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Orbiting Deep Space Relay Station Study Final Report

Volume II. Conceptual Design

John A. Hunter

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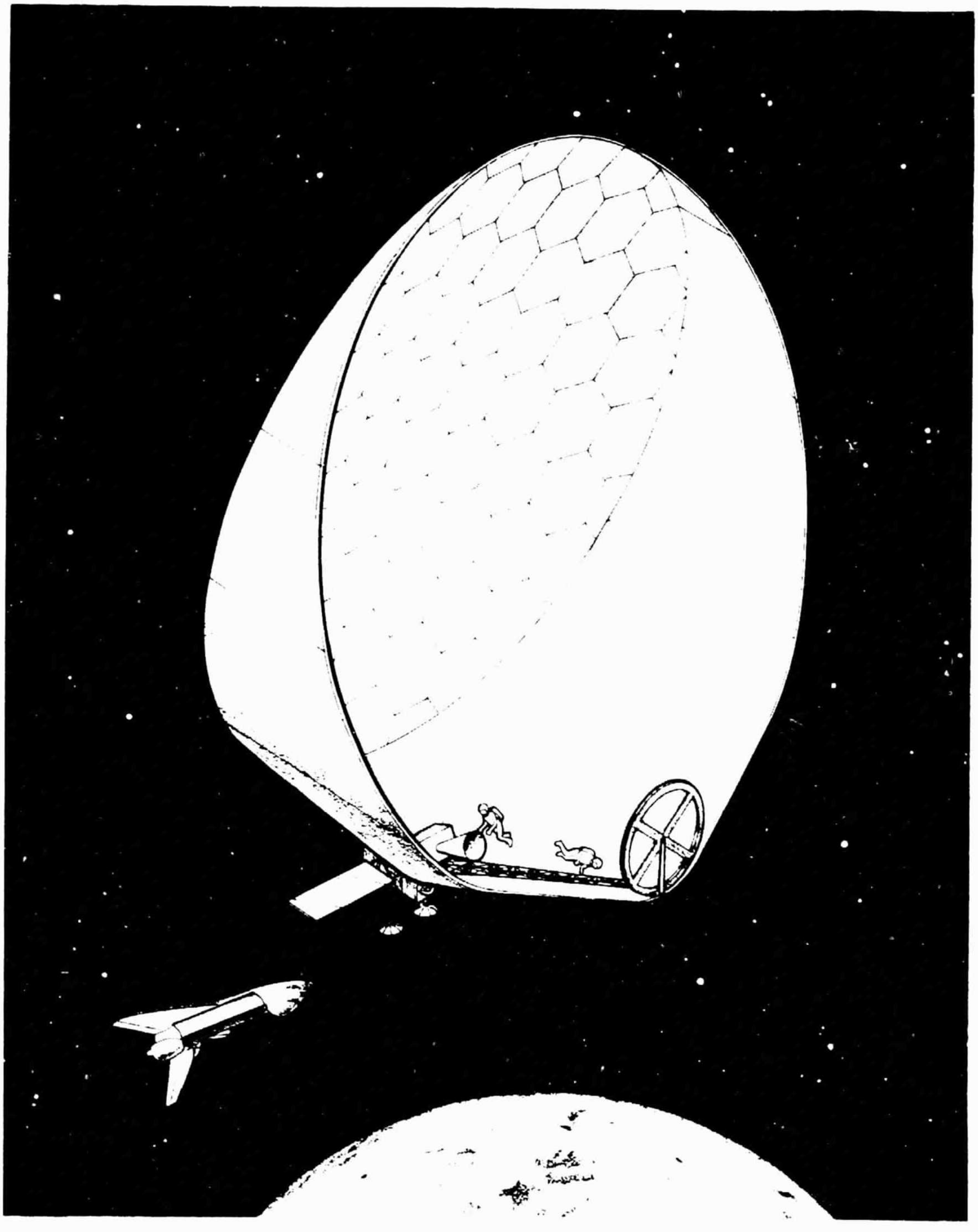
June 15, 1979

National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California



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 of economically boosting 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. This study was jointly sponsored by NASA OSS, OAST, and OSTDS. Volume I of this report presents the deep space tracking and communications requirements for 1985-2000. Volume II describes the ODSRS conceptual design, and provides the baseline for implementation cost and schedule estimates. Volume III 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.

