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Orbiting Deep Space Relay Station

Final Report

Volume 1. Requirement Determination

John A. Hunter

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April 1, 1979

National Aeronautics and
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Jet Propulsion Laboratory
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Pasadena, California

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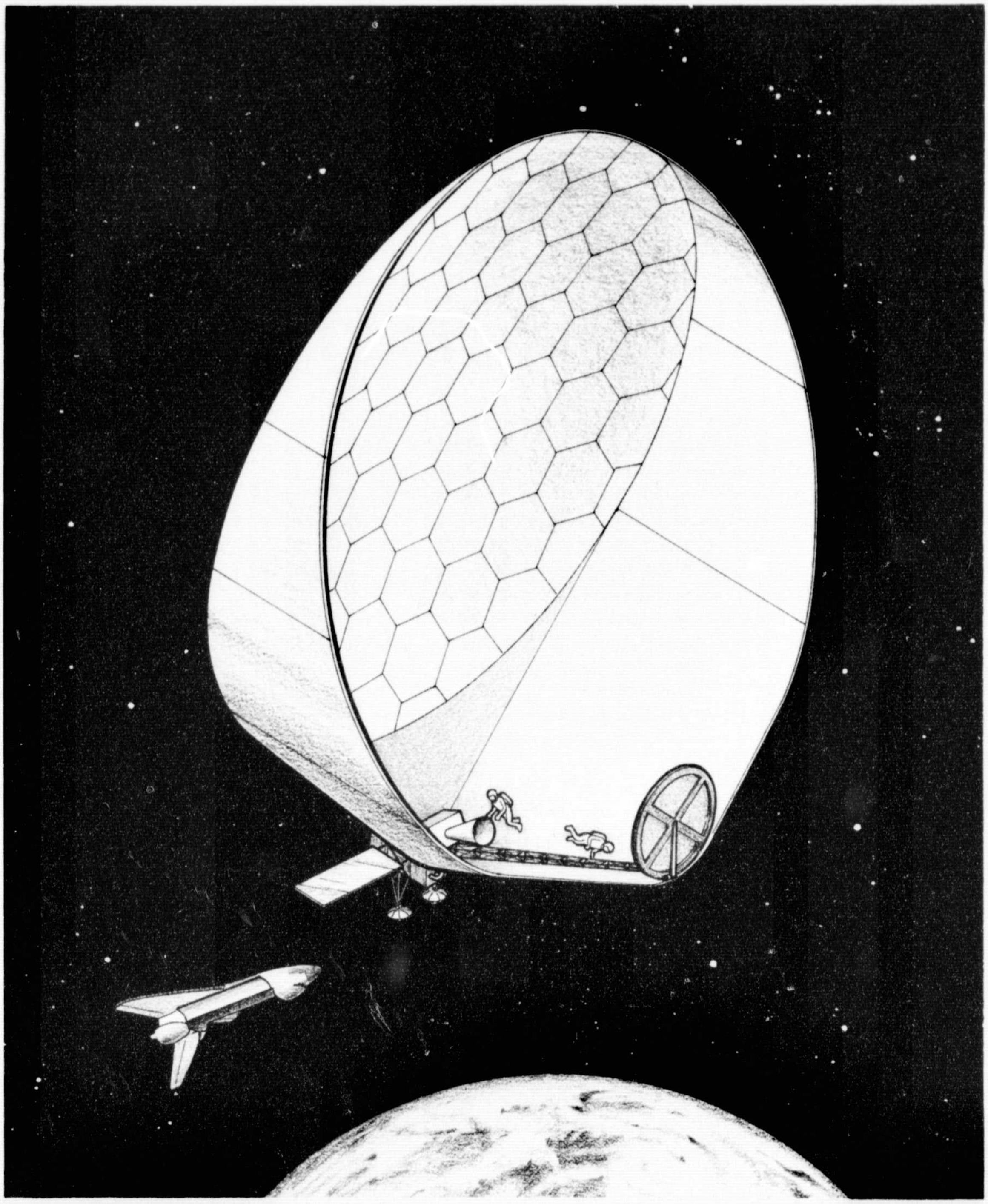

ODSRS Conceptual Configuration

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Foreword

The concept of a deep space tracking station in Earth orbit has been of interest for many years. With the advent of the Space Transportation System (STS) and its capability to economically boost large payloads into orbit, it becomes practical to seriously consider such an orbiting station. The technical feasibility of an orbiting Deep Space Relay Station (ODSRS) was demonstrated in a 1977 study sponsored by NASA OSTDS. The present study (1978) had broader objectives, including an evaluation of the deep space communications requirements in the post-1985 time frame, a conceptual design of an ODSRS system, and an implementation plan with schedule and cost estimates and new technology requirements. The study was jointly sponsored by NASA OSS, OAST, and OSTDS. Volume 1 of this report presents the deep space tracking and communications requirements for 1985-2000. Volume 2 describes the ODSRS conceptual design and provides the baseline for implementation cost and schedule estimates. Volume 3 is an implementation plan for an ODSRS, including a comparison of the ODSRS life cycle costs to other configuration options for meeting communications requirements in 1985-2000.

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Abstract

This three volume report describes the deep space communications requirements of the post-1985 time frame and presents the Orbiting Deep Space Relay Station (ODSRS) as an option for meeting these requirements. It is concluded that, under current conditions, the ODSRS is not yet cost competitive with Earth based stations to increase DSN telemetry performance. It is also concluded that the ODSRS has significant advantages over a ground station, and these are sufficient to maintain it as a future option. These advantages include the ability to track a spacecraft 24 hours per day with ground stations located only in the USA, the ability to operate at higher frequencies that would be attenuated by Earth's atmosphere, and the potential for building very large structures without the constraints of Earth's gravity. Future technology development to reduce the cost of the ODSRS and orbital operations and a need for its unique capabilities are expected to make the ODSRS attractive for implementation as an element of the long-term future DSN.

