SMALL DEEP SPACE MISSION TELECOMMUNICATIONS

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Abstract

Unique requirements imposed on deep space telecommunications, such as operation at extreme ranges, have historically led to high cost, one-of-a-kind spacecraft telecommunications systems. Yet future deep space missions must fit within severe cost, mass and power constraints.

JPL recently completed a study to find ways of reducing telecommunications cost for future deep space missions. Study team members surveyed designers of proposed deep space missions to characterize their telecommunications needs and design constraints. They identified and evaluated alternative telecommunications systems architectures capable of satisfying these needs and constraints. They traded spacecraft capabilities against DSN capabilities to determine optimal flight/ground combinations. The task culminated in a final report identifying needed telecommunications technology development.

The survey demonstrated that future deep space missions will have requirements that are relatively modest compared to those of most other deep space missions launched over the past 17 years. Future missions are expected to occur more frequently than in the past. As a result, the study recommends that a standard deep space transponder be developed and that transponder procurement be coordinated between missions to minimize NASA's costs. It also recommends spacecraft power amplifier and antenna development efforts.

This paper summarizes survey results. It then presents key system analysis results of interest to the designers of future deep space missions. It concludes with a review of telecommunications technology development recommendations and plans.

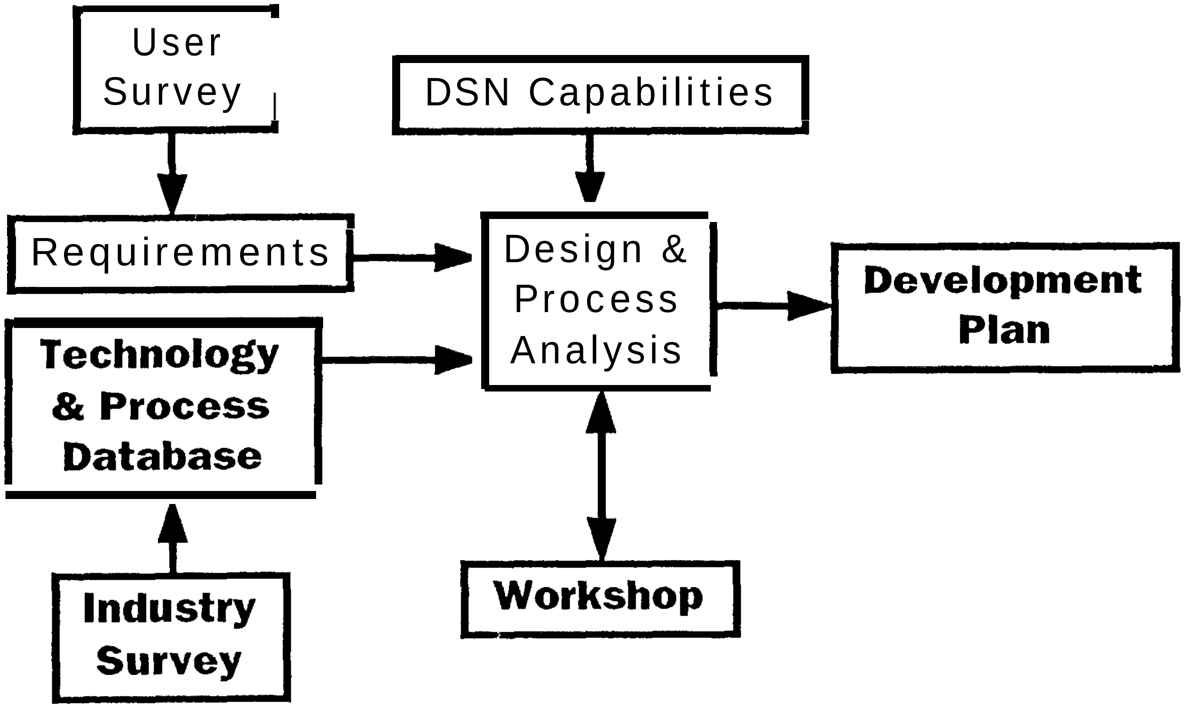

Fig. 1. Small Deep Space Mission Telecommunications System Task Process Overview

I. Background

The principal objective of the Small Deep Space Mission Telecommunications Task was to develop new approaches to building spacecraft telecommunications sys-

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terns for small deep space missions that significantly decrease system cost. The task focused on spacecraft to be launched in 2 to 10 years. The task was limited to Category B (deep space) spacecraft which communicate directly with NASA's Deep Space Network (DSN).[1]

The task began with a survey of future missions to characterize telecommunications requirements (Fig. 1). These requirements were modest compared the requirements of past interplanetary missions. The results of the survey were analyzed to identify key design drivers.

Data on industry capabilities were compiled to identify means by which mission requirements could best be met. A workshop was held at JPL midway through the process to review both mission design considerations and technical solutions with designers of future missions.

II. Functions & Components

Deep space telecommunications systems[2] provide four fundamental functions: command, telemetry, position and velocity determination and atmospheric measurements during occultations. The telecommunications system is used to precisely determine spacecraft position and velocity both for navigation and for radio science, such as geodesy and gravity field measurements.

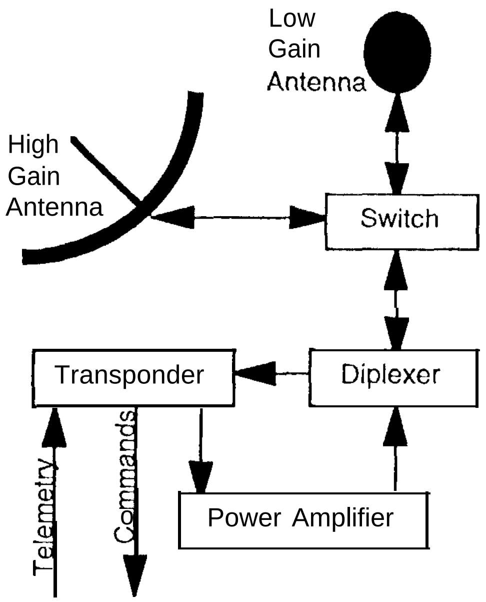

Fig. 2. Spacecraft Telecom Block Diagram

A deep space telecommunications system typically has three principal spacecraft components: a transponder, a power amplifier and antennas (Fig. 2). The spacecraft transponder receives signals from the DSN through an antenna. The transponder demodulates the received signal into spacecraft commands. It generates a downlink carrier, either from an external oscillator or phase coherent with the uplink carrier. It modulates the downlink carrier with telemetry and, if necessary, a ranging signal to generate a downlink signal. The power amplifier amplifies the downlink signal for transmission through an antenna.

III. Survey

To understand customer needs, we surveyed designers of future deep space missions. A total of 20 survey forms were filled out, most through the use of telephone interviews with mission designers.

Mission	*'Max. Range AU*	*Opr. Range, AU*	*Data Rate, kbps*
NEAR	*3.3*	*2.63*	3
Mars Pathfinder	*2.7*	*1.29*	11.4
Mars Surveyor Orb.	*2,7*	1.6	42
Mars Surveyor Lndr.	*2.7*	2.7	6
Discovery 1	1.29	1.29	11.4
Discovery 2	2.7	2.7	4
Discovery 3	*0.4*	*0.4*	*0.04*
Discovery 4	1.3	1.3	1
Discovery 5	*1". 3*	1.3	*35*
Discovery 6	*2*	*2*	*0.1*
Discovery 7	*5*	*2".5*	*7.9*
Discovery 8	3.3	*2.63*	*3*
Discovery 9	1.2	*2.63*	*3*
Discovery 10	*5 "*	*2.7*	1.2
Discovery *11*	4.7	*4*	0.1
SIRTF	*0.28"*	*0.28*	2000
Small Solar Probe	*' 6*	1	*4*
Measure Jupiter	*6 . 5*	6.5	*"0.1*
Saturn mini-probes	*9"*		*0.05"*
Pluto Fast Flyby	*35*	*2*	0.21

Table 1. Key Survey Results

Table 1 shows maximum range to Earth, operational range to Earth, and required data rate at the operational range for the surveyed missions. These parameters characterize fundamental command anti telemetry mission requirements.

None of the missions had specified command data rate requirements at the time of the survey, though none of the mission designers interviewed felt that their missions would require unusual command data rates.

Few missions had considered radio science or navigation requirements at the time the survey was conducted. It appears that radio science requirements will be substantially reduced in future missions. Navigation requirements are discussed later in this paper, based on independent JPL assessments of future navigation needs rather than on survey results,

Maximum range for both previous and proposed future deep space missions are shown on a logarithmic scale in Fig. 3. Note that all but two proposed missions go beyond 1 AU. Proposed missions span a set of ranges not unlike previous missions.