ACKNOWLEDGMENTS

The author wishes to acknowledge the contribution of the many individuals at JPL who participated in the ODSRS study. Inputs, critiques, and generally helpful comments were received from too many people to list here. The following were designated as members of the study team and made major contributions to this report: T. Bird, D. Cain, S. Deese, W. Higa, D. Hixon, C. Ivie, D. Le Blanc, R. Levy, B. Mulhall, P. Potter, M. Swerdling, J. Wright, M. Koerner, G. Ragsdale, M. Katow, H. Price, C. Guernsey, A. Galbraith, B. Sharpe, and H. Partma. In addition, a steering committee composed of A. Hibbs, T. Thornton, K. Heftman, and R. Powell provided continuing review and direction throughout the study and J. James provided valuable guidance in planning the study and reporting the results.

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 than 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.

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I. ODSRS CONCEPTUAL DESIGN

This volume of the Orbiting Deep Space Relay Station (ODSRS) study describes the conceptual design of the ODSRS system and subsystems and summarizes the process by which this design was accomplished. It provides the baseline from which the cost and schedule estimates for integrating an ODSRS with the DSN, which are presented in Volume III, were developed. In addition, this volume describes the system requirements and assumptions from which this conceptual design evolved, and provides a basis for evaluating the effect of future changes in requirements on this design.

A. Design Process

The ODSRS conceptual design was accomplished by first defining the system level requirements, and then selecting the subsystem concepts to meet these requirements. System requirements fell into two major categories. The first category was requirements that are firm by definition, such as Shuttle payload mass and volume, launch and orbital environments, and international agreements on radio signal frequencies. The second category was requirements that were assumed in order to bound this study. Assumed requirements are called out when they are made so that their effect on the study results can be identified.

After the system requirements were defined, subsystem concept options to meet these requirements were identified. The optimum subsystem concept was selected, based on the following criteria:

- The subsystem had to meet the ODSRS system performance and operations requirements.
- The subsystem should result in minimizing total ODSRS system cost including implementation and operations.
- The subsystem concept should be based on technology that has a high expectation of being developed in time for a project start in the 1985 time frame.

Note that the data available to this study did not permit an exhaustive quantitative optimization of all subsystem future costs and technology. In many cases, the judgment of the engineers involved as to the most likely cost and technology availability was used. The cost and technology assumptions used are defined for each subsystem, so that the effect of future subsystem developments on the overall ODSRS system design can be evaluated as appropriate.

B. Design Summary

This section is intended to provide an overall perspective of the results of this ODSRS design, so that the detailed technical material to follow can be more easily read and understood.

1. Launch and Low-Earth Orbital Assembly

The ODSRS will be launched into a low-Earth orbit by the Space Shuttle. This orbit has an inclination of about 28.5 deg. It is anticipated that three Shuttles will be required to transport all of the ODSRS hardware into orbit, including one Shuttle for the orbit transfer propulsion system. The ODSRS will be assembled, aligned, and tested in the low-Earth orbit (LEO), and then boosted to a geosynchronous orbit (GEO). Final system level performance and environmental tests will be performed in LEO prior to a decision to transfer to GEO. Although it is desirable for the final GEO to be geostationary (0-deg inclination), a low-inclination orbit is acceptable if its minimum elevation angle from its receiving station on Earth is at least 30 deg. The ODSRS will be precisely aligned and tested prior to Shuttle launch, with the intention of minimizing alignment requirements in orbit. It is recognized that some alignment will probably be required in orbit due to manufacturing and assembly tolerances and to the difference between the 1-g and 0-g environments. The time required for in-orbit alignment is critical due to the maximum orbital time constraints of the Shuttle and to the cost of Shuttle in-orbit operations.

2. Geosynchronous Orbital Operations

When tracking a spacecraft, the ODSRS will be slewed so as to point at the spacecraft, using a precision stellar-referenced attitude control system. After the spacecraft is acquired, ODSRS pointing will be by a closed-loop monopulse system using the signal received from the target spacecraft as a pointing reference. The ODSRS can track S-, X-, and K_A-band signals, with any combination of two bands simultaneously. Reception is via a cryogenically-cooled, low-noise receiver. The received spacecraft signals are translated in frequency to the ODSRS-to-Earth frequency (14 Ghz), amplified, and retransmitted to the ODSRS Earth station.