I. Deep Space Exploration Tracking and Communications Requirements for 1985 to 2000 AD

This volume of the Orbiting Deep Space Relay Station (ODSRS) study describes the development of a set of mission requirements for DSN tracking and communications support of deep space probes in the 1985 to 2000 AD time period. These mission requirements are translated into functional design requirements for a tracking and communications system. The functional design requirements used for the conceptual design of the ODSRS are described in Volume 2, and integration with the existing Deep Space Network (DSN) is presented in Volume 3. It is expected that these mission requirements will be useful for future tracking and communications system studies and will provide a basis for tradeoff studies to select optimum ways to meet these requirements.

Existing space missions planning for the post-1985 time period has not included the definition of functional and performance requirements to the level necessary to specify a tracking and communications system. An assessment of these requirements is needed at this time, so that ODSRS system planning, long-lead developments, and implementation can be started.

A. Study Approach

It is recognized that it would be virtually impossible to define a specific set of space missions for 1985-2000 that would be accepted by the National Aeronautics and Space Administration (NASA), the scientific community, and the Congress. Any definition of future missions will also be subject to change due to new scientific discoveries, changing budgets, and a changing political climate. Yet, a set of space mission requirements for the post-1985 time period is needed now to begin planning for tracking and communications systems to meet them. Attempts to define a credible set of requirements for a tracking system presented a dilemma since the missions which this system will be required to support have not been defined. This problem was approached by developing a set of requirements based on an envelope of existing future mission designs, combined with predictions of future instrument capabilities and data requirements. These items were then subjected to a sensitivity analysis to determine how system functional requirements varied with different assumed missions and instruments.

B. Post-1985 Mission Requirements

A search was made of existing candidate mission designs and projections for the 1985-2000 time period (Ref. 1). Requirements of these missions were then estimated for telemetry, command, navigation, radio science, and operations coverage. In cases where no previous studies have looked at the requirements for a proposed mission, the requirements were estimated by similarity to other missions of that type. In addition the requirements and needs of ground based radio astronomy and radio science were estimated.

1. **Future Mission Design Studies.** The mission types and specific missions from each type that were considered are listed in Table 1. This list is not intended to be a complete set of all possible missions for 1985-2000, nor is it intended to represent a judgment as to the most likely missions. It is intended to contain at least one mission of each type that is a candidate for this time frame. The requirements of a typical mission will be considered applicable to all missions of that type.

Note that Table 1 has some blank entries. This reflects the lack of design data for many candidate future missions and the absence of a basis for estimating the requirements. The potential effect of these mission requirements on a tracking and communications system design will be considered in the sensitivity analysis. As results of more detailed mission studies become available, Table 1 will be updated to reflect new requirements.

The requirements listed in Table 1 are, in general, the results of studies that have been done with the knowledge of existing tracking and communications system capabilities. This knowledge has biased the study results to be compatible with hardware and constraints that currently exist and are understood. It is likely that 1985-2000 technology will provide some significant new capabilities that are not now being considered by mission planners. In designing future tracking and communications systems, we must be careful not to be irreversibly constrained by requirements based on existing technology, and must provide flexibility to accept new requirements as the capability to meet them is developed.

2. **Mission Requirements from Design Studies.** From Table 1, the mission requirements can be derived for telemetry, command, navigation, and radio science for the period 1985-2000.

a. Telemetry. Mission requirements for telemetry bit rates from Table 1 are plotted as a function of range in Figure 1. These rates are converted to the ratio of required receiving antenna gain to system noise temperature (G/T) in Figure 2. G/T is the primary parameter that defines the overall receiving system performance.

From Figures 1 and 2, it would be concluded that little or no improvement in receiving system threshold performance or spacecraft transmitting performance for telemetry will be required between now and the year 2000. The most stringent telemetry requirements for most missions are based on 125 kbps capability at Jupiter (current Voyager capability) and scaled by range for closer or farther planets. Even the Venus Orbiter Imaging Radar (VOIR) requirement for 8 Mbps does not require an extension of current ground antenna and receiver capability due to the short communications range. VOIR does, however, require a major increase in ground data handling capability immediately after the signal leaves the RF receiver at the DSN stations.

When defining requirements for deep space telemetry systems in the post-1985 time frame, the impetus for advancing receiving system capability or spacecraft transmitting capability is not coming from mission designers. This is so even though it is clear that instruments can produce useful data at the same rate at Saturn or Pluto that they can at Mars or Jupiter. If we were to map some of the large outer planets to the same detail we have mapped Mars, we would have to either significantly increase the operations time (and cost) or the maximum bit rate at outer planets ranges. A JPL/NASA position on future telemetry bit rate requirements is needed so that candidate systems to meet these requirements can be properly evaluated. Section I-D of this report provides additional data that can be used for developing a position on