Fig. 4 shows normalized downlink telemetry data rate of past and future missions, computed by multiplying data rate (in kbps) at maximum operating range by range (in AU) squared. This provides a measure of relative downlink telemetry performance for past and future missions. It is evident from Fig, 4 that most future missions require relatively modest link performance for telemetry. All but two of the proposed missions (SIRTF and Pluto Fast Flyby) require less link performance than all but three of the missions launched since 1972 (Pioneer Venus 1 & 2 and Clementine).

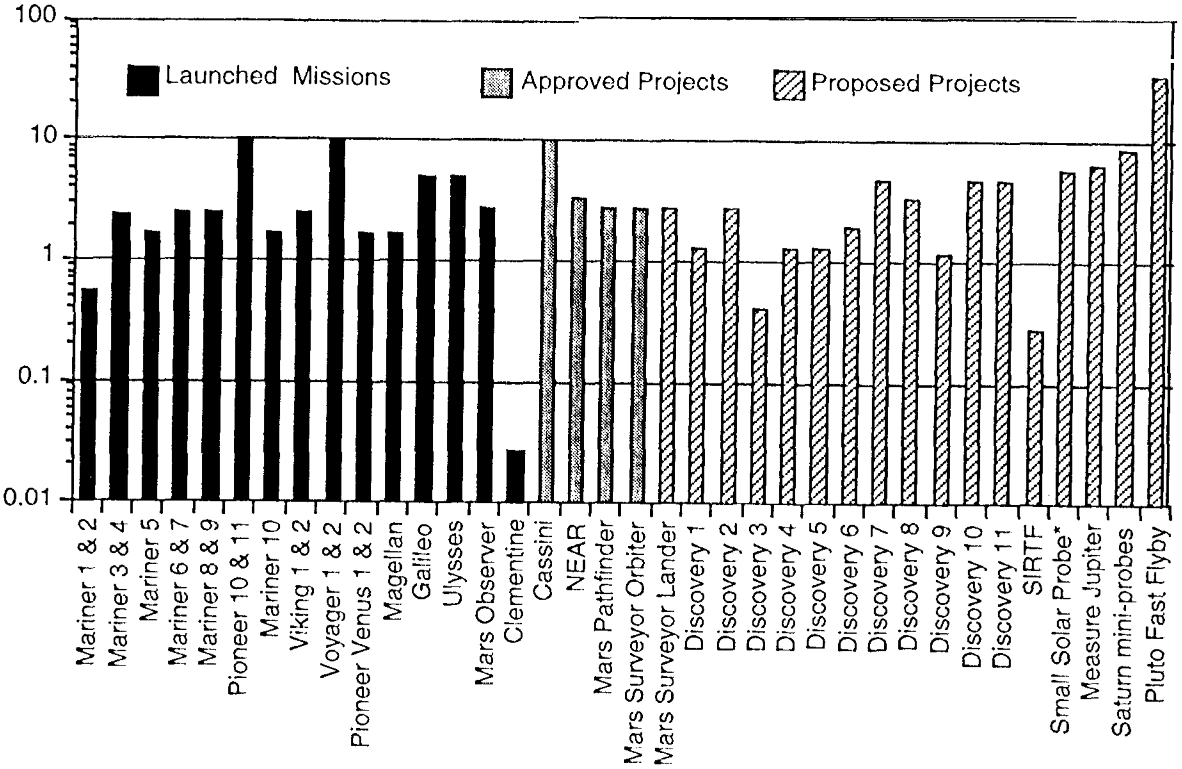

Fig. 3. Maximum Range, AU

Y/... Downlink Frequency Selection

Downlink frequency selection for telemetry is generally driven by two operating modes: emergency telemetry and high rate telemetry. These modes use, typically, a spacecraft Low Gain Antenna (LGA) or High Gain Antenna (HGA), respectively. LGAs are generally used for command and for engineering telemetry when relatively near earth, as well as in emergency conditions. HGAs are used for high rate telemetry and commanding when far from earth.

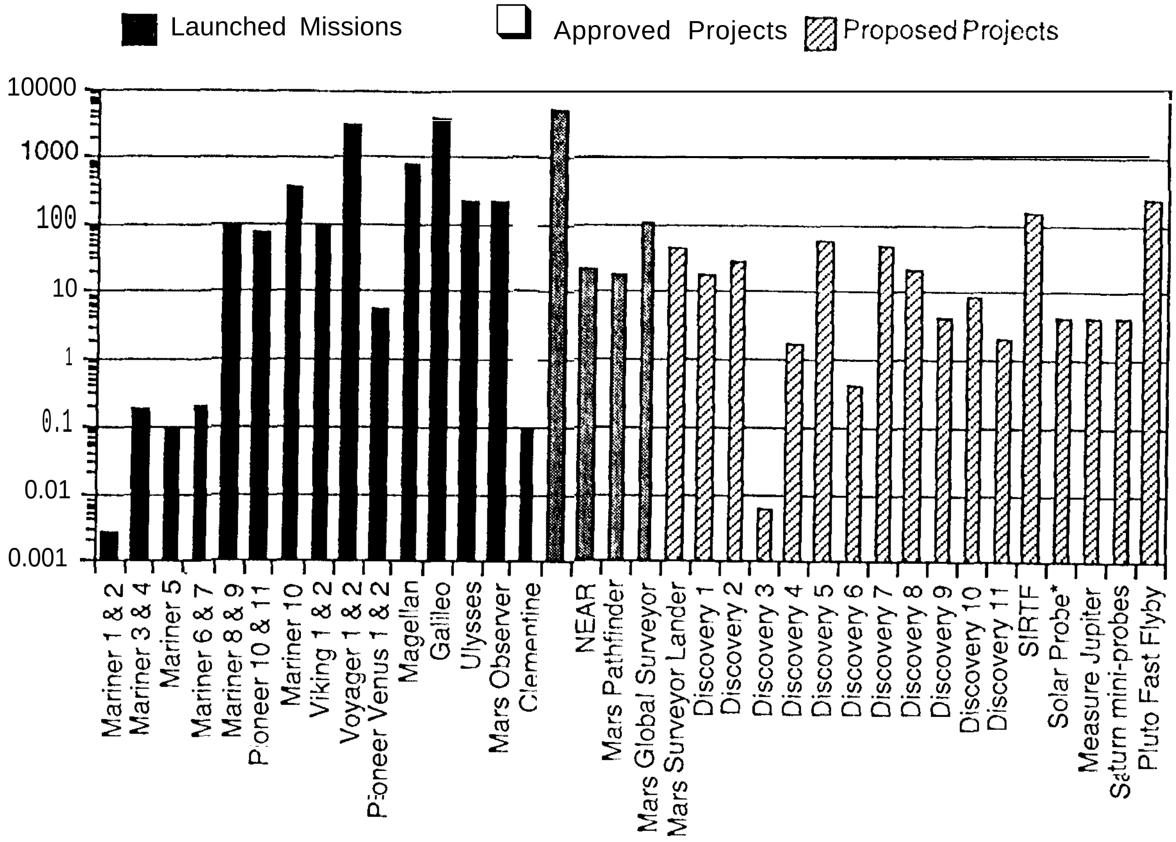

Fig. 4. Normalized Operational Data Rate (kbps x AU2)

Link Performance through HGA

To a first approximation, data rate depends on antenna apertures, frequency, transmit power and range as follows:

$$\textbf{Data Rate} \propto \frac{P_T A_T A_R f^2}{R^2} \qquad (1)$$

where

P_T is transmitter Power,

A_T and AR are transmit and receive antenna aperture (area), respectively,

f Is frequency, and

R is range between the transmitter and receiver.

Equation 1 demonstrates that the data rate that a communications system can support between two aperture-limited (fixed area) antennas is, to a first approximation, proportional to f^2. The DSN can be considered a fixed-aperture resource, while the aperture of a spacecraft High Gain Antenna (HGA) is normally limited by configuration considerations independent - to a first approximation - of frequency. Thus communications through the spacecraft HGA improve with the square of frequency - once again, to a first approximation.

At frequencies above S-band, other factors become significant. At X-band, rain attenuation can be significant on the downlink, though this generally has not caused serious problems. The ratio f^2 between S-band and X-band in the deep space bands is 13.5, and we see this level of improvement in practice; i.e., the data rate supported by a DSN station receiving a signal from a fixed RF power, fixed aperture spacecraft is 13.5 times higher at X-band than at S-band.

There are substantial additional degradations at Ka-band. These include severe rain losses, lower SSPA power conversion efficiency, and reduced antenna efficiency due to greater sensitivity to antenna surface imperfections. These and other additional degradations limit the performance improvement in going from X-band to K_a-band to a factor of 2.6 to 5 — in spite of the fact that the ratio of K_a-band to X-band f^2 is 14.4, slightly more than for S-band to X-band.

Table 2 summarizes relative downlink performance of S-, X- and Ka-band links through a spacecraft high gain antenna. Data Rates, in kbps, are for a 3 W transmitter and a 1 m dia. antenna on a spacecraft at 1 AU transmitting to a 34 m DSS.

