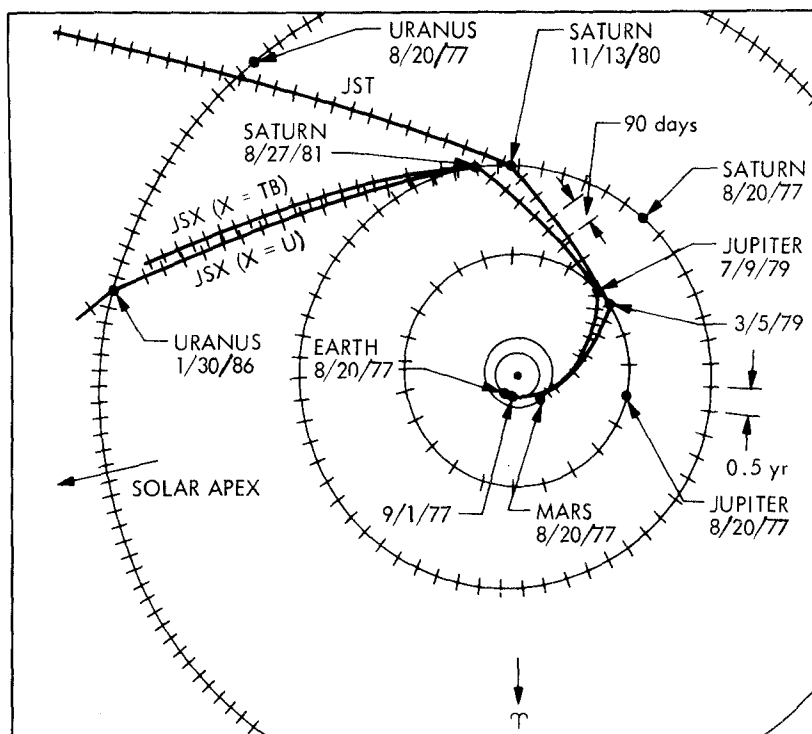


Fig. 6. Voyager heliocentric trajectories. This view from the ecliptic north pole shows the planetary orbits of Earth through Uranus, together with the JST and JSX trajectories. Past Saturn, the JST trajectory rises considerably out of the ecliptic due to the requirement to encounter Titan before Saturn periapsis passage. The two options for JSX are shown, with the trajectory remaining close to the ecliptic if the Uranus option is chosen ($X=U$), and rising out of the ecliptic if the Titan encounter is chosen ($X=TB$). The arrow for the solar apex points approximately in the direction in which the solar system is moving relative to the interstellar medium.

be retargeted for a 15 000 km closest approach distance together with Earth and Sun occultations. Past Saturn, as shown in Figure 6, both trajectories head in the general direction of the solar apex at a rate of about 3 AU per year.

5. Navigation Capabilities

The navigation function employs a combination of radiometric tracking data, approach optical data, and *a priori* ephemeris knowledge, together with the spacecraft trajectory correction capability, to direct the Voyagers onto the desired flyby trajectories, and to provide knowledge of the actual trajectories achieved. The navigation process (Hildebrand *et al.*, 1973; Jacobson *et al.*, 1976; McKinley *et al.*, 1976) is complex and will not be described in this summary paper. However, the estimated navigation accuracy capabilities are very relevant to the science objectives of delivering the instrument fields-of-view to the desired target areas.