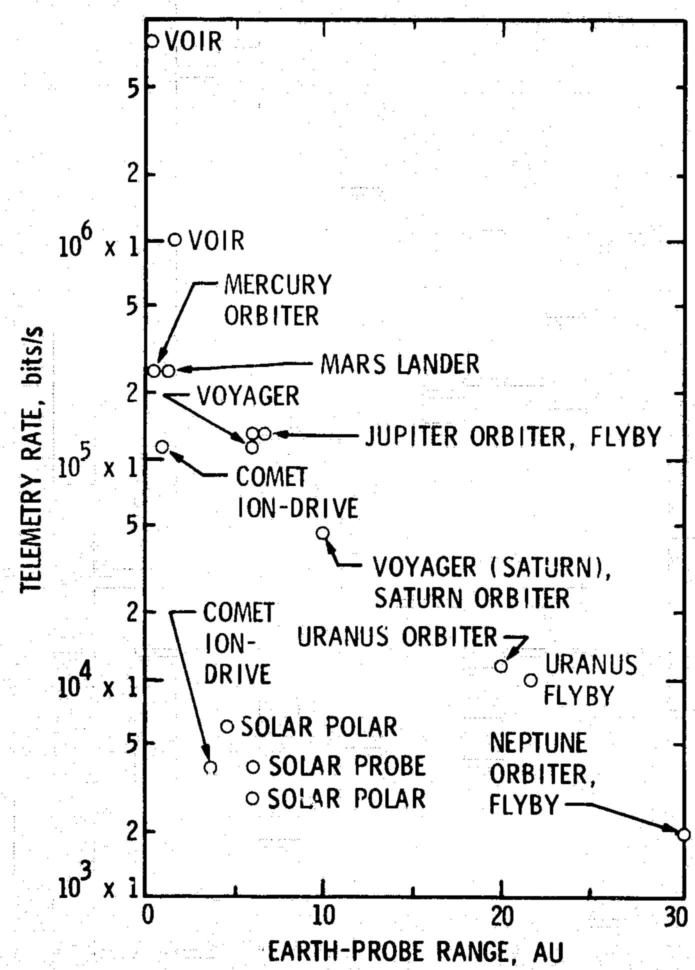

Fig. 1. Required bit rate vs range from future mission studies

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Table 1. Tracking and Communications Requirements from Future Mission Studies

MISSION TYPE	MISSION OR APPLICATION	TELEMETRY PARAMETERS						COMMAND PARAMETERS			RADIOMETRIC PARAMETERS				OPERATIONS REQUIREMENTS			NOTES
		MAX BIT RATE	RANGE @ MAX BIT RATE, AU	MAX RANGE, AU	BIT RATE @ MAX RANGE	THRESHOLD BIT ERROR RATE	EIRP	BIT RATE	MAX RANGE, AU	THRESHOLD BIT ERROR RATE	RANGING ACCURACY, m	DOPPLER ACCURACY	ANGLE ACCURACY	RF FREQUENCIES	POSSIBLE LAUNCH DATE	MISSION LIFETIME, yr	ANGULAR COVERAGE	
CURRENT DSN	VOYGER	115 kbps	6	10^+	44.8 kbps	1 5×10^{-3}	92.3	16 bps	10^+	10^{-5}	5	1 mm/s	0.25 TO 1 μrad	S&X	1977	2 4^+	3 23°	1 CONCATENATED INNER CODE REDUCES ERROR RATE TO 10^{-5} FOR ~5% OF DATA 2 POSSIBLE EXTENDED MISSION TO URANUS 3 23° + TOLERANCE WILL COVER ALL MISSIONS EXCEPT OUT OF ECLIPTIC
RADAR MAPPERS	VOIR	8 mbps 4	0.3	1.6	1 mbps	1×10^{-2}	84	2 kbps	1.6	10^{-5}	1	0.1 mm/s	0.05 μrad	S&X	1984	1	3	4 WOULD LIKE 15 mpbs, BUT 8 IS MAX CAPABILITY OF CURRENT S/C → EARTH LINK
OUT OF ECLIPTIC	SOLAR POLAR	6 kbps	4.5	6	3 kbps	10^{-5}	–	32 bps	6	–	–	0.1 mm/s	–	S&X 5	1985^+	5	$\pm 90^\circ$ 6	5 WANT S-BAND FOR SOLAR PLASMA – ALSO WANT SIMULTANEOUS S AND X BAND 2-WAY 6 90° FOR OUT OF ECLIPTIC MISSIONS
	SOLAR PROBE	4 kbps 7	6	–	–	5×10^{-5}	–	32 bps	6	–	–	–	–	S&X 5	1985^+	7.5	6	7 AT 4 R_{SOLAR}, SUN WILL AFFECT COMMUNICATIONS CHANNEL BIT RATE DROPS TO 1.7 kbps
SMALL BODIES	HALLEYS COMET (ION-DRIVE)	115 kbps	0.7	4	4 kbps	10^{-5}	76.1	16 bps	4	–	1 8	–	0.1 μrad 8	–	1985^+	4.5	–	8 DUE TO UNCERTAINTY IN ORBIT OF TARGET, OPTICAL NAVIGATION WILL PROBABLY BE REQUIRED FOR ENCOUNTER
	ASTEROID MULTIPLE RENDEZVOUS	128 kbps	4	–	–	10^{-5}	88.6	16 bps	4	–	1 8	–	0.1 μrad 8	–	1989^+	8	–	
ORBITERS	JUPITER ORBITER (WITH PROBE) GALILEO	128 kbps	6	6	128 kbps	5×10^{-3}	92.7	32 bps	6	–	–	–	–	X AND S BAND 3	1982	4.5-6.5	3	9 X AND S CHOSEN BECAUSE OF AVAILABILITY – NEED 2 FREQUENCIES TO CALIBRATE PARTICLES, HIGHER FREQUENCIES PROBABLY BETTER – FOR EXAMPLE X AND K_A

Table 1 (contd)