C. System Concept

Conceptual system interfaces for a tracking and communications system that include an orbiting station are shown in Figure 1. This figure shows an overall system that includes existing DSN stations, an ODSRS, and the ground-based telemetry receiving station(s) associated with the ODSRS. A future system with an ODSRS may include existing DSN stations, DSN stations in the territorial U.S. only, or no DSN stations. The ODSRS ground stations can be very simple, with an antenna approximately 5 meters in diameter and a noncryogenic receiver. They would have telemetry demodulation equipment similar to that of an existing DSN station, and would have equipment to receive and handle radiometric data. It is expected that one of these stations would be colocated with the Space Flight Operations Facility. A significant difference between the ODSRS and a DSN station is that the ODSRS does not have a transmitting capability to transmit to the spacecraft it is tracking.

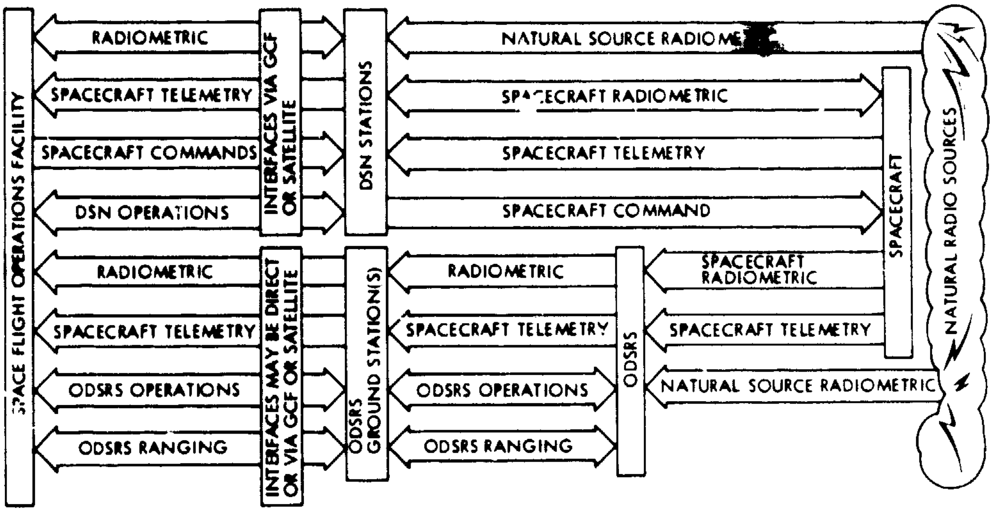


Figure 1. ODSRS conceptual system interfaces

The ODSRS will not do any processing of the data it receives from a deep space probe, but will relay it to Earth in a "bent pipe" mode. This means that the ODSRS will receive the modulated RF carrier from the deep space probe, translate its frequency, amplify it, and retransmit it to Earth. The telemetry and ranging subcarriers will not be demodulated, and no clean-up of the data will take place. The ODSRS-to-Earth RF signal will be coherent with the RF signal from the deep space probe and will contain the frequency and phase information needed for navigation and radio science.

Stationkeeping operations for the ODSRS will require an Earth-to-ODSRS command link, an ODSRS-to-Earth telemetry link, and a precise ranging link to maintain accurate knowledge of the ODSRS location for spacecraft navigation purposes. It is expected that the ODSRS stationkeeping operations function will be colocated with the telemetry receiving site to minimize the total number of operators needed.

1. System Description

The ODSRS conceptual design is a 28-meter, offset feed, two-reflector cassegrain antenna. It has a lightweight deployable backup structure with precision surface panels attached in low-Earth orbit, using the Shuttle as a work platform. Support subsystems for the ODSRS are contained in a boxlike bus attached to the main antenna backup structure. The estimated ODSRS mass is 8500 kg, and its stowed volume is approximately 2 Shuttle cargo bays. The orbit transfer vehicle to boost the ODSRS from Shuttle orbit to synchronous orbit will require a third Shuttle flight. ODSRS power consumption is estimated to be 5.5 kW, most of which will be a continuous load for refrigerators for the cryogenic receivers.

Figure 2 shows the major functions the ODSRS will perform and their relationship to each other. Note that these functions are not defined as subsystems and that more than one of the functions shown may be performed by one subsystem.

2. Subsystem Descriptions

Table 1 defines the design concept selected for each of the ODSRS subsystems and summarizes the considerations that went into the selection of that concept. Details will be found in the subsystem design, Section III.

3. ODSRS Ground Station

The ground stations that will be required to support the ODSRS are significantly different in form and function from the existing DSN stations. A description of the relay telemetry, ranging stationkeeping, and data processing requirements that the ground stations must meet to support the ODSRS is found in Section IV.