Freq. Band	*Freq. MHz*	*f^2 Ratio*	*Data Rate*	*BPS Ratio*
S-Band	2295	1	1	1
X-Band	8425	13.5	13.5	13.5
K_a-Band	32000	14.4	35.1-67.5	2.6 - 5

Table 2. High Rate Telemetry Comparison

Table 2 shows that by going from S-band to X-band, data rate can be increased by a factor of 13.5, while there is only a 2.6 to 5 times further improvement in data rate by going from X-band to Ka-band.

Link Performance through LGA

Antenna gain G is proportional to antenna aperture A and f^2:

$$G \propto f^2 A \qquad (2)$$

LGAs are usually gain-constrained, i.e. the gain of LGAs is usually limited by broad coverage requirements, From Equation 2, we see that the aperture of a gain-constrained (i.e., constant gain) LGA is inversely proportional to f^2. Given that the DSN, at one end of the link, has a fixed aperture and that the LGA at the other end of the link has an aperture inversely proportional to f^2, we see that:

$$\text{Data Rate} \propto \frac{P_T A_T G}{R^2} \qquad (3)$$

Data rate from a spacecraft LGA is thus independent of frequency (to a first approximation). In practice, there is very little difference in the data rate for downlink telemetry from LGAs with equal gain at S- and X-bands. However, the performance at K_a-band is much worse than at S- or X-band through LGAs due to the same degradations cited above.

Emergency Telemetry

It is desirable to be able to receive telemetry through a low gain antenna in anomalous conditions. In such an event, the spacecraft is usually autonomously pointed towards the sun, but may not be able to determine the position of earth or point the HGA towards earth. Thus the LGA must have sufficient beamwidth to span the range of possible sun-probe-earth angles. Minimum LGA beamwidth generally determines maximum LGA gain, typically 6 dB.

In this mode, the principal objective is to send sufficient engineering telemetry in a short enough period of time to permit analysis of the state of the spacecraft and the transmission of commands to avoid spacecraft failure. A data rate of 10 bps is often used in this mode.

Table 7 in the Appendix is a Design Control Table for an emergency telemetry link at 1 AU. A 70 m Deep Space Station (DSS) is normally used in this mode. While this table is for an X-band link, performance at S-band is similar. This table shows that a transmitter power of about 1 W is required, assuming an LGA gain of 6 dB (and minimal margin). It is for a one-way link, typical of emergency conditions where an uplink carrier cannot be assumed to be present and an Ultra Stable Oscillator (USO) may not be present. Thus the downlink carrier must be generated from an onboard oscillator. Using conventional coherent demodulation tracking techniques, if the onboard oscillator is a USO, the DSN can typically track the carrier in a bandwidth of under 1 Hz (Galileo will use 0.1 Hz operationally). If a USO is not available, a spacecraft Auxiliary Oscillator (Aux Osc) with much lower stability must be used instead. The Block V receiver will require a 1 or 3 Hz tracking loop to track such carriers (depending on Aux Osc stability). Since few future missions are planning to carry USOs, the DSN will have to use 1 or 3 Hz carrier tracking loop bandwidths to track the carrier. With carrier tracking loop bandwidths that wide, and data rates so low, carrier power must be fairly high --- generally higher than data power, as in Table 7.

In these conditions, little power is available to split between the carrier and data sidebands. In this mode, the squaring loss introduced by the Costas loop receiver exceeds the power lost by using a residual carrier. As a result, carrier tracking performance dominates link design, and more power must be put into the carrier than into the modulated data.

Noncoherent demodulation techniques present a possible alternative. The performance of DPSK is 3 dB worse than coherent BPSK (assuming a suppressed carrier). New pseudo-coherent demodulation schemes have recently been developed for mobile satellite applications that could be of substantial benefit here.[3] These schemes offer demodulation performance approaching that of coherent demodulation. They use the received signal to generate a maximum-likelihood estimate of carrier phase.

Transmitter and Antenna Sizing

Transmitter power required for a deep space mission is normally at least enough to ensure reception of emergency telemetry through a 70 m 0SS at maximum range.

Required spacecraft HGA size depends on transmitter power, on required data rate, and on range. Table 8 in the Appendix is an X-band high rate telemetry downlink Design Control Table for a typical spacecraft with a 10 W PA and 1.5 m diameter HGA at 1 AU.

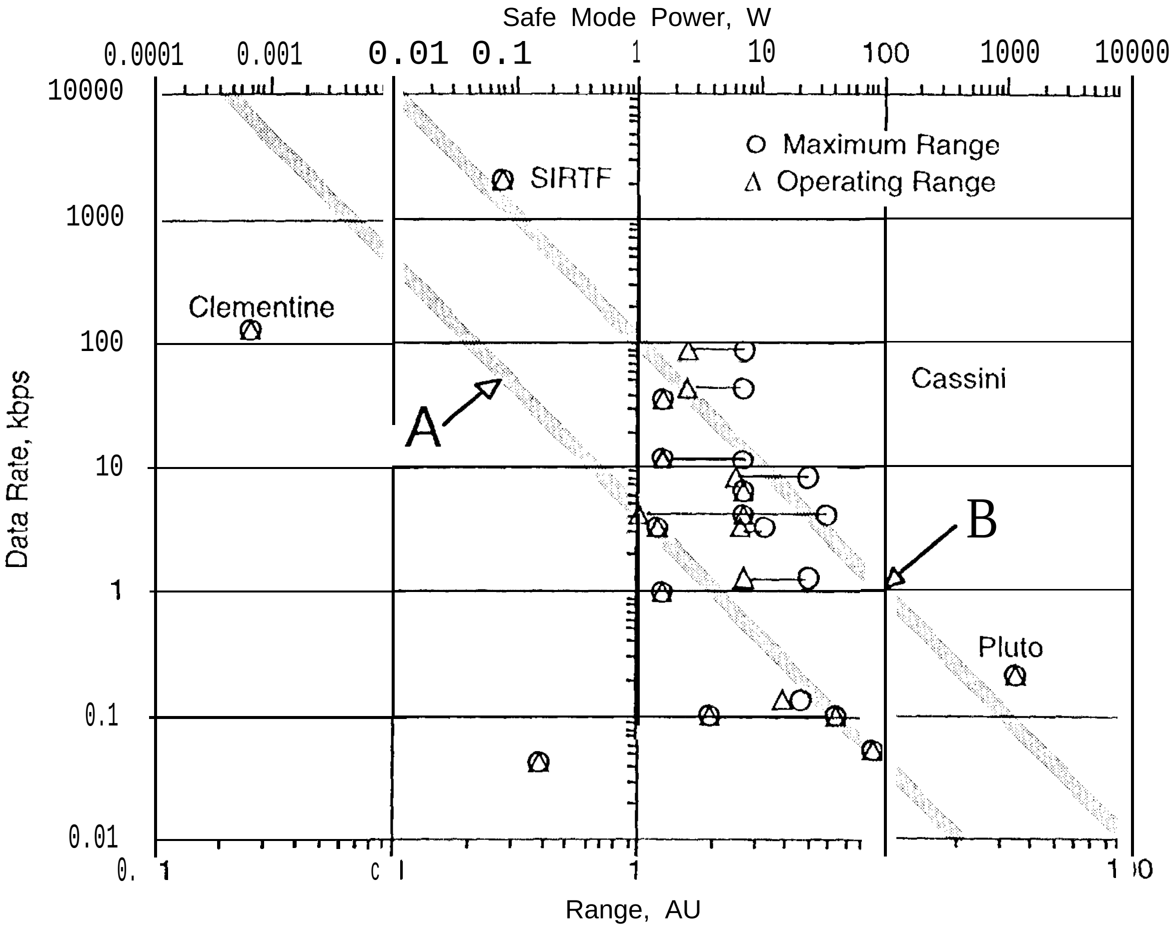

Fig. 5. X-Band Power Amplifier and HGA Sizing Chart

Fig. 5 shows the data rates and ranges of future missions. It also shows the safe mode power required (top line) as a function of range (bottom line). The safe mode power requirement of each mission is shown as a circle, while the data rate and range of each mission are shown with triangles. Circles do not correspond to data rates; they are intended only to show required X-"or S-band power in emergency telemetry mode.

It is desirable to fit the spacecraft high gain antenna within the shroud of the launch vehicle as a single unit, i.e. without unfurling. Table 3 shows the shroud diameters of typical launch vehicles expected for future deep space missions.

Launch Vehicle	Shroud Diameter
Pegasus XL	1.1 meters
Taurus	1.25 meters
Lockheed Launch Vehicle	2 to 3.25 meters
Delta	2.5 meters

Table 3. Launch Vehicle Shrouds

The diagonal lines A and B in Fig. 3 correspond to constant EIRP. Table 4 below shows possible S-, X- and Ka-band PA and antenna combinations corresponding to each of the lines in Fig. 3.