MISSION TYPE	MISSION OR APPLICATION	TELEMETRY PARAMETERS: MAX BIT RATE	TELEMETRY PARAMETERS: RANGE @ MAX BIT RATE, AU	TELEMETRY PARAMETERS: MAX RANGE, AU	TELEMETRY PARAMETERS: BIT RATE @ MAX RANGE	TELEMETRY PARAMETERS: THRESHOLD BIT ERROR RATE	TELEMETRY PARAMETERS: EIRP	COMMAND PARAMETERS: BIT RATE	COMMAND PARAMETERS: MAX RANGE, AU	COMMAND PARAMETERS: THRESHOLD BIT ERROR RATE	RADIOMETRIC PARAMETERS: RANGING ACCURACY, m	RADIOMETRIC PARAMETERS: DOPPLER ACCURACY	RADIOMETRIC PARAMETERS: ANGLE ACCURACY	RADIOMETRIC PARAMETERS: RF FREQUENCIES	OPERATIONS REQUIREMENTS: POSSIBLE LAUNCH DATE	OPERATIONS REQUIREMENTS: MISSION LIFETIME, yr	OPERATIONS REQUIREMENTS: ANGULAR COVERAGE	NOTES
ORBITERS	MERCURY ORBITER	256 kbps	0.3 - 1	1	256 kbps	–	79.6	500 bps	1	–	1	1 mm/s	0.05 μrad	X AND S BAND	–	3.5	(3)	
	SATURN ORBITER (DUAL PROBES)	44.8 kbps	10	–	–	–	93.0	–	–	–	1	1 mm/s	0.05 μrad	–	–	7	(3)	
	URANUS ORBITER (WITH PROBES)	11 kbps	20	–	–	–	92.9	–	–	–	1	1 mm/s	0.05 μrad	–	–	7	(3)	
	NEPTUNE ORBITER (WITH JUPITER FLYBY)	2 kbps	30	–	–	–	91.6	–	–	–	1	1 mm/s	0.05 μrad	–	–	13	(3)	
FLYBYS	URANUS (WITH PROBES)	11 kbps	20	20	11 kbps	–	92.9	–	–	–	1	1 mm/s	0.05 μrad	–	–	7	(3)	
	NEPTUNE (WITH URANUS FLYBY)	2 kbps	20	30	2 kbps	–	91.6	–	–	–	1		0.05 μrad	–	–	9+	(3)	
	JUPITER - PLUTO	–	–	40+	–	–	–	–	–	–	1	–	–	–	–	9+	(3)	
OUT OF SOLAR SYSTEM	PLUTO - INTERSTELLAR (ION DRIVE)	2 kbps MINIMUM 100 kbps MAX (11)	30 (IN 2005)	500-1000	(10) 20-40 bps (AVG)	–	–	–	–	–	(12)	(12)	(12)	–	CIRCA 2000	20+ TO 50	~15°	(10) AT MAX RANGE, WOULD REQUIRE NEW DATA SYSTEM CONCEPTS, WITH GREAT AMOUNTS OF COMPRESSION (11) TOTAL BITS AT PLUTO ~ 3×10^{10}
	PARALLEL TO SOLAR AXIS	–	–	–	–	–	–	–	–	–	(12)	(12)	(12)	–	CIRCA 2000	20+ TO 50	90°	(12) RADIOMETRIC ACCURACIES WILL BE LARGELY DETERMINED BY RADIO SCIENCE REQUIREMENTS – NAVIGATION WILL BE BY VISIBLE STARS
LANDERS ROVERS	MARS (WITH MARS ORBITER)	250 kbps	0.5	2.5	20 kbps	10^{-5}	73.5	125	1.6	–	1	1 mm/s	0.05 μrad	X AND S BAND	–	3	(3)	
	GALLILEAN SATELLITES (WITH JUPITER ORBITER)	128 kbps	6	6	–	–	92.8	–	–	–	–	–	–	X BAND	–	5	(3)	
	TITAN (WITH SATURN ORBITER)	44.8 kbps	10	10	–	–	93.0	–	–	–	1	1 mm/s	0.05 μrad	–	–	7	(3)	

Table 1 (contd)

MISSION TYPE	MISSION OR APPLICATION	TELEMETRY PARAMETERS: MAX BIT RATE	TELEMETRY PARAMETERS: RANGE @ MAX BIT RATE, AU	TELEMETRY PARAMETERS: MAX RANGE, AU	TELEMETRY PARAMETERS: BIT RATE @ MAX RANGE	TELEMETRY PARAMETERS: THRESHOLD BIT ERROR RATE	TELEMETRY PARAMETERS: EIRP	COMMAND PARAMETERS: BIT RATE	COMMAND PARAMETERS: MAX RANGE, AU	COMMAND PARAMETERS: THRESHOLD BIT ERROR RATE	RADIOMETRIC PARAMETERS: RANGING ACCURACY, m	RADIOMETRIC PARAMETERS: DOPPLER ACCURACY	RADIOMETRIC PARAMETERS: ANGLE ACCURACY	RADIOMETRIC PARAMETERS: RF FREQUENCIES	OPERATIONS REQUIREMENTS: POSSIBLE LAUNCH DATE	OPERATIONS REQUIREMENTS: MISSION LIFETIME, yr	OPERATIONS REQUIREMENTS: ANGULAR COVERAGE	NOTES
LANDERS	VENUS (WITH BOUYANT STATION	280 kbps	0.5	1.7	–	–	84.5	–	–	–	–	–	–	–	–	1.2	(3)	
SAMPLE RETURNS	MARS	250 kbps	0.5	2.5	20 kbps	10^{-5}	73.5	125 bps (13)	1.6	–	1 (13)	1 mm/s (13)	0.05 μrad (13)	–	–	3.5	(3)	(13) MARS SAMPLE RETURN REQUIRES RENDEZVOUS IN MARS ORBIT. THIS WOULD PROBABLY NOT BE EARTH CONTROLLED
	(14) MERCURY OR VENUS	8 mbps	0.3	1	256 kbps	–	–	–	–	–	–	–	–	–	–	2.3	(3)	(14) NOT LIKELY
	COMET	115 kbps	0.7	4	4	–	73.0	–	–	–	–	–	0.1 μrad	–	–	4		
	ASTEROID	128 kbps	4	–	–	–	88.6	–	–	–	–	–	–	–	–	6		
RADIO SCIENCE WITH S/C SOURCE	OCCULATION EXPERIMENTS	SMALL-CONTAINED IN SCIENCE OR ENGINEERING DATA SYSTEM	–	–	–	–	–	–	–	–	1	0.1 mm/s	–	DUAL (9)	ALL	–	–	
	PLANETARY GRAVITY FIELD OBSERVATIONS (15)		–	–	–	–	–	–	–	–	–	–	–	–	–	–	(3)	(15) REQUIRES ORBITING SPACECRAFT
	GRAVITY WAVE											(18)						(18) INITIAL PROPOSALS MAY REQUIRE UNREAL ACCURACY FURTHER PROPOSALS IN PROCESS
RADIO ASTRONOMY WITH NATURAL SOURCES	RESOLUTION & CATALOGING OF RADIO SOURCES (16)		–	–	–	–	–	–	–	–	1-10 cm	–	–	TO 300 ghz (17)	–	–	4-STER RADIANS	(16) LONG MUTUAL STATION VIEW PERIODS FOR ΔVLBI
	SETI		–	–	–	–	–	–	–	–	–	–	–	TO 300 ghz (17)	–	–	4-STER RADIANS	(17) EARTH STATIONS LIMITED BY ATMOSPHERE