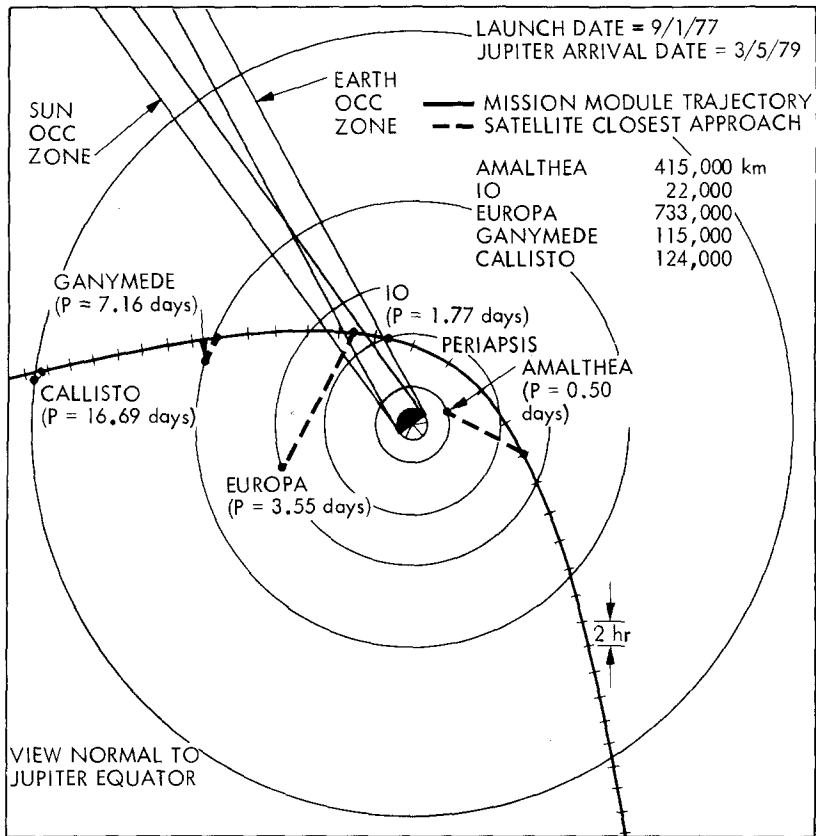


Figure 7. JST Jupiter encounter. This view from the planet north pole shows trajectory closest approach distances to the planet and selected satellites, satellite periods, and two-hour tick marks along the trajectory. Note Io flux tube passage at 22 000 km.

In order to understand the navigation language as related to the Voyager requirements, it is first necessary to define a few key terms. 'Global' navigation, using primarily the proven radiometric tracking system, has been assumed in meeting basic trajectory control functions which enable the spacecraft to proceed from Earth to Jupiter, and on to Saturn, while performing planet-oriented science measurements during the encounter periods. 'Local' navigation, using both radiometric and optical data, has been assumed in meeting the full satellite-oriented science measurements. Two subcategories, 'delivery' and 'knowledge', distinguish between those requirements which must be met at the time of the last pre-planet trajectory correction maneuver, and those requirements which must be met just prior to the final science sequence update for orientation/pointing control during the near-encounter period. Finally, trajectory 'reconstruction' assumes the use of all data types to obtain a final estimate of the spacecraft trajectory and target viewing directions for use in the detailed analysis and interpretation of the science data after the encounter.

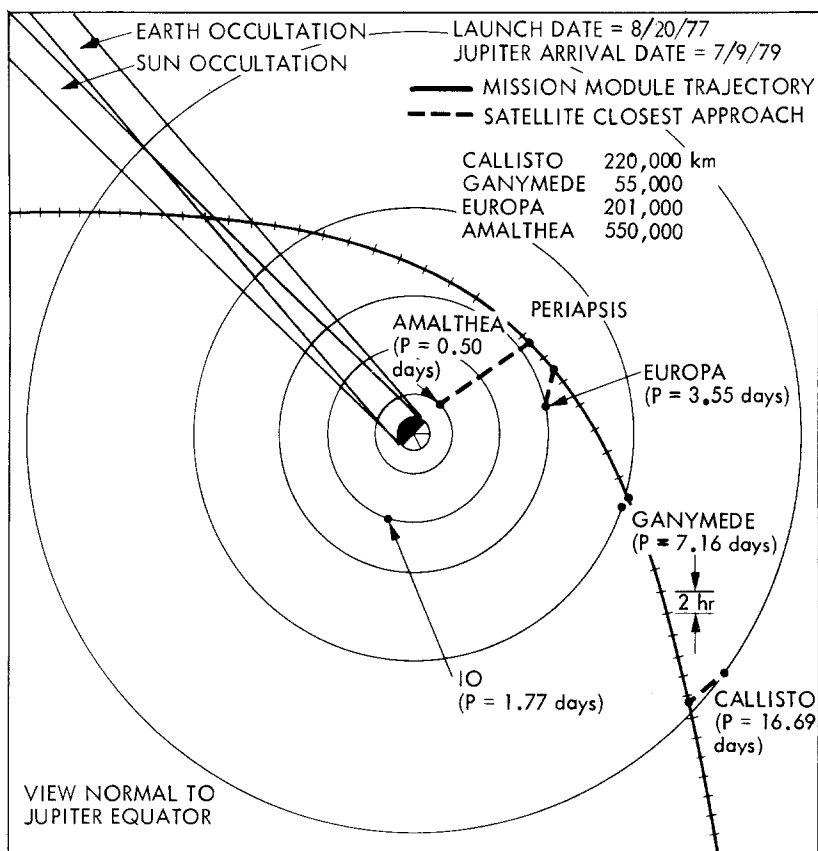


Fig. 8. JSX Jupiter encounter. This view from the planet north pole shows trajectory closest approach distances to the planet and selected satellites, satellite periods, and two-hour tick marks along the trajectory. Note close Ganymede encounter at distance of 55 000 km.