Line	Freq. Band	Ant. Dia., m	RF Power, W
A	S-Band	1.5	7
	X-Band	0.7	2
	Ka-Band	0.5	1
B	S-Band	2.5	50
	X-Band	1.5	10
	Ka-Band	1.0	5

Table 4. PA & Antenna Combinations

Note that nearly every triangle in Fig. 3 falls to the left of diagonal line B, corresponding to an X-band 10 W PA with a 1.5 m HGA. This means that the high rate telemetry requirements of nearly every mission can be met with a 10 W PA and a 1.5 m HGA — which can be fit within most launch vehicle shrouds. When antenna requirements of individual missions are evaluated, in every case the antenna required for high rate telemetry (assuming an X-band power amplifier meeting the safe mode requirement) fits within the shroud of the planned launch vehicle, This means that X-band can satisfy the needs of every mission without the need for an unfurlable antenna.

While several missions could use S-band for high rate downlink telemetry, in most cases this would require excessive power or unfurlable antennas, or both.

Ka-band has been suggested as a means of reducing spacecraft power and antenna requirements. Unfortunately, its poor performance in emergency mode (Ka-band can only be received by 34 m Deep Space Stations) renders Ka-band unusable for emergency telemetry, so an X- or S-band transmitter would generally be required as well, Ka-band has the potential of reducing DSN tracking time as a second downlink frequency. Ka-band would aLso benefit missions traveling very close to the sun (such as Small Solar Probe), which suffer severe solar scintillation losses at S- and X-bands.

Transponder			***Loral CXS-600B***	***SMEX***	***Cassini***	***SDST***
Minimum Data Rate			*250* bps	7.8125 bps	7.8125 bps	7.8125 bps
Noise Figure			*5* dB	6 dB	1.5 dB	1.8 dB
Frequency Band			S-Band	S-Band	X-Band	X-Band
Loop Noise Bandwidth, 2BL O			*800* Hz	*200* Hz	*17.5* Hz	*20* Hz
Carrier Tracking Threshold			*-125* dBm	-135 dBm	≤-157.3 dBm	-158 dBm
S/C Ant.	***DSS***	***Power, kW***				
LGA	*34*	*2*	*0.1*	*0,4*	*1.9*	*1.7*
L GA	*34*	*20*	*0.37*	*1.2*	*6*	*5.5*
L GA	*70*	*20/1 00 x/s*	*1.9*	*6*	*12*	11
HGA	34	2	1.6	3.2	23.1	21.2
HGA	*34*	*20*	*5*	*10*	*73*	*67*

Table 5. Maximum Command Range

Command Requirements

Table 5 shows maximum command range for several transponders with the following assumptions:

- BPSK modulation, no coding
- 1.5 m diameter HGA
- 6 dB spacecraft LGA

- 7.8125 bps data rate through LGA (except Loral transponder, which has a minimum data rate of 250 bps)
- *250* bps data rate through HGA

Table 5 shows that the Loral CXS-600B transponder can be commanded at Mars maximum range, 2.7 AU, only through an HGA. The SMEX transponder can be commanded through an LGA at maximum Mars range only with the use of a 70 m DSS. The Cassini and SDST can be commanded with 34 m stations at maximum Mars range, and require only a 2 kW transmitter at a 34 m DSS for commands at 250 bps. Table 9 in the Appendix is a design control table for an uplink command link from a 34 m DSS to a Cassini transponder through an L. GA.

At this time, there are no 2 kW amplifiers at the DSN, but future stations may incorporate such transmitters as a cost-saving measure. Assuming a 1.5 m HGA on each spacecraft and that a 250 bps data rate is sufficient, Figure 1 and Table 4 together demonstrate that a 2 kW DSS transmitter and an X-band SDST would work for all missions, except PFF, whenever they are using their HGA for commanding.

V. Navigation

Navigation is the determination by statistical inference and control of a spacecraft's position and velocity based on measurements of its behavior. The predominant type of measurements used for navigation are radio metric measurements made by the DSN. These measurements make use of the radio communications system and are thus part of the overall telecommunication system design.

Each mission generates requirements on the navigation system which are intended to satisfy mission health and safety requirements as well, as to allow for the acquisition of science observations of a desired target. The nature of the observations, as well as the spacecraft design and the mission design, will determine the level of the requirement that is levied on the navigation system. This will, in turn, determine the requirement levied by the navigation system on the overall telecommunications design. It is rare that there is only a single solution to a given navigation problem, consequently there is a significant trade space in which to operate. Some of the more important considerations in this trade space are radio metric vs. target observation data, data type choices, and frequency band choices.

Navigation requirements are generally of two types, absolute or target relative. Absolute requirements are misnamed as they are in fact Earth relative navigation requirements as that is where the radio tracking occurs. These requirements generally are not stringent and most commonly are driven by the need to acquire telemetry from and send commands to the spacecraft. More common, and generally more stringent, are target-relative navigation requirements. These may be levied by the needs of science pointing, spacecraft health and safety, or mission design (e.g. gravity assists). Target-relative navigation may be performed using Earth based radio metric tracking and the knowledge of the target body ephemeris (and its uncertainty) relative to the Earth. The limiting capability in these cases is often the target body ephemeris knowledge. Table 6 summarizes current knowledge of these ephemerides.

Body	***Ephemeris Accuracy, 1σ***	***Comments***
Mercury	10km	
Venus	10km	Should improve
Mars	5km	
Asteroids	100 km	Can improve with more observations
Comets	500 km	Can improve with more observations
Jupiter	150 km	
Neptune	2000 km	
Pluto	20,000 km	In radial direction

Table 6. Approximate Position Knowledge of Solar System Bodies

It is also possible to measure the position of the spacecraft directly against the target body. The most common of these target relative techniques is optical navigation, in which an image of the target against a background of stars of known positions is taken, but other types of observations, such as LIDAR or RADAR, are possible when the spacecraft is sufficiently close to a target body, such as an asteroid. Except for certain cases, target body relative data types exhibit insensitivities in certain directions. Consequently, target relative data types are traditionally used in conjunction with Earth based radio metric data. They generally decrease the amount and accuracy of radio tracking needed. Target relative navigation data types, however , levy a telemetry requirement of maintaining enough data rate capability to downlink them. On-board processing of the data can decrease or potentially obviate this requirement.

The data types which are commonly used for navigation are Doppler, range, and ADOR (Delta Differential One-way Range). Doppler is a measurement of the spacecraft's velocity along the line from the spacecraft to the Deep Space Station. DSN coherent (2-way) X-band (8.4 GHz) Doppler data has an accuracy of 0.1 mm/s (60 sec average). Doppler data over a sufficient data arc can be used to infer angular position information as well as line of sight information and coherent X-band Doppler data have demonstrated accuracies of 150 nanoradians (geocentric angular uncertainty). Ranging data provide a measure of the round trip light time between the Earth and the spacecraft. Ranging data accuracy is highly dependent on signal strength, but can be as good as 1 to 2 meters. Current DSN operation requires the reception of coherent Doppler simultaneous with ranging. These two data types in conjunction (X-band) have in operation provided angular position accuracy of 50 nanoradians.

Direct measurement of angular position and velocity requires the use of differential (2 station) data types. These include the use of Doppler and ranging data taken at two stations (not at the same complex) simultaneously and difference to generate angular information. ADOR involves the differencing of signals received simultaneously from the spacecraft at two stations. This difference quantity is then difference again against a similar measurement of a quasar signal. This results in a highly precise determination of the angular position of the spacecraft in the inertial radio reference frame. ADOR data have a precision of 25 nanoradians. Differential data types have additional scheduling complexities over single station data in that it is necessary to schedule two DSN stations at a time when both can see the spacecraft. The advantage is that 30 minutes of ADOR data provide superior angular accuracy to 100 or more hours of coherent X-band Doppler and ranging data.

The radio frequency of the communications plays a significant part in determining the accuracy of radio metric data. Traditionally Deep Space missions have used S-band (2.2 GHz) for communication, although recent missions have used X-band more extensively and future missions are investigating the use of Ka-band data. It is not required that the same frequency be used on the uplink as the downlink; Voyager made use of S-band on the uplink and X-band on the downlink to achieve higher data rate performance (S/X). The higher frequency data shows a decreased sensitivity to data corruption caused by interplanetary charged particles and consequently provides greater accuracy. The accuracy degradation of a single (60 second average) Doppler point degrades from 0.1 mm/s at X-band up/X-band down, to 0.5 mm/s at S-band up/X-band down, and to 1.0 mm/s for S-band up/S-band down data. The overall navigation performance (expressed in terms of 1 sigma geocentric angular uncertainty) degrades from typical numbers of 40 nanoradians for X/X tracking, to 100 nanoradians for S/X, and to 250 nanoradians for S/S tracking.