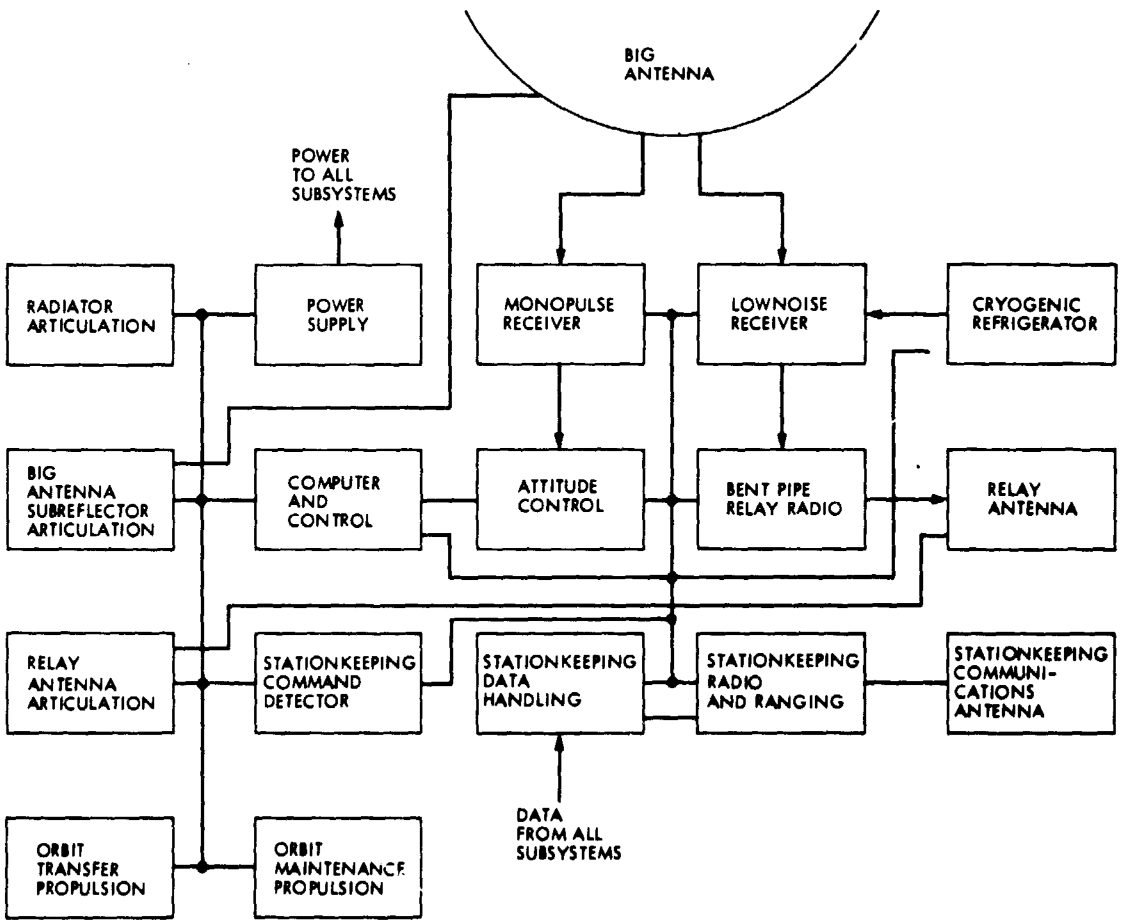


Figure 2. ODSRS functional block diagram

Table 1. ODSRS subsystem design concepts selected

Subsystem	Candidate design concepts	Design concept selected	Rationale
Receiving antenna configuration	Array of small antennas--signals combined in orbit Array of small antennas--signals combined on Earth Single antenna with symmetrical feed Single antenna with offset feed	Single antenna with offset feed	Arrays require either more cryogenic receivers or precision low-noise combining assembly that would be difficult to set up and align in space RFI rejection characteristics of array uncertain Offset feed provides rejection of RFI from Earth
Receiving antenna surface	Solid panels (erectible) Mesh (deployable)	Solid panels	Technology for 32-GHz, 30-m mesh deployable antenna in 1985 time frame uncertain Solid panel concepts that meet ODSRS requirements have been demonstrated on Earth
Receiving antenna size	Combinations of frequency, size, and receiver noise temperature to yield 6-dB improvement over existing DSN	28 m	Can be assembled using a Shuttle as an assembly facility with "stock" RMS At 32 GHz, manufacturing assembly, and thermal tolerances for 28-m dish yield 1-db surface losses Parts for 28-m solid panel dish fill 2 Shuttles At 32 GHz, 28-m dish can be pointed with attitude control technology that is planned for 1985 time frame
Low-noise receiver configuration	Noncryogenic Cryogenic with refrigerator Cryogenic with expendable cryogenic fluid	Cryogenic with refrigerator	Noncryogenic receiver required antenna diameter increase of 3 times - manufacturing, precision orbital assembly, and pointing of the larger dish size would be significantly more difficult Expendable cryogenic fluid would require a very large mass of cryogenic fluid to be stored in space for 10 years