Navigation requirements have been established for several different mission functions, the most important of which fall into the following categories: reaching the final destination within available ΔV (hydrazine) reserves; honoring planetary and satellite impact-avoidance quarantine constraints; delivering the spacecraft to satellite-relative target zones such as occultation, flux tube, or wake regions; controlling the Saturn ring gap delivery for the RSS occultation experiment; estimating the near-encounter trajectory with sufficient accuracy to point the scan platform at selected targets within allowable tolerances; and providing a post-encounter orbit reconstruction accuracy of sufficient quality to support the final analysis and interpretation of the science data. Table V provides a summary of the major navigation accuracy capability estimates, expressed in terms of the 1σ semi-major axis of the total navigator error ellipsoid. Performance of the navigational system at these levels will meet most of the presently known mission accuracy requirements.

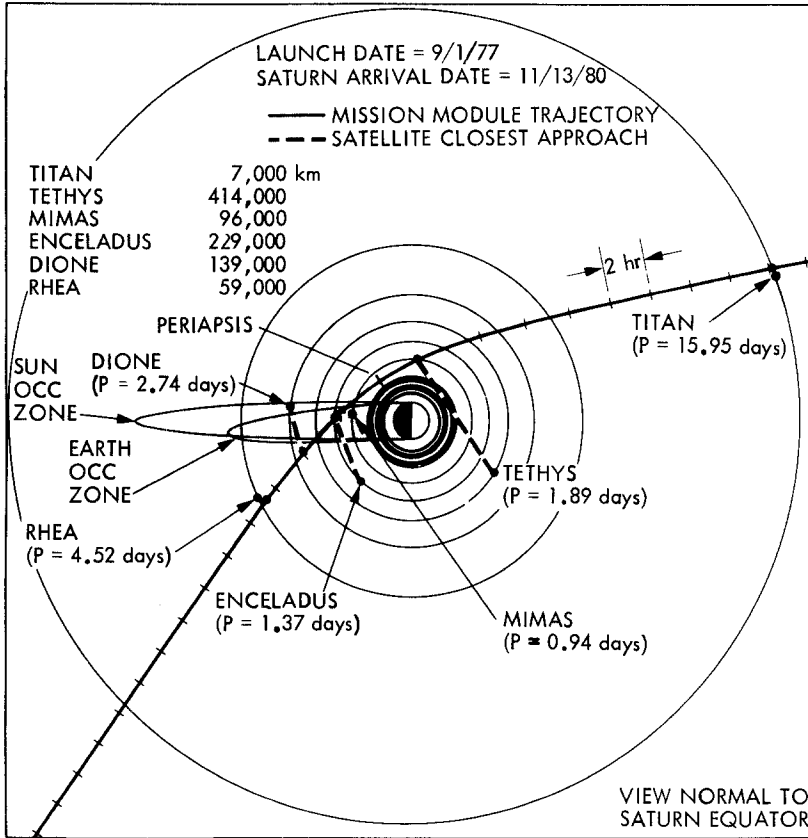


Fig. 9. JST Saturn encounter. This view from the planet north pole shows trajectory closest approach distances to the planet and selected satellites, satellite periods, and two-hour tick marks along the trajectory. The Titan emphasis provides a very close Titan encounter at 7000 km with dual Earth and Sun occultation.

6. Observation Sequences

All science instruments will be turned on and will be operational shortly after injection from Earth orbit. Since the Earth and Moon provide many characteristics which may be expected for Jupiter, Saturn, and their satellites, observations useful for instrument calibrations can be made and are planned during the first week after launch. Also, star fields will be imaged for scan platform calibration in addition to other engineering calibrations and tests to ensure that each spacecraft is operating properly. The first trajectory correction maneuver is performed about six days after launch for the purpose of correcting launch vehicle and spacecraft solid rocket injection errors.