An additional issue concerning the choice of band is the effect of being angularly close to the Sun as viewed from the Earth. If the radio signal from the spacecraft passes close by the Sun there can be significant degradation of the signal. This effect is 15 times worse at S-band than at X-band. The result is that precision navigation is not possible when the Sun-Earth-S/C angle is less than 15" and the spacecraft is opposite the Sun from the Earth. Operational experience indicates that useful navigation is difficult or impossible to perform when the Sun-Earth-S/C angle drops below 5° to 7". These angles are approximate because the effect is dependent on solar activity which can vary considerably. A spacecraft in orbit at Venus or Mercury would spend a considerable amount of time at low Sun-Earth-S/C angles and opposite the Sun from the Earth. Angles less than 15" would occur as much as 30% of the time for a Mercury orbiter and 20% of the time for a Venus orbiter,

Determining the best system to meet navigation needs is highly mission dependent. Many future small missions do not have extremely stringent navigation requirements which will drive the design of the telecommunication system. However, for some missions with a need for highly precise radio metric navigation, especially those with critical operations needs at low Sun-Earth-S/C angles, the use of traditionally less expensive S-band systems may be precluded.

Cast is the major driver for the majority of future small missions. These missions are willing to take major performance reductions to meet cost requirements. An examination of many of the missions being discussed does not indicate that any new navigation technology will be required to meet the accuracy requirements of these missions, It is the general preference of JPL. navigation to use X-band data in preference to S-band data because of the better and more consistent performance and decreased susceptibility to charged particle degradation. However, for this to occur the cost of X-band transponders must be brought in line with that for S-band. [f this does not occur, those missions which do not require high accuracy navigation will choose to use lower cost options and those missions which need the better performance will either be shut out or forced to shoulder the cost burden of a more expensive system.

VI. Technology Recommendations

Spacecraft telecom system costs are dominated by three components: high gain antennas, transponders and power amplifiers. We considered new technologies for each of these components and generated technology development recommendations based on the needs of future missions.

Our technology recommendations take account of the changing nature of future deep space missions. These missions are expected to be far more frequent, enabling the benefits of economies of scale from the use of standardized components. They are far more cost- and mass-driven than performance-driven, so our focus has been on technologies that can lead to lower telecom cost and lower spacecraft mass.

High Gain Antenna Technology ----

None of the missions surveyed require deployable antennas. Each mission can fit an HGA large enough to suit its needs within its chosen launch vehicle shroud. However, many missions would benefit from an antenna that could share the limited area on the side of the spacecraft with a solar array. An integrated antenna/solar array could greatly simplify antenna structure and cost, while maximizing utilization of available area on the spacecraft.

The simplest, least expensive place to put spacecraft equipment is on the body of the spacecraft. It is highly desirable to attach both a solar array and a high gain antenna directly to the spacecraft body, i.e. without articulation. Articulated mechanisms add substantial complexity, cost, mass and risk to the spacecraft. In addition to the direct cost and mass of additional structures and mechanisms, such devices complicate thermal and attitude control design by adding additional modes that must be analyzed. The risk that one or more mechanisms fail to operate adds a need to evaluate still further contingency modes to prevent a single-point failure.

The solar array and HGA of spacecraft with body-fixed HGAs sent to targets beyond the Earth's orbit must be on the same side of the spacecraft. They must be designed for a limited range of Sun-Probe-Earth (EWE) angles -- for example, in Mars orbit, SPE does not exceed 42°. For missions such as these, with limited area available on one spacecraft side that must accommodate both the solar array and the antenna, it would be desirable to share as much of this limited area as possible. This can be done if an optically transparent reflector is used for the HGA.

Reflect array antennas[4] appear well suited to this situation, A reflect array can be constructed on a set of interleaved tensile elements resembling the strings of a tennis racket. A pair of tuned wires in a + shape is crimped onto the tensile elements at each intersection (Fig. 6).

The reflect array is structurally quite simple, The tensile elements are suspended from posts placed around the spacecraft or from the spacecraft rim. The reflect array itself is fiat. The reflect array electronically mimics a parabolic reflect, in effect creating a virtual parabolic dish reflector from a flat surface.

The reflect array should be far lighter and more resilient than reflectors which must maintain a parabolic or other curved shape. The tensile elements can be flexible ---- fundamentally, just strings. The reflect array structure should be quite inexpensive, since it does not require special materials. It could be made from flight-qualified wire and kapton string components.

The principal performance drawbacks of the reflect array are expected to be a narrow bandwidth and somewhat reduced efficiency compared to a true parabolic reflector. The narrow bandwidth may prevent the reflect array from being used for both transmit and receive. However, many missions could use the reflect array for the downlink only, with an LGA for uplink communications.

We believe that reflect array technology is potentially revolutionary. Reflect arrays appear ideally suited to a wide range of future missions. They warrant a serious proof-of-concept demonstration.

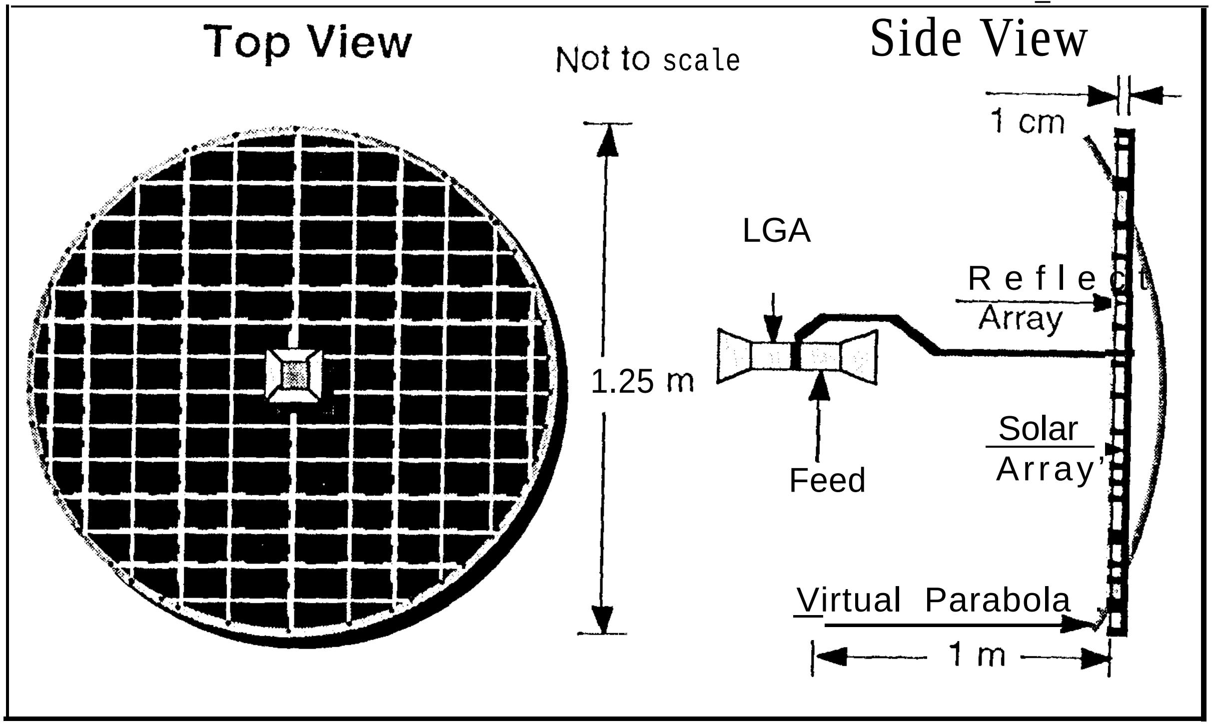

Figure 6. Integrated Reflect/Solar Array

Transponder Technology

The survey and analysis presented herein demonstrate that the data communications needs of all future deep space missions can be met with an X-band uplink and an X-band downlink. An X/X telecommunications system would also meet all expected navigation needs of future missions. Furthermore, future missions are expected to be more frequent than previous missions. A standard X/X Small Deep Space Transponder (SDST) could meet the needs of most, if not all, future deep space missions at substantially reduced mass and cost.