Table 1. ODSRS subsystem design concepts selected (continuation 1)

Subsystem	Candidate design concepts	Design concept selected	Rationale
Receiving antenna and low-noise receiver frequency	S- and X-band for existing spacecraft designs Higher frequency for performance and operations	S, X, K_A (32 GHz)	Antenna surface tolerance at 32 GHz does not require active surface control for 28-m dish Technology for 32-GHz transmitters in 1985 is possible Technology for 32-GHz, low-noise, space-qualified receivers in 1985 is possible
Relay radio	ODSRS to Earth frequency, antenna size, power levels	14 GHz 2 m antenna on ODSRS, 5 m antenna on Earth Transmitter power 1 mW to 3 W	No frequency allocation exists for orbiting deep space relay service -- expect allocation around 14 GHz from next WARC Maximum power levels limited by CCIR agreements on max flux density on Earth Not a technically difficult link to implement — variations in antenna size and power levels not a major cost driver
Stationkeeping telecommunications	NASA standard transponder	NASA standard transponder 10-cm ranging capability	Not a technically difficult link -- standard transponder meets requirements and should be lowest cost Expect 10-cm ranging system will exist by 1985
Computer and control Stationkeeping data handling	NASA standard CCS	NASA standard CCS	ODSRS requirements are not technically difficult and can be easily handled by the NASA standard
Orbit transfer propulsion	Single-stage, cryogenic chemical Orbital Transfer Vehicle (OTV)	For size and mass, a single-stage, cryogenic chemical OTV was analyzed. It would require 1 Shuttle to boost it to low-Earth orbit	Due to the enormous cost of developing an OTV, it was assumed that a "standard" OTV will be developed for use by many future geosynchronous orbit projects and it could be used by the ODSRS

Table 1. ODSRS subsystem design concepts selected (continuation 2)

Subsystem	Candidate design concepts	Design concept selected	Rationale
Power	Solar array RTGs Isotope dynamic power converters (Brayton cycle -- "BIPS", and Rankine cycle -- "KIPS")	Kilowatt Isotope Power System (KIPS)	Solar array requires 85 m^2 area, 3 d.f. would increase attitude control problems, and would require large batteries to operate during occultation of the Sun by Earth, and large batteries for shadowing of the solar panels by the antenna RTGs for 5.5 kW are large and heavy, and also would present a large heat load while in the shuttle BIPS technology does not look likely for 1985 KIPS technology looks likely for 1985
Attitude control -- techniques for unloading reaction wheels	Electric thrusters Chemical thrusters Gravity gradient Solar pressure control Magnetic torquers	Hydrazine thrusters	Eliminated magnetic torquers because Earth's magnetic field at ODSRS altitude is weak and uncertain Gravity gradient and solar pressure eliminated due to requirement of arbitrary orientation of ODSRS with respect to Earth and Sun Electric thrusters have RFI problem and require long periods for unloading, and require lots of power
Stationkeeping propulsion	Pulsed plasma Hydrazine thrusters	Hydrazine thrusters	Pulsed plasma thrusters have RFI problem, require long periods of operation with the ODSRS not pointed at a spacecraft, and require lots of power Attitude control and stationkeeping propulsion share some hardware and control functions with hydrazine system

II. ODSRS SYSTEM DESIGN

A. Design Criteria

The ODSRS system design was begun with no hard constraints on the configuration of the structure, antenna, or any of the subsystems. The existing interfaces and functions of the deep space probes and stations of the DSN were not assumed as constraints. A few basic design goals were defined by the study team, and hard constraints were allowed to develop as the study progressed. The initial design goals were as follows:

(1) The ODSRS should be designed for a nonrefurbished lifetime in orbit of 10 years. If this became a major technological or cost driver, design compromises to shorter lifetime would be made. The electronic bays should be removable and replaceable by remote manipulators or astronauts.