The cruise phase officially begins 30 days after launch and continues until 80 days before Jupiter encounter. This period provides the fields and particles instruments

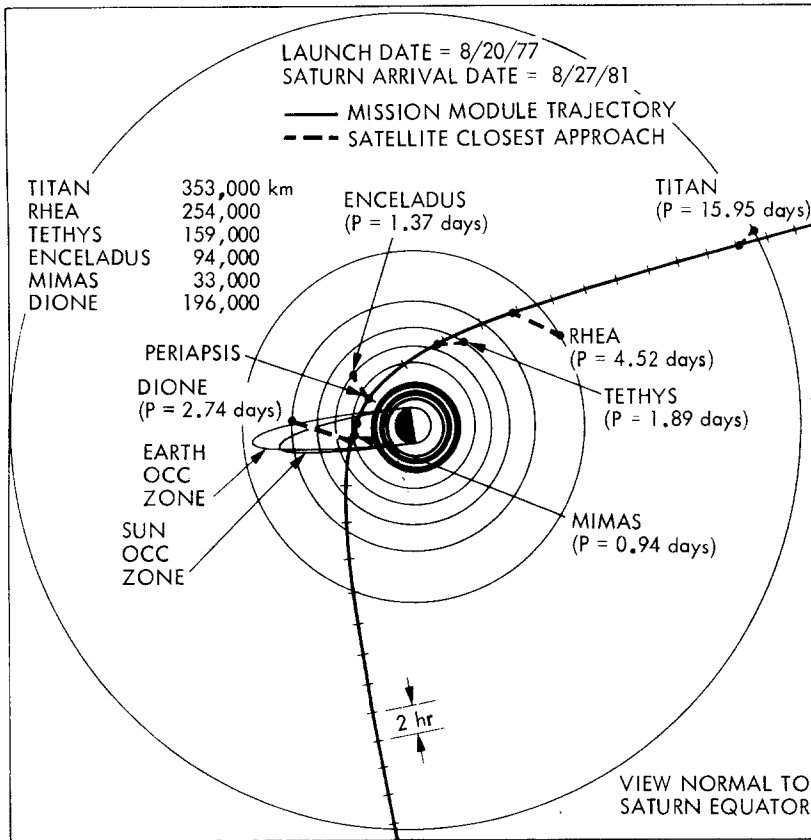


Fig. 10. JSX Saturn encounter (Uranus option). This view from the planet north pole shows trajectory closest approach distances to the planet and selected satellites, satellite periods and two-hour tick marks along the trajectory. Note that several satellite encounters are provided in addition to a mid-range Titan encounter.

the opportunity to investigate the Earth-to-Jupiter interplanetary region. Engineering activities include scan platform, antenna, and celestial sensor calibrations, in addition to the required navigation activities. A major science activity, lasting about 20 hours and requiring many yaw and roll maneuvers, will be performed once every two months on each spacecraft to permit the UVS and PPS instruments to map the celestial sphere, and to allow the fields and particles instruments to perform calibrations. The ISS and IRIS instruments also perform calibrations by looking at celestial bodies, or by looking at the calibration plate attached to the spacecraft.

At Jupiter encounter minus 80 days, observations of Jupiter and the Galilean satellites begin. At this time, periodic X-band radio tracking over the 64 m net becomes available and provides the higher data rate required for return of recorded imaging data. The ISS narrow angle camera can obtain Earth-based resolution or better, and will take color images every two hours. Other optical instruments will also



Fig. 11. JST at Saturn as viewed from Earth. The path of the JST trajectory during Earth occultation, as seen from the Earth, is shown here. The spacecraft enters Earth occultation about two hours after Saturn encounter near 60 degrees south latitude. Occultation exit occurs about 1 hour 45 minutes later near the equator and clear of the rings. After a brief period in the gap, the spacecraft is occulted by Saturn's rings for about 20 minutes.

TABLE V

Navigation accuracy capability estimates (1α Semi-Major Axis, km). The navigation error shown is that of the largest axis of the target-relative dispersion ellipsoid.