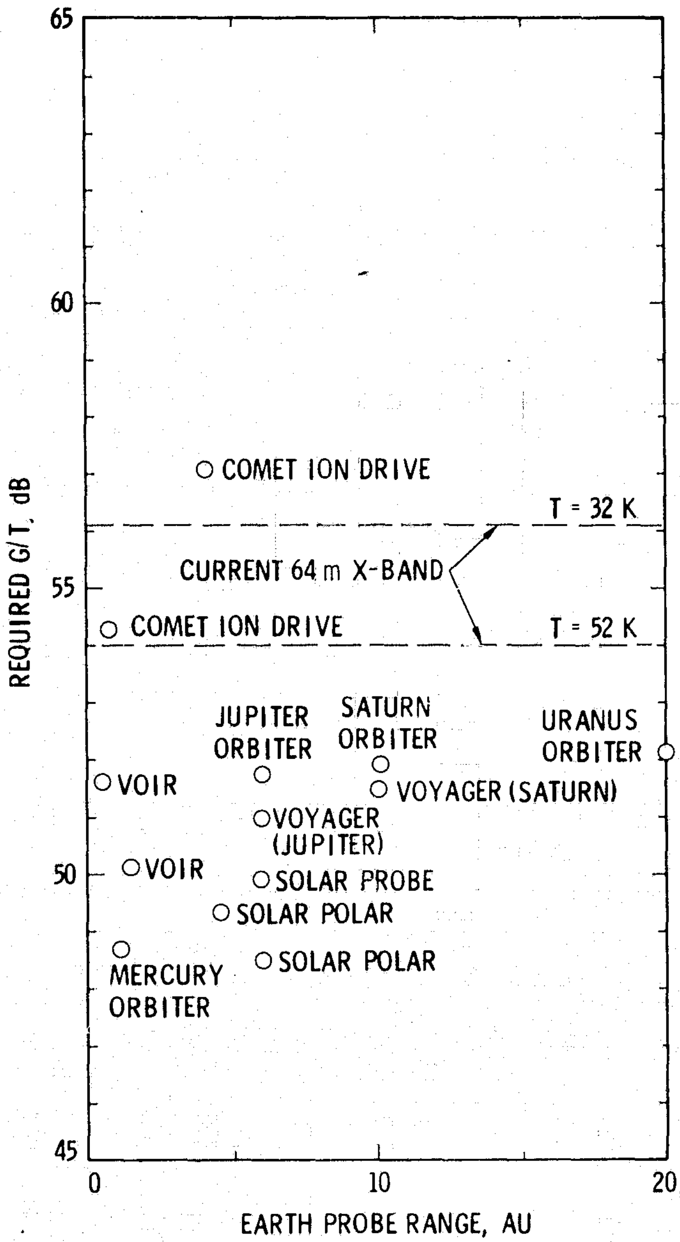

Fig. 2. Required G/T vs range from future mission studies

future requirements, and Section II defines the requirements that were assumed for the ODSRS system design.

b. Command. Mission requirements for command bit rates from Table 1 were compared to existing DSN capabilities. It was found that future command performance requirements can be satisfied with large margins assuming 26 or 64 meter stations with 20 kW. Thus, command performance will not be considered a major driver on 1985-2000 communications systems technology requirements.

c. Navigation (Radiometrics). Navigation mission requirements in Table 1 generally represent a factor of 5 to 10 increase in accuracy from the existing capability. Means to achieve these improvements are largely understood, and implementation of some of them is currently underway (wideband one-way range and dual-frequency uplink). The only area in which a significant technology development may be required is in precision two-way ranging. To meet requirements for some applications, such as radio science and ODSRS, the capability to determine range to ~10 cm will be needed. This implies a wider band, higher clock frequency system than now exists and would require a new spacecraft transponder and a new ground station system.

The improved radiometric capabilities for navigation will also satisfy many of the radio science requirements. Radio science requirements are generally more severe than for navigation, and ways to meet all of them are not clear at this time.

d. Operations. The mission operations requirements of Table 1 do not readily correlate to requirements on a tracking and communications system design. There is not an obvious basis to derive station tracking time requirements until launch dates and mission profiles are better known. If a mission from Table 1 is launched every 2 years, the existing DSN system will be unable to provide the mission support that is currently required by deep space projects. To resolve this problem would require either more tracking stations or a change in project philosophy about "nearly continuous" tracking.

A major factor which affects operations requirements is the need for 24-hour-per-day telemetry and command capability. Current deep space projects request the capability to command a spacecraft anytime an anomaly or problem is detected. This drives the DSN requirement to have stations located around the World in a geometry that allows at least one ground station with command capability to be in view of any spacecraft 24 hours per day. Future mission requirements have not been defined in this level of detail. If future missions can be constrained to require command capability for a maximum of 1 station pass per day, it would allow all command activities to take place from ground stations located in the territorial USA. If navigation and radio science requirements for 2-way doppler and ranging can be similarly constrained, the only stations with transmit capability could be located in the territorial USA, Goldstone for example. This constraint should reduce networks operations costs.