(2) Baseline performance of the ODSRS should offer a 6-dB advantage over the existing DSN, and the design concept should have potential for performance growth in the future. This is similar to the planned performance improvement for the Large Advanced Antenna (LAAS) and will provide a basis for tradeoff and cost comparison studies.

(3) Subsystem design should emphasize configurations with zero expendables, where possible.

(4) The ODSRS should be able to receive the existing spacecraft-to-Earth frequencies and should have the capability to operate at higher frequencies.

(5) New technology developments should be limited to ones that are reasonably forecastable for the 1985 time period.

(6) A tracking network, consisting of an ODSRS and DSN stations located only in the territorial U.S., should be capable of providing all telemetry, command, and navigation functions for a deep space mission in the post-1985 time period.

(7) One alternate configuration should be designed such that the entire ODSRS system and orbit change propulsion would fit in one Shuttle. (This goal was determined early in the design to significantly limit the maximum ODSRS diameter.) The single Shuttle option was carried until it became obvious that the maximum performance of a single Shuttle ODSRS would be too low to justify its cost.

(8) Tradeoffs between communications systems to achieve future performance requirements will consider spacecraft design changes as well as changes to ground stations, new ground stations, and an ODSRS.

During the ODSRS design, additional constraints on the overall system and on the subsystem hardware evolved. These are as follows:

(9) The ODSRS will not have the capability to transmit to a deep space probe. This constraint developed from considering the size of the power supply on the ODSRS that would be required to provide a transmit capability competitive with the existing DSN ground station capability.

(10) The ODSRS orbit inclination must be such that the minimum elevation angle from its receiving station on Earth will be 30 deg at the southernmost point in the orbit. The constraint is necessary for design of an ODSRS-to-Earth telemetry link that will provide adequate data quality at maximum bit rates under adverse weather conditions without violating CCIR requirements.

(11) The maximum extra-vehicular assembly (EVA) time required by the ODSRS must be limited by Shuttle astronaut capabilities. This maximum is not completely defined at this time. As Shuttle requirements develop, they will be included in the ODSRS-Shuttle interface.

B. Configuration Drawings

1. Operational Configuration

The 28-m ODSRS operational configuration is shown in Figure 3. Figure 4 shows the same view with the RFI shield omitted to provide visibility of other components. Key elements are labeled, and scale-size astronaut figures are shown for size perspective. Orthographic views showing the precision antenna surface panels and the PETA structure are shown in Figures 5 and 6.

2. Launch Configuration

A potential launch configuration is shown in Figure 7. Note that this arrangement would have to be adjusted to meet Shuttle center-of-mass requirements. It is expected that the final packaging configuration for launch will require two Shuttle bays to carry all of the ODSRS components and assembly, alignment and test equipment into orbit. A third Shuttle will be required for the orbit transfer propulsion system.

C. Equipment, Mass, and Power List

Table 2 lists the subsystem hardware planned to make up the ODSRS system. Also shown are the estimated mass and power consumption for each subsystem.