TARGET OBJECTIVES		GLOBAL DELIVERY (RADIO ONLY)	LOCAL NAVIGATION (RADIO - PLUS - OPTICAL)	
			DELIVERY	KNOWLEDGE
GALILEAN SATELLITES	ΔV CONTROL	750	-	-
	FLUX TUBE, OCCULTATION, WAKE	-	200	-
	PICTURE BUDGET EFFICIENCY	-	-	125
SATURN RING GAP OCCULTATION DELIVERY		1300	-	-
TITAN BEFORE WITH DUAL EARTH AND SUN OCCULTATION		1650	200	-
TITAN MOSAIC (PICTURE BUDGET AND UVS SLIT ALIGNMENT)		-	-	125
SATURN DELIVERY FOR URANUS OPTION CONTINUATION WITHIN ΔV LIMITS		1300	200	-

be observing Jupiter, as well as the Galilean satellites and their surrounding environments. Figure 12 presents a simplified timeline showing the major science activities to be performed during the observatory phase, as well as during the

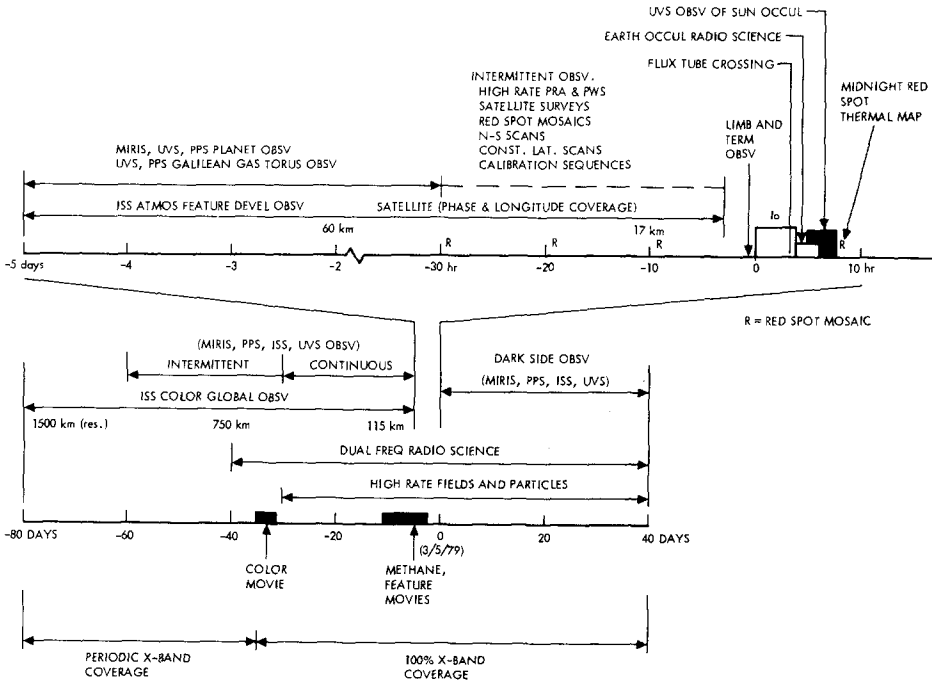


Fig. 12. Typical JST Jupiter encounter period science activities. This figure shows a typical timeline of science activities for the JST Jupiter encounter period from -80 days to +40 days. The time period near Jupiter has an expanded scale to show the higher science activity at encounter.

succeeding encounter phases. At about minus 34 days on JST, when ISS begins frequent imaging of Jupiter in a systematic manner so that a movie simulation of cloud motions may be obtained, the spacecraft will receive full time X-band coverage from the 64 m net.

Full time X-band coverage is required in the far-encounter phase (Jupiter encounter minus 30 days to encounter minus 1 day) to support the high-rate fields and particles measurements, as well as imaging and optical navigation. The science observations are interrupted at encounter minus 12 days for the final pre-Jupiter trajectory correction maneuver.

The near-encounter phase includes the Jupiter encounter ± 1 day and is the highest activity period for Jupiter science. On the approach to Jupiter, spectral instrument viewing will include north-south and constant latitude scans, Great Red Spot mosaics, such as in Figure 13, and viewing of special features on Jupiter such as hot spots, which are locations on Jupiter with higher temperatures than their surroundings. Closer in, observations will be made of Jupiter's bright limb, terminator, dark limb, and dark side. Past perijove, Earth and solar occultations of the spacecraft provide radio and optical penetration deep into Jupiter's atmosphere. During the occultations, the spacecraft will be under inertial attitude control instead of the celestial control it maintains during the majority of the mission. Being on gyros will