Future transponders can achieve higher levels of integration with greater use of digital circuitry and less reliance on analog circuits, which have expensive alignment requirements. The transponder can be integrated with command detection and telemetry modulation functions into one assembly. The transponder can be implemented with new technologies, such as microwave monolithic integrated circuits (MMIC) and application specific digital integrated circuits (ASIC), that significantly reduce size, mass and parts count. These approaches, with relaxation of some of the requirements imposed on the Cassini transponder, can reduce parts count from approximately 2,000 to about 400, with the number of select parts (used for alignment) reduced from about 120 to 20. In addition, advanced packaging methods can be used to reduce volume and mass,

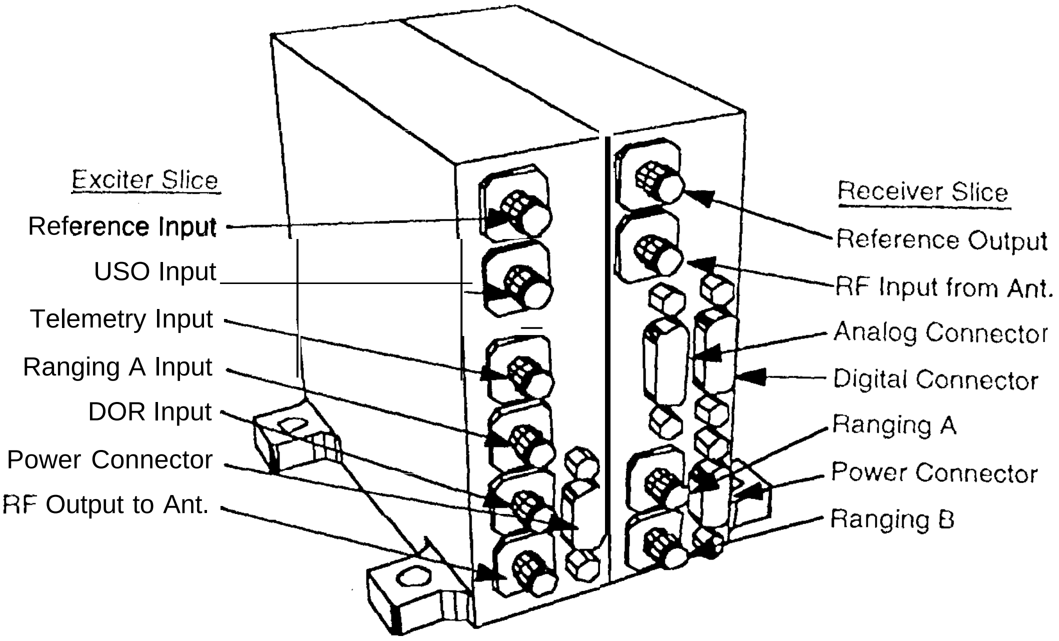

Fig. 7. Small Deep Space Transponder Diagram

Fig. 7 shows a diagram of the SDST. Fig. 8 illustrates an SDST in relation to the Cassini Deep Space Transponder. SDST volume is 70% less than that of equivalent Cassini elements and mass should be reduced by approximately 60%. The cost of flight units is expected to be reduced by about 45% when compared with Cassini elements manufactured under the same set of constraints.

The Pluto Fast Flyby Advanced Technology Insertion program funded an advanced digital receiver development effort at TRW that has initiated many of the activities necessary to complete the SDST.[5]

Transponder costs can be minimized by coordinating procurement between missions. SDST block buys, if possible, or other means of consolidating parts purchases can result in very substantial savings to multiple missions and should be encouraged,

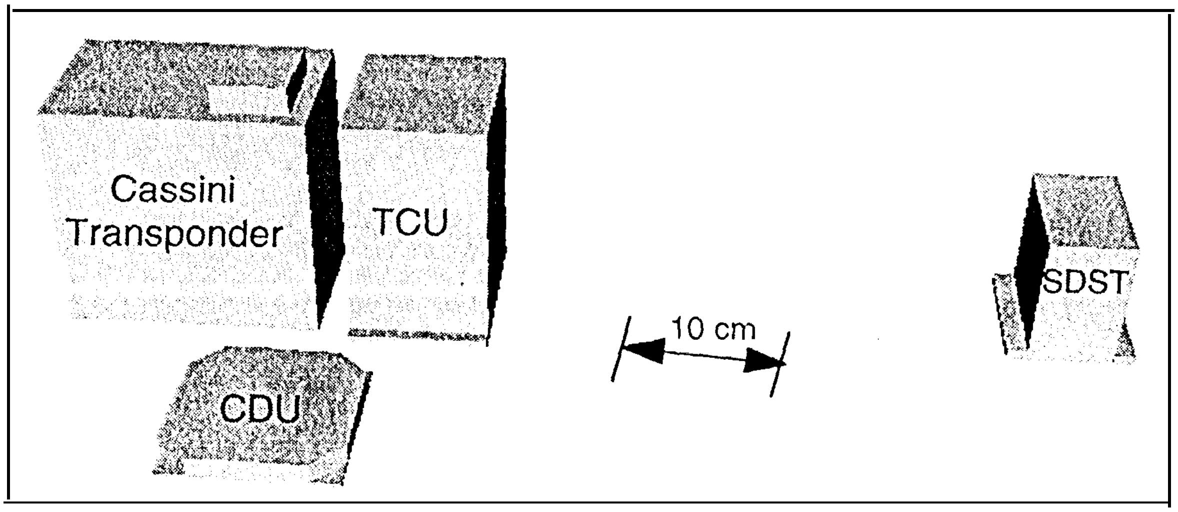

Fig. 8. Comparison of Cassini Telecom Elements and Equivalent SDST

Transmitter Technology

Transmitters can consume as much as 40% of total spacecraft power. Deep space missions have historically used Traveling Wave Tube Amplifier (TWTA) transmitters. A majority of small missions have severe DC power limitations and require modest (<20W) transmitter power levels, a regime in which solid state power amplifiers (SSPA) tend to have equal or greater efficiency than TWTA'S. In addition, SSPA'S tend to have inherently greater reliability than tubes.

There is a strong need to space qualify X-band high efficiency power transistors for solid state transmitters and to develop X-band power amplifier module EM building blocks for multi-mission application. The goal is to implement power module efficiencies of 40-50% to enable S. SPA's with 30-40% efficiencies. These efficiencies will reduce spacecraft SSPA power consumption by as much as 40%.

The power modules (Fig. 9) will have a nominal output power of 5W; but, by bias changes, this power can be reduced to as low as 2-3W. The modules will be designed to be ganged together with power summers to be produce higher power levels. For example, four of these units connected in parallel will be able to produce 20W of transmitter power. These modules than can function as the heart of solid state power amplifiers having a wide range of power levels (2-20W) with minimum additional design required for each version. The modules will be utilized in engineering models of each power amplifier type which will serve as the basis for flight models for small deep space missions.

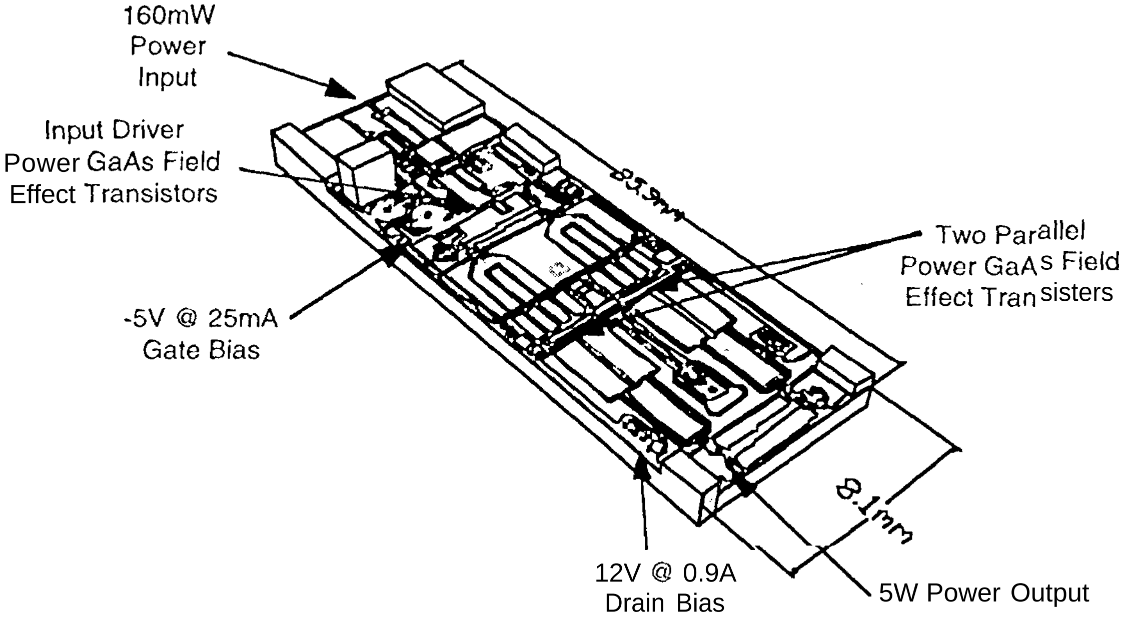

Fig. 9. 5W Power Amplifier Module

VII. Technology Development Plan

The goals of the deep space telecommunications technology plan are to reduce spacecraft telecommunications systems cost and mass, to reduce power consumption and to provide adequate telecommunications and radiometries performance for small missions.

The plan has three thrusts to meet multi-mission needs: high efficiency solid state power amplifier modules, engineering models of small "deep space transponders, and a proof-of-concept reflect array antenna demonstration.

Small Deep Space Transponder Task

The goal of the transponder development task is to implement a low cost X-band Small Deep Space Transponder (SDST) to meet needs of MSP '98, Pluto Fast Flyby and near term Discovery missions.