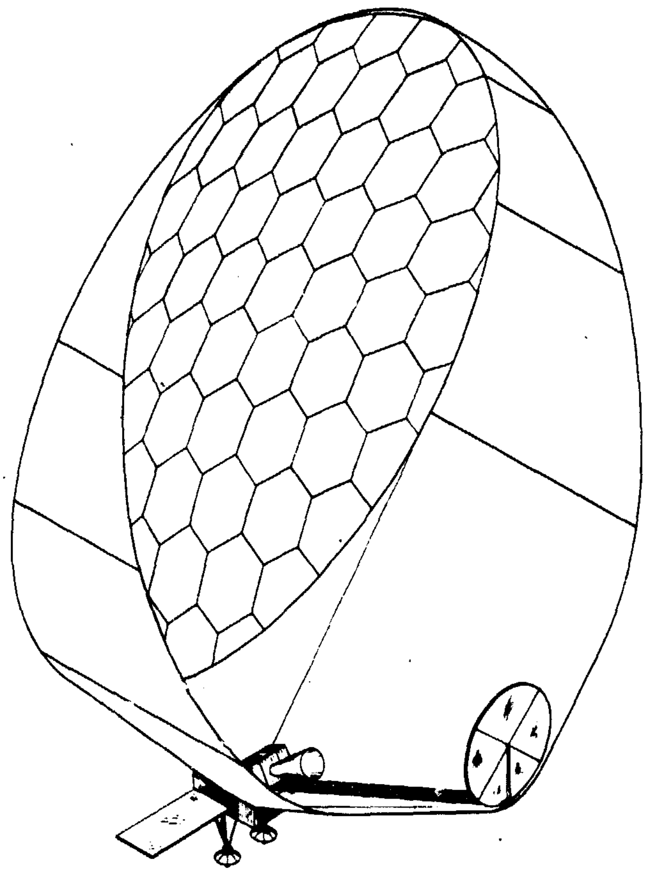


Figure 3. ODSRS operational configuration

D. Environmental Requirements

The objective of the ODSRS Environmental Requirements Program is to verify the environmental adequacy of the ODSRS to perform its intended mission. This will be accomplished by analysis and definition of the expected environmental extremes and by the implementation of a formal environmental test program.

The launch ascent, and flight environmental requirements were derived from:

(1) Space shuttle system payload accommodations (Ref. 1).

(2) NASA payload requirements for IUS (Ref. 2).

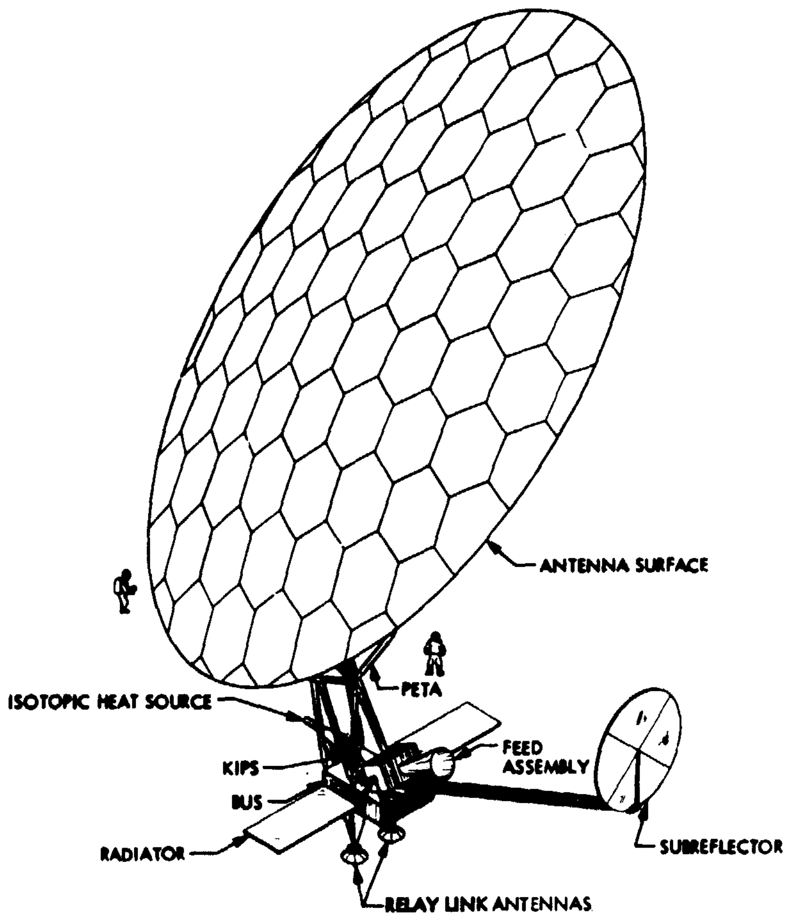


Figure 4. ODSRS without radio interference shield

1. Launch Environment

a. <u>Launch Pressure Profile</u>. The Orbiter payload bay is vented during launch. The payload bay pressure history during ascent is shown in Figure 8. The ascent time sequence is shown in Figure 9.

b. <u>Acoustics</u>. The Shuttle internal noise environments are generated by rocket engines during liftoff and by aerodynamic turbulence during the boost phase. The acoustic noise levels for payload equipment are presented in Table 3 as one-third octave and spectra. (These levels assume 0-dB attenuation by the contamination control shroud.)

c. <u>Sinusoidal Vibration</u>. The expected sinusoidal vibration levels are presented in Table 4. These levels should be assumed at the mounting points in any direction. The sweep rate is 2 oct/minute.