TWO COLOR NARROW ANGLE MOSAIC OF GREAT RED SPOT

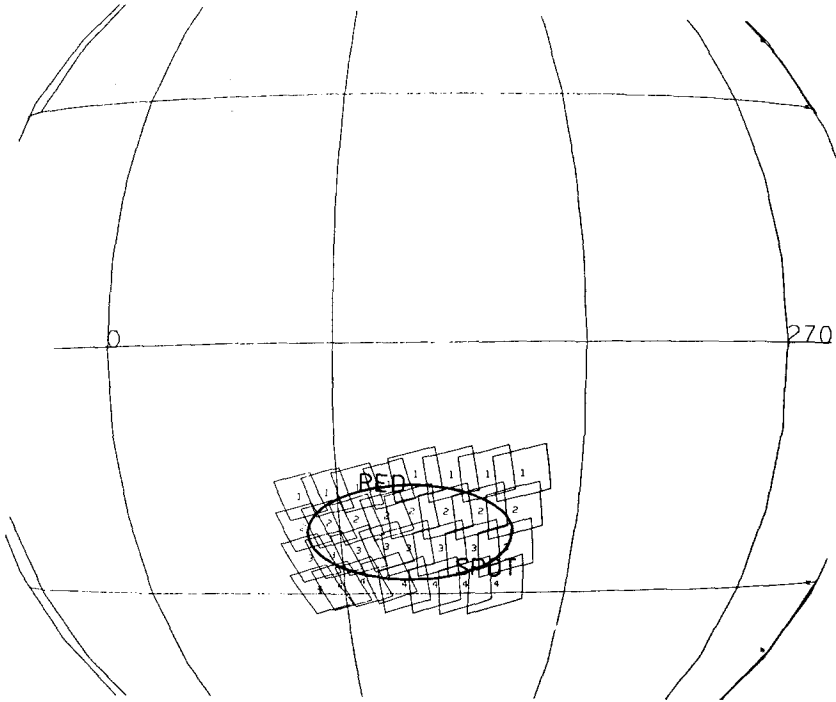


Fig. 13. Two color mosaic of the Great Red Spot. Several Great Red Spot observations will be made on approach to Jupiter. Shown is an ISSNA two-color mosaic planned to be taken on the JST Trajectory about 8 hours before Jupiter closest approach.

permit the spacecraft to roll to an optimum orientation for UVS observation of the solar occultation, and to maneuver to point the High Gain Antenna to track the virtual image of the Earth on the planet's limb during the Earth occultation.

Each Voyager spacecraft is within the Galilean satellite system during the entire near-encounter phase, and a large fraction of the time is spent viewing these bodies. From a distance, observations can be made of bright limbs, and terminators, and at various phase angles. At closest approach to the satellites, imaging mosaics of the lit sides, and scans of the lit and dark sides may be made. For the JST trajectory, Figure 14 shows a scan of Io by several of the spectral instruments. This scan is planned to occur soon after the Io flux tube passage. Figure 15 indicates the projected FOV areas that can be obtained by several instruments during the Ganymede closest approach.

Beyond Jupiter, science measurements will continue to be made. Continuous S/X-band tracking is planned for navigation and radio science purposes to encounter plus 10 days. Continuous high-rate general science data is planned until encounter

ATMOSPHERIC MEASUREMENTS DURING Io SOUTH POLAR FLY-BY

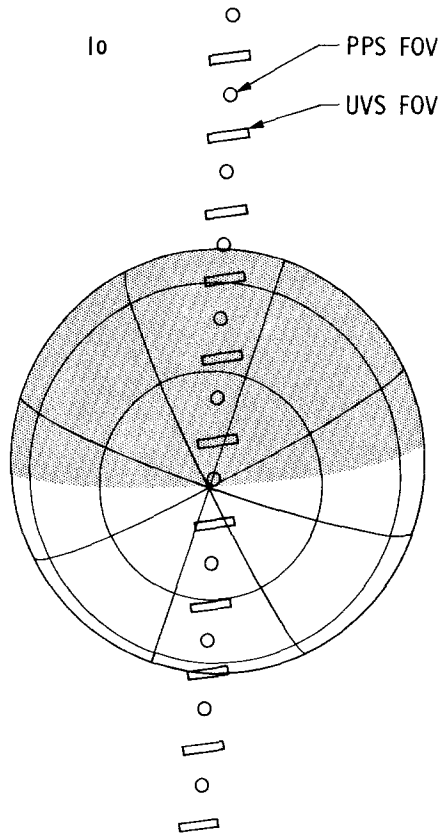


Fig. 14. South polar scan of Io. Following the Io flux tube passage, about 3 hours past Jupiter closest approach, spectral instruments will scan the south polar region of Io. Shown is a UVS and PPS scan lasting about 8 minutes. The PPS field of view is 0.25 degrees.