This task will leverage transponder technology investment made by the Pluto Fast Flyby Advanced Technology Insertion Program, which has resulted in the design of a small digital receiver. This program has demonstrated many of the technologies required to implement a Small Deep Space Transponder. These include extensive utilization of advanced digital architecture, microwave monolithic integrated circuit (MMIC) devices and advanced packaging.

High Efficiency SSPA Modules Task

This task will flight qualify a new high efficiency X-band power transistor for possible use in the Mars Surveyor Program and identify and qualify a second device which will be available as a back up for the Mars Surveyor Program and for potential use on the Pluto Fast Flyby and Discovery missions. In addition, power modules will be designed in which to life test the devices and for use as an engineering model for a building block for solid state power amplifiers. These modules will be designed to produce 5W of X-band power with high power added efficiency (40-50% goal). These modules will be designed using approaches which enables flight units to be manufactured in-house or by an industrial contractor.

Flight qualification of solid state power transistors will consist of analysis of devices and packages to assure their suitability for space flight use and an accelerated life test of a set of devices operating at three elevated temperatures. Forty devices will be tested to assure a statistically significant sample set.

Reflect. Array_ Task

JPL's Telecommunications and Mission Operations Directorate is funding a K_a-band reflect array demonstration. The goal of this effort is to demonstrate a reflect array for deep space use.

Schedule

Fig, 10 shows a top level schedule for the planned tasks. Funding has not been committed to this schedule. It is driven by the need to initiate the flight versions of the SDST by the beginning of FY'95 and to complete flight qualification of SSPA devices by the end of FY '96 for use by the Mars Surveyor Program.

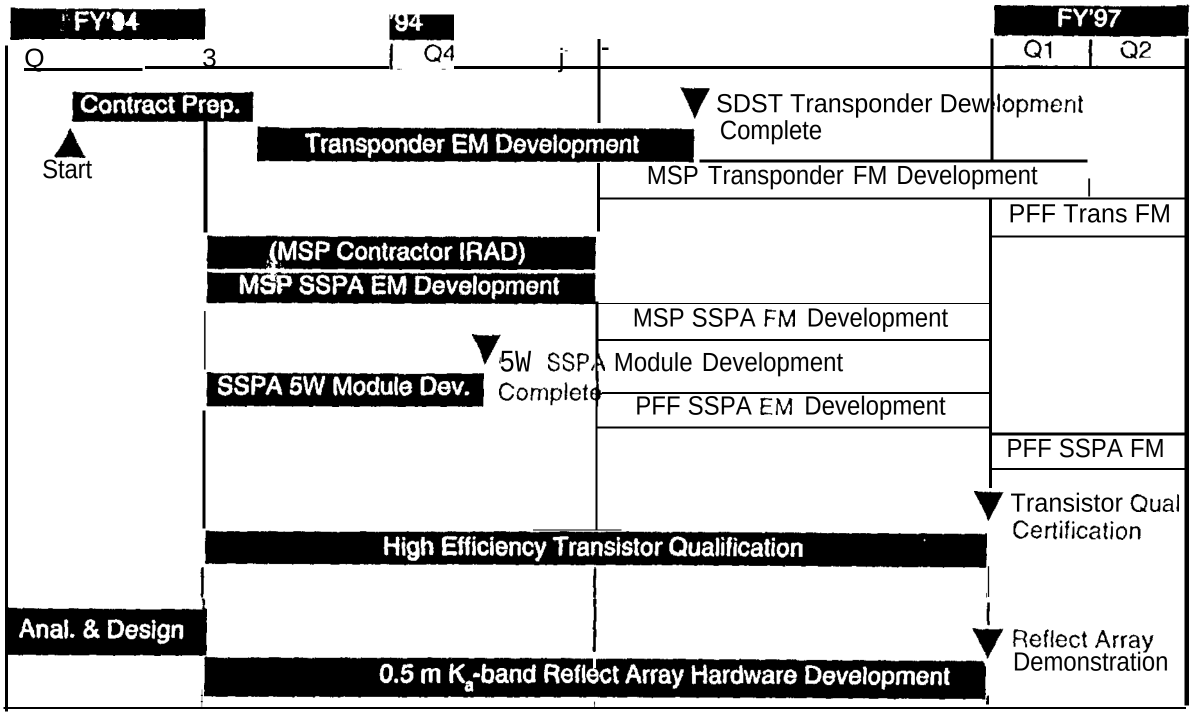

Fig. 10. Top Level Development Schedule

Conclusions

The survey conducted in the Small Deep Space Mission Telecommunications Task demonstrated that future missions will have relatively modest telecommunications requirements: The needs of all surveyed missions (with the possible exception of Small Solar Probe) can be met with an X/X -band telecommunications system. Given the expected higher rate of missions, a standardized transponder can be produced at a far lower cost than previous deep space transponders and would have much lower mass and volume.

Most missions would also benefit from a higher efficiency X-band solid state power amplifier, and many could benefit from integrated reflect/solar arrays. All these technologies should be fully funded.

Acknowledgments

The work described here was carried out at the Jet Propulsion Laboratory, California Institute of Technology under a contract with the National Aeronautics and Space Administration.

Our sponsors at JPL were James R. Cutts in the Space and Earth Science Programs Directorate and J.R. Hall and Robert Ceserone in the Telecommunications and Mission Operations Directorate.

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[5] Herman, M. I., et. al., “Microtechnology in Telecommunications for Spacecraft Cost and Mass Reduction,” IAA International Conference on Low-Cost Planetary Missions, April 12-15, 1994, Laurel, Maryland, Paper IAF-L-0808.

Table 7. X-Band Emergency Telemetry Design Control Table

GA *Downlink*
(-band
GA *Gain:* 6 *dBi*
)SN 70 moter Station
;olds tent)/25 degreos elevation angle/810-5 Weather modol
lot body noise: none
)SN Block V Receiver, 3 Hz mode
:oding: Viterbi (K= 15, R= 1/6),

Generic	Spacecraft
1.500E+08	Range, km
1.00	Flange, AU
8.34	OWLT, min
25	Elev. Angle

	Link Parameter	Unit	Design Value	Fav Tol	Adv Tol	Mean Value	Var	Shapo		
	TRANSMITTER PARAMETERS									
1	S/C RF Power Output	dBm	30.00	0.25	-0.25	30.00	0,0104	T	1	Xmtr Pwr, W
2	Xmitter Circuit Loss	dB	-1.00	0.00	0,00	-1.00	0.0000	u		
3	Antenna Gain	dBi	6.00	0.00	0.00	6.00	0.0000	T	LGA	S/C Antenna
4	Ant Pointing Loss	dB	0.00	0,00	0.00	0.00	0,0000	u	0	Pointing Loss
5	EIRP (1+2+3+4)	dBm				35.00	0,0104	U		
	PA1 H PARAME TERS									
6	Space Loss	dB	-274.47	0.00	0.00	-274.47	0,0000	D	X	" band
7	Atmospheric Attn	dB	-0.11	0.00	0.00	-0.11	0.0000	D	8417.72	Freq, MHz
	RECEIVER PARAMETERS									
8	DSN Antenna Gain	dB	74.09	0.20	-0.20	74,09	0.0134	U	95	Weather %
9	Ant Pointing Loss	dB	-0.10	0.00	0.00	-0.10	0.0000	u	14	DSS antenna
0	Polarization Loss	dB	0.00	0,00	0,00	0.00	0.0000	T		
	TOTAL POWER SUMMARY									
1	Total Rcvd Pwr (Pt) (5+6+7+8+9+10)	dBm				-165.60	0.0238	G		
2	Noiso Spec Dens	dBm/Hz	-184.08	-0.32	(),30	-184.09	0.0099	G		
	System Noise Temp	K	28.31	-2.00	2.00			G	1	Way
3	Available Pt/No	dB*Hz				18.49	0.0337	G		
	CARRIER PERFORMANCE									
4	Tlm Carrier Supp	dB	-2.31	0.29	-0.32	-2.32	0.0156	T	TRUE	TLM.MOD
5	Rng Carrier Supp	dB	0.00	0.00	0.00	0.00	0.0000	T	FALSE	RNG.MOD
6	DOR Carrier Supp	dB	0.00	0.00	0,00	0.00	0.0000	T	FALSE	DOR.MOD
7	Rcvd Carr Pwr (Pc)	dET				-167.92	0.0394	T		
8	Carr Noise BW, 2BL0	dB	4.77	-0.46	0.41	4.76	0.0317	T	3	RF.BW.SELECT
9	Available CNR in 2BL0	dB				11.41	0.0810	U	3	RF Bandwidth
O	Threshold CNR	dB				10.00	0.0000	D		
1	CNR Margin	dB			[	1.41	0.0810	U		
	TELEMETRY PERFORMANCE									
2	Tlm Data Supp	dB	-3.84	-0.45	0.42	-3.85	0.0315	T	40	tlm MI, deg
3	Rng Data Supp	dB	0.00	0.00	0,00	0.00	0.0000	T	0.29	rng MI, rad
4	DOR Data Supp	dB	0.00	0.00	0.00	0,00	0.0000	T	0.64	dor 1 MI, rad
5	Data Rata	dB	10.00	0.00	0.00	10,00	0.0000	D	0.32	dor 2 MI, rad
6	Eb/No to Receiver	de				4.64	0,0652	T	10	data rate
7	system Lossos	dB	-2.00	0.25	-0.25	-2.00	0.0104	T		
'8	Eb/No Output	dB				2.64	0.0756	T		
9	Threshold Eb/No	dB				1.00	0,0000	D		
O	Performance Margin	dB			[	1.64	0.0756	1		

Table 8.