For comparison purposes, the effect that an ODSRS would have on DSN loading can be summarized as follows: (1) It would add the capability for 24 station hours per day that could be available for receiving from one or more spacecraft, one at a time. This 24 hours would be reduced by the time required to slew between spacecraft and to reprogram the ODSRS for a new spacecraft. (2) it would add the capability for 2-way tracking by Goldstone of a spacecraft to which the 2-way round trip light time exceeded the length of a station pass.

C. Future Spacecraft Instrument Capabilities

This section will address future telemetry data requirements based on the expected spacecraft instrument capabilities. The major drivers on data rate capability are summarized in Table 2. Note that these are all imaging related devices. Instruments can generate data at the far-outer planets as fast as they can at Jupiter. To define communications system requirements to support these instruments for future missions, a strategy for sending this data to Earth is needed. This strategy could range from requiring real time, non-compressed data transmission to having large data storage capability on the spacecraft and using the existing link data rate capability and long playback times. Future mission studies to date have chosen to require existing telemetry link capabilities and have assumed either slow real-time data rates (down to ~1000 bps at far-outer planets) or recording of all high-rate data and non-real-time playback at data rates down to ~1000 bps. It appears to be an unrealistic assumption, for missions 15 to 20 years in the future that will likely cost hundreds of millions of dollars, to return only about 1/100 the data of the existing Voyager class missions to Jupiter. If this assumption stands, the amount of data returned from Pluto, for example, may not justify the cost of a mission.

D. Future Telemetry Link Technology Requirements

At this time, the new technology needed to provide dramatic increases in telemetry link capability on the order of 20 dB (at least) is credible for the 1985 to 2000 time period. This includes both spacecraft and receiving station technologies, such as:

- Higher communications frequencies.
- Larger antennas.
- More powerful transmitters.

In addition, we can anticipate continued advances in the density and speed of solid state data generating instruments and processing equipment that will result in:

- Even higher raw data rates.
- On-board data processing to reduce telemetry channel data rates below the raw data rate.
- Requirements for lower bit error rate telemetry channels for compressed data.

Since the technology of the future contains many unknowns, it is likely that a new technology that is not currently being considered could play a major role in deep space tracking and communications in the year 2000. Therefore, it does not seem prudent to plan future missions based on existing capabilities. Nor does it seem prudent to plan future tracking and communications system performance requirements to be the same as they are today. A new strategy is needed for planning future deep space telemetry link capabilities. This strategy should be based on credible advances in technology,

Table 2. Major drivers on deep space telemetry data rate requirements

Instrument description	Data rates	Planets of interest	Notes
Real time TV, Voyager class	125-250 kbps	All	
Non-real time TV, Voyager class	10-20 kbps	All	Assumes 10^9 bit on-board recorder. Requires 10 to 20 times longer operations time for playback.
Real time TV, CCD camera	1-5 Mbps	All	
Active microwave coherent imaging, VOIR class	8 Mbps (15 Mbps desired)	"Cloudy" targets like Venus, Jupiter, and Saturn for surface features.	Will require 5-10 yr to determine if microwave imaging has value at outer planets.
		All for some applications.	Data rate will likely be compressed by on-board processing.

be flexible in time and cost, allow for technological "surprises" in the future, and be related to an overall mission plan including future science objectives and spacecraft systems to use the telemetry capability.

E. A Telemetry Strategy Based on Technology Advances

This section proposes a strawman future telemetry strategy. The numbers and years may be questioned, but the form of the strategy is the important factor.

Figure 3 shows communications range to the planets of the Solar System versus the delta dB required to maintain a constant bit rate. Jupiter has been assumed as the 0 dB point, so that performance improvement for real time TV at Voyager rates can be read directly for the chosen planet. Note that to achieve real-time TV at Saturn requires ~5 dB over Jupiter, Uranus requires ~6 dB over Saturn, and Pluto requires ~6 dB over Uranus. If a strategy of achieving real time Voyager quality TV from Pluto in even increments through the year 2000 were adopted, the plan would be as shown in Figure 3. Note that when the communications system capability will support real-time Voyager quality TV from Pluto, it will also support VOIR class active microwave imaging from Jupiter.

This form of a strategy has the feature of clearly defining when a communications capability will exist as a function of time and target planet. Mission designers can then determine if the planned capability matches planetary windows, mission plans, and science objectives, and can suggest changes to the time axis. Technology development plans can then be implemented to provide the improved performance when it is planned. Note that this is an iterative process between mission design, technology development, and communications system implementation. Integrating these elements with funding availability would be one approach to developing a total deep space tracking and communications plan for the future.