plus 40 days. Then, the Jupiter-to-Saturn cruise period will begin, when the science activities will be similar to those of the Earth-to-Jupiter cruise period. At Saturn, the science measurements will be similar to those of Jupiter, but details will vary significantly because of different trajectory geometry and the lower available data rate. This lower rate will require the recording of some of the high-rate data for later playback. Of particular interest at Saturn, of course, are Titan, which is known to have a substantial atmosphere, and Saturn's rings. Beyond Saturn, if all goes well, and the Uranus option is exercised, the Voyager 2 will continue in cruise until it arrives at Uranus in January, 1986. Observation sequences during the approach and

GANYMEDE JST Trajectory

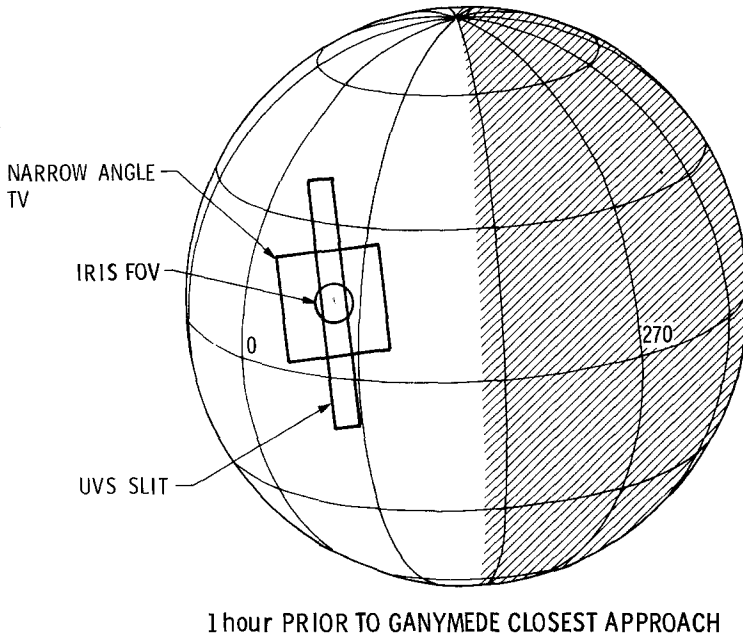


Fig. 15. Spectral measurements at GanyমেDE closest approach. Several Galilean satellite encounters come within 200,000 km. Shown are the FOV are projections for IRIS, UVS, and the ISSNA camera (0.424 deg FOV) for the GanyমেDE encounter on the JST trajectory.

flyby of Uranus and its satellites would exhibit many similarities to the earlier planetary encounters for most of the non-imaging science investigations, but would differ markedly for imaging due to the reduced data rate capability. Further discussions of this topic are left to future papers.

7. Concluding Remarks

This paper has summarized the highlights of the Voyager mission design in order to establish a framework upon which to better understand the objectives and potential returns from the eleven scientific investigations which are described in subsequent papers. Selection of the attractive JST and JSX nominal trajectories permits the observation of several satellites at close to moderate flyby distances. The Voyager mission will provide a broad survey of many bodies whose formation occurred under different conditions than those of the terrestrial planets, thereby extending our knowledge of bodies within the Solar System. In addition to the many thousands of spectra, photometric, and thermal data frames, Voyager expects to achieve imaging resolutions of better than 10 km on portions of as many as three planets and a dozen

satellites. This represents a resolution improvement between one and three orders-of-magnitude over previous scientific measurements. We look forward, therefore, with much excitement to a successful Voyager mission, and can only wonder about the nature of future missions which may evolve from its discoveries.

Acknowledgements

It is not practical to list all of the people who helped to achieve the present state of mission design, but special acknowledgement should be extended to the following persons: J. G. Beerer, J. B. Jones, A. L. Lane, J. E. Long, J. E. Randolph, E. C. Stone, and F. M. Sturms.

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