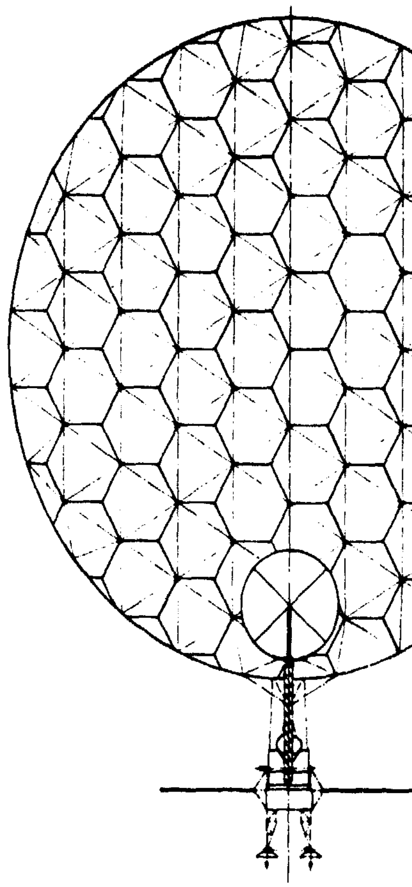


Figure 5. Orthographic view showing surface panels

d. Random Vibration. The expected random vibration levels are presented in Table 5. These levels should be assumed at the mounting points in any direction.

e. Static Acceleration. The acceleration is 9 g in any direction.

2. Flight Environments

These requirements consist of the environments that the ODSRS spacecraft will encounter after its insertion into geosynchronous orbit.

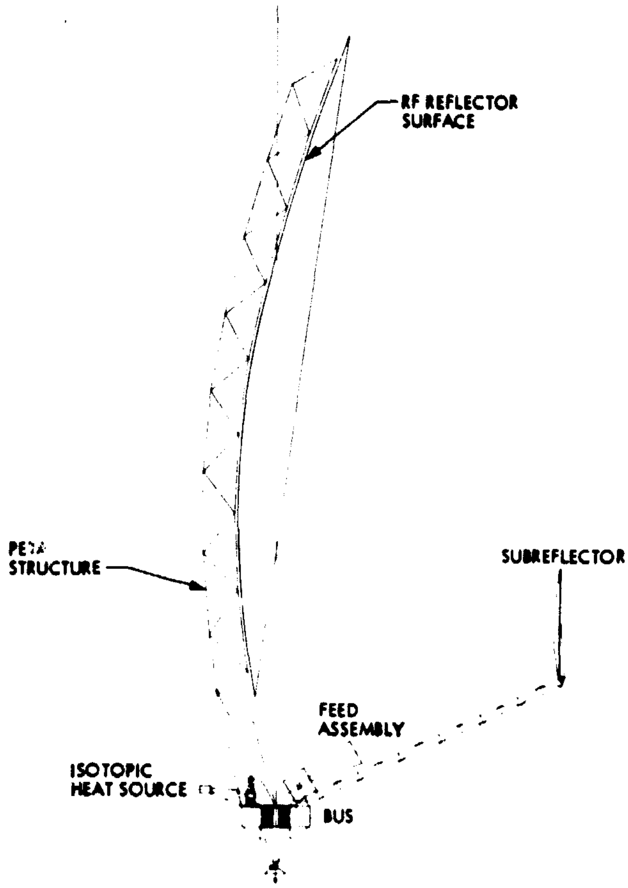


Figure 6. Orthographic view showing surface contours

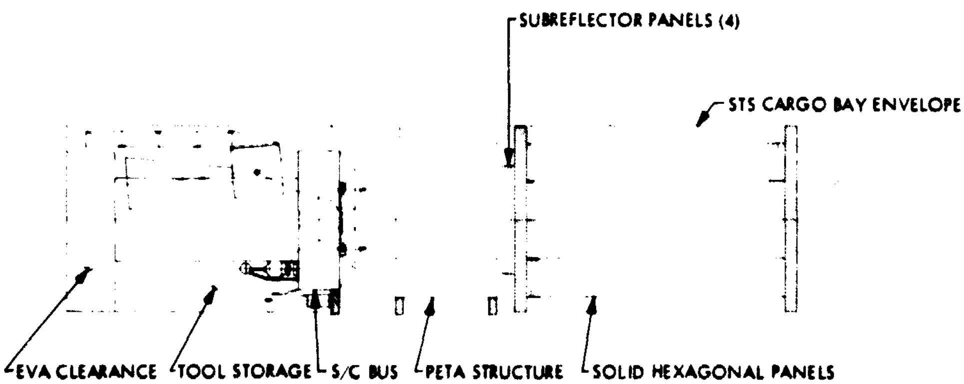