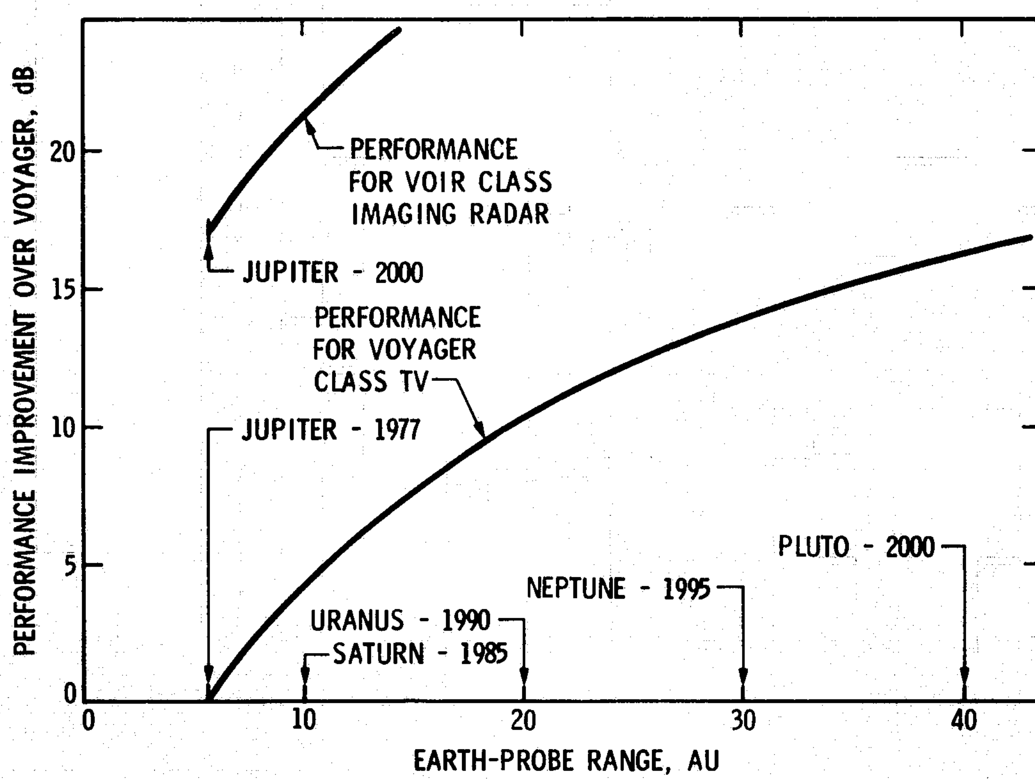

Fig. 3. Example telemetry performance vs time plan

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II. Post-1985 Tracking System Design Requirements

From the mission requirements defined in Section I and Table 1, a set of design requirements can be derived. Table 3 contains these system design requirements and also shows the derivation from mission requirements. Due to the uncertainty in future mission set definition, it is important to determine how changes in the mission set affect tracking and communications system design requirements and technology development. This section will address the sensitivity of telemetry, command, navigation, and operations requirements to changes in the mission set.

A. Telemetry Requirements

From the telemetry requirements discussion of Section I, future missions that have been studied nearly all require the existing 64-meter DSN receiving capability. A first-order conclusion from this would be that telemetry reception requirements for future missions are insensitive to variations in the mission set chosen.

There are two factors which argue against this conclusion. First, the existing DSN capability provides only 1/100 of the existing Voyager (Jupiter) data rate when the communication range is extended to Pluto. This vastly reduced capability may not be adequate to justify the cost of a far-outer planets mission. The second factor indicating that telemetry communications requirements are sensitive to the mission set chosen is imaging radar. The missions studied to date have not assumed the use of imaging radar at ranges beyond Venus. If this technique proves valuable at Venus, it is possible that it will be planned for more distant planets. including Jupiter and beyond. Referring to Figure 3, the telemetry performance capability for imaging radar from Jupiter is equivalent to the capability for real time Voyager class video from Pluto. This level of performance will require major improvements in communications performance and will likely be a long-term requirement.

The conclusion is that increased telemetry communications capability will likely be required, and the amount of increase is sensitive to missions beyond Jupiter and to imaging radar. Telemetry performance can be increased in increments as a function of time leading to the final capability. Phasing mission designs to use performance increments as they become available could be one element of developing an overall deep space exploration plan.

B. Command Requirements

Command requirements vary considerably between missions described in Table 1. Variations in choice of mission set would have a large effect on command requirements if each mission was designed at command threshold. However, all future missions studied have large margins above command

Table 3. Deep space tracking and communications system design requirements

Function	Mission requirement	System design requirement	Notes
Telemetry	Bit rates and bit error rate vs range:	Receiving antenna gain to system noise temperature ratio:	Considers S/C transmitter power and antenna gain as defined in mission studies.
	see Table 1.	G/T ⩾ 56 dB.	Existing 64-m X-band performance is ~56 dB.
	Bit rate vs range: per Fig. 3 for 1985.	S/C to receiver telemetry link performance 6 dB greater than existing DSN.	
	Max bit rates: 250 kbps, 8 Mbps (VOIR).	RF receiver to telemetry processor channel bandwidth: 250 kbps 8 Mbps (imaging radar)	Assume real time transmission from RF receiver to telemetry processor.
	Max bit error rates: 5×10^{-3} to 1×10^{-5}.	Receiver to telemetry processor bit error rate: $< 1 \times 10^{-6}$.	For ODSRS to earth link, assume a maximum degradation of 0.2 dB at threshold with worst case weather.
Command	Bit rates and bit error rate vs range: see Table 1.	Transmitter power-gain product: P•G ⩾ 118.	Assume S/C receiving antenna pattern and system noise temperature equivalent to Galileo. Existing P•G ≅ 133 (64 meter) and ≅ 123 (26 meter) at 20 kW.
Radiometric	Absolute range accuracy 1 m (for navigation).	Station location known to 1 m in all 3 axes (relative to Earth-fixed reference system).	For an ODSRS, would need 3 widely spaced ground stations – could be all territorial U.S. Would also require 10 cm ranging system for ODSRS to determine location to 1 m.
		End-to-end group delay calibration absolute accuracy: likely ~ 20 cm	Real time end-to-end group delay calibration technique desirable. ODSRS could be far-field calibration source for ground stations.
		End-to-end group delay stability: likely factor of 10 better than 1978.	Absolute configuration control after calibration is required.
		Frequency and timing accuracy: 1 part in 10^{13} (for Saturn-Uranus distance).	Implies use of hydrogen maser.
	Absolute range accuracy 10 cm (for science and for ODSRS).		Requires new wideband ranging system on ground and new wideband transponder on spacecraft.
	Doppler accuracy 0.1 mm/sec.	End-to-end phase stability controlled or calibrated to: 1 mm (10 sec averaging time; 10 mm (100 sec averaging time).	Implies some sort of near real time calibration of tropospheric changes. Would require stable S/C temperature when taking data. Attitude motion of S/C (and ODSRS) would have to be modeled. Navigation within ±30° of the Sun would require 2-frequency 2-way capability (X-S is OK, X-X is better, X-K is even better). Note that radio science prefers S-Band near Sun.
		Station location known to 1 m in all 3 axes (relative to Earth-fixed system).	For an ODSRS, its velocity would have to be known to 0.1 mm/sec.
		Frequency and timing accuracy: 1 part in 10^{13}	Implies use of hydrogen maser.