Appendix
X-Band High Rate Telemetry

Design Control Table

-HGA-Downlink
X-band
HGA Gain: 40 dBi
DSN 34 meter HEF Station
Goldstone/25 degrees elevation angle/810-5 Weather model
Hot body noise: none
DSN Block III Rcvr, 10.8 Hz bandwidth mode
Coding: Viterbi (K= 7, R= 1/2),

Generic	
1.500E+08	Spacecraft Range, km
1,00	Range, AU
8.34	OWLT, min
25	Elev. Angle
10	Xmtr Pwr, W
HGA	S/C Antenna
0	Pointing Loss
X	RF band
8417.72	Freq, MHz
80	Weather %
15	DSS antenna
1	Way
TRUE	1 LM.MOD
FALSE	RNG.MOD
FALSE	DOR.MOD
10.8	RF. BW.SELECT
10.8	RF Bandwidth
80	tlm MI, deg
0.29	rng MI, rad
0,64	dor 1 MI, rad
0,32	dor 2 MI, rad
100000	data rate

	Link Parameter	Unit	Design Value	Fav Tol	Adv Tol	Mean Value	Var	Shape
	TRANSMITTER PARAMETERS							
1	S/C RF Power Output	dBm	40.00	0.25	-0.25	40.00	0.0104	T
2	Xmitter Circuit Loss	dB	-2.00	0.00	0.00	-2.00	0,0000	U
31	Antenna Gain	dBi	40.00	0.40	-0.40	40.00	0.0267	T
4	Ant Pointing Loss	dB	0.00	0.00	0.00	0.00	0.0000	U
5	EIRP (1+2+3+4)	dBm				78.00	0.0371	U
	PATH PARAMETERS							
6	Space Loss	dB	-274.47	0.00	0.00	-274.47	0.0000	D
7	Atmospheric Attn	dB	-0.09	0.00	0.00	-0.09	0.0000	D
	RECEIVER PARAMETERS							
8	DSN Antenna Gain	dB	68.26	0.20	-0.20	68.26	0.0134	U
9	Ant Pointing Loss	dB	-0.10	0,00	0.00	-0.10	0,0000	U
0	polarization Loss	dB	0.00	0.00	0.00	0.00	0.0000	T
	TOTAL POWER SUMMARY							
1	Total Rcvd Pwr (Pt) (5+6+7+8+9+10)	dBm				-128.40	0.0505	G
2	Noise Spec Dens	dBm/Hz	-184.87	-0.38	0.35	.184.88	0.0142	G
	System Noise Temp	K	23.62	-2.00	2.oo			G
3	Available Pt/No	dB*Hz				56.48	0,0647	G
	CARRIER PERFORMANCE							
I	Tlm Carrier Supp	dB	-15.21	3.35	-5.65	-15.97	3.4527	T
	Rng Carrier Supp	dB	0.00	0,00	0.00	0.00	0.0000	T
	DOR Carrier Supp	dB	0.00	0.00	0.00	0.00	0.0000	T
	Rcvd Carr Pwr (PC)	dB				-144.38	3.5032	T
	Carr Noise BW, 2BLo	dB	10.33	-0.46	0.41	10.32	0.0317	T
	Available CNR in $2BL_0$	dB				30.19	3,5491	u
O	Threshold CNR	dB				10.00	0.0000	D
1	CNR Margin	dB				20.19	3.549	u
	TELEMETRY PERFORMANCE							
2	Tlm Data SUpp	dE3	'0.13	-0.16	0.10	-0.15	0.0028	T
3	Rng Data Supp	dB	0.00	0.00	0.00	0.00	0.0000	T
4	DOR Data SUpp	dE3	0.00	0.00	0.00	0.00	0.0000	T
5	Data Rate	dB	50.00	0,00	0.00	50.00	0.0000	D
6	Eb/No to Receiver	dB				6.32	0.0675	T
7	System Losses	dB	-0.85	0.26	-0.26	-0.85	0,0113	T
3	Eb/No Output	dB				5.47	0.0788	T
9	Threshold Eb/No	dB				3.01	0.0000	D
0	Performance Margin	dB				2.46	0.0788	T

Table 9.

Appendix

Cassini Transponder Uplink

Design Control Table

.GA Uplink	MGS	**Spacecraft**
Y-band	9.000E+08	Range, km
.GA Gain: 6 *dBi*	*6.02*	Range, AU
)SN 34 *meter HEF Station*	50.03	**OWLT,** min
:anberra/25 degrees elevation angle/810-5 weather **model**	1.50E+08	AU, krn
-lot body noise: none		
18 Hz bandwidth		
:oding: None	*25*	Elev. Angle

	Link Parameter	Unit	Design Value	Fav Tol	Adv Tol	Mean Value	Var	Shape		
	TRANSMITTER PARAMETERS									
1	Total Xmitter Pwr	dBm	73.01	0.00	0.00	73.01	0.0000	T	20	Xmtr Pwr, kW
2	DSN Antenna Gain	dBi	67.06	0.20	-0.20	67.06	0.0134	U	15	DSS antenna
3	Ant Pointing Loss	dB	-0.10	0.00	0.00	-0.10	0.0000	u		
4	EIRP (1+2+3)	dBm				139.97	0.0134	u		
	PATH PARAMETERS								X	" band
5	Space Loss	dB	-288.63	0.00	0.00	-288.63	0.0000	D	7162.31	Freq, MHz
6	Atmospheric Attn	dB	-0.09	0.00	0.00	-0.09	0.0000	D	80	Weather %
	RECEIVER PARAMETERS									
7	Polarization Loss	dB	0.00	0.00	0.00	0.00	0.0000	T		
8	Ant Pointing Loss	dB	0.00	0.00	0.00	0.00	0.0000	u	o"	Pointing Loss
9	S/C Antenna Gain	dB	6.00	0.00	0.00	6.00	0.0000	T	LGA	S/C Antenna
I O	Lumped Ckt/Ant Loss	dB	-2.00	0.00	0.00	-2.00	0.0000	u		
	TOTAL POWER SUMMARY									
I 1	Total Rcvd Pwr (Pt) (4+5+6+7+8+9+10)	dBm				-144.75	0.0134	G		
2	Noise Spec Dens	dBm/Hz	-172.48	0.00	0.00	-172.48	0.0000	G	290.00	k, Trcvr
	System Noise Temp	K	409.64	0.00	0.00			G	1.50	dBNF
3	Rcvd Pt/No	dB*Hz				27.72	0.0134	G		
	CARRIER PERFORMANCE									
4	Cmd Carrier Supp	dB	-2.08	0.00	0.00	-2.08	0.0000	T	TRUE	CMD.MOD
5	Rng Carrier Supp	dB	0.00	0.00	0.00	0.00	0.0000	T	0	Rng Supp, dB
6	Rcvd Carr Power (Pc)	dB				-146.84	0.0134	T		
7	Carr Noise BW, 2BL0	dB/Hz	12.43	-1.25	0.97	12.29	0.4117	u	17.5 Hz	
8	Threshold CNR	dB				10.00	0.0000	D		
9	Carrier Threshold Pwr	dBm				-150.18	0.4117	u	(12+17+18)	
o	CNR Margin	dB				3.35	0.4250	u	(16-19)	
	CHANNEL PERFORWE									
1	Data Pwr to Rcvr (Pal)	dB				.149.21	0.0134	T		
2	Cmd Modulation Loss	dB	-4.45	0.00	0.00	-4.45	0.0000	T	0.95	cmd MI, rad
3	Rng Data Supp	dB	0.00	0.00	0.00	0.00	0.0000	T		
4	Data Rate	dB	8.93	0.00	0.00	8.93	0.0000	D	7.8125	data rate
5	Eb/No	dB				12.80	0.0095	T		
6	Radio Loss	dB	-1.00	0.05	-0.10	-1.02	0.0010	T		
7	System Losses	dB	-0.50	0.05	-0.10	-0.52	0.0010	T		
8	Threshold Eb/No	dB				**9.60**	**0.0000**	**D**	**BER = 1 e-5, uncoded**	
9	Performance Margin	dB				3.20	**0.0095**	**T**		