Table 3 (contd)

Function	Mission requirements	System design requirement	Notes
Radiometric (cont)	Angle accuracy 0.05 μrad.	Timing accuracy to 10^{-9} sec. End-to-end time delay calibrations to < 20 cm. 3-station simultaneous viewperiod or 2 each of 2 station simultaneous viewperiod with different baseline orientation. Requires knowledge of Earth orientation to ±0.03 μrad.	Requires either "ΔVLBI" or "wideband differential ranging". Wideband differential ranging requires a signal generator and switching on the S/C; could use separate, smaller ground stations and require minimum S/C time. OR ΔVLBI needs a Quasar catalog to ±0.03 μrad; requires long periods of taking data while alternating between a Quasar and the S/C (possible loss of telemetry).
	Dual frequency for calibration of transmission medium and radio science.	Capability to receive 2 RF frequency bands simultaneously.	Existing system meets requirement. Addition of K_A band would improve accuracy.
Operations support	DSN station critical mission phase support.	24 hr per day telemetry reception. One pass per day uplink for tracking and command.*	Assumes that future S/C designs will not require continuous command capability.
	DSN station cruise mission phase support.	Tracking for telemetry and navigation periodically as required to maintain S/C analysis and radiometrics. Commands as required to update S/C computer and fix anomalies.*	

*Proposed; not to be considered a firm requirement.

threshold for the existing DSN configuration. The conclusion is that if the existing DSN command capability is assumed, implementation of command communications requirements for the future are not sensitive to choice of mission set.

C. Navigation Requirements

Navigation requirements are stated in terms of accuracies for range, doppler, and angle determination.

1. Angle accuracy. Angle accuracy requirements for all future missions except small body rendezvous are 0.05 μrad. Small body rendezvous missions require 0.1 μrad. Since any mission set chosen will likely include more than small body missions, the more severe constraint of 0.05 μrad will be assumed and it will likely not be sensitive to variations in the mission set.

2. Range accuracy. Absolute range accuracy requirements for all of the deep space missions studied in Table 1 are 1 m. This number is not sensitive to a change in mission set, and is probably attainable with existing ranging techniques. Future navigation techniques will likely not rely on precision ranging data. However, there are other system requirements, including radio science and ODSRS, that need ~10 cm ranging accuracy. This will require a redesigned spacecraft transponder and a new ranging system. The conclusion is that the ground system should be designed to handle 1 m or 10 cm ranging requirements, and the individual projects can build and operate their spacecraft at whatever accuracy level they require.

3. Doppler accuracy. Doppler accuracy required for navigation purposes is 1 mm per second for most future deep space mission studies. There are specific missions that use doppler in conjunction with science experiments that require accuracy on the order of 0.1 mm per second. These specific missions include VOIR and ISP. Missions with occultation experiments desire 0.1 mm per second during the entry and exit occultation. Achieving 0.1 mm per second is significantly more difficult that 1 mm per second, and requires calibration and control of ground station and spacecraft hardware, and calibration of the interplanetary medium.

The conclusion is that the requirement for doppler accuracy is sensitive to the inclusion of specific missions in the mission set. It is likely that the future mission set will include one or more missions with the requirement for 0.1 mm per second accuracy. The ground stations should be capable of supporting a 0.1 mm per second requirement. The spacecraft can then be designed, calibrated, and operated to provide 0.1 or 1 mm as required.

D. Operations Requirements

Operations requirements are very sensitive to the choice of missions, the number of missions flown, and the frequency of launches. Only a defined mission set for the post-1985 period would allow definition of a firm requirement for operations coverage. Several assumptions can, however, be made about post-1985 missions that affect operations requirements, and the sensitivity to change in assumptions of tracking system requirements can be assessed.

1. Length of missions. More future missions to the far-outer planets that require many years transit time are being studied. Inclusion of these missions means that more spacecraft will be in transit (cruise) at one time and will require some kind of monitoring.

2. Automation (autonomy) of spacecraft. Many future studies are considering a spacecraft that can take care of itself for long periods of cruise without continuous monitoring and intervention from Earth. Acceptance of this philosophy would reduce the total daily tracking load on the DSN and would result in the stations being used more for critical operations such as encountering and orbital data taking. Some provisions will be needed for detection of spacecraft emergencies during the period when the spacecraft is on its own. In general, inclusion of autonomous spacecraft missions in the mission set would reduce the total tracking time, reduce the number of DSN stations required to track a given number of missions, and increase the importance of tracking time to the spacecraft and mission.

3. Frequency of launch. Frequency of launch of missions to be tracked after 1985 is a major driver of operations coverage. As an upper bound, it is likely that no more than 1 launch every 2 years will occur. The lower bound is probably in the 1 launch every 3 or 4 year area, and this is highly dependent on funding availability. If 1 major deep space mission is launched every 2 years, the existing DSN would be overloaded unless current tracking requirements imposed by the projects are relaxed.

4. Timing of critical periods. Critical periods, such as encounters and orbital insertions, create a major strain on DSN facilities. Even with the addition of more DSN stations, the timing of critical periods would have to be coordinated between projects so they don't all occur at the same time. This is a factor that should be considered when defining a future mission set.

5. Length of critical periods. If the mission set includes several missions, such as orbiters that have long critical operations periods, more stations would be required than if the mission set consists mostly of fast flybys.

6. Requirement for 24-hour per day tracking. If future missions can be constrained to require 24-hour per day telemetry only during critical periods, this would reduce the requirement on the total number of DSN stations. If they can be constrained further, to only requiring command and uplink capability for a maximum of 1 station pass per day, the Goldstone stations could be the only ones requiring a transmit capability.

Reference

1. *NASA Lunar and Planetary Mission Handbook*, Report 710-14, Vol. 4, "Mission Descriptions," Edition 2. Jet Propulsion Laboratory, Pasadena, CA 91103, May 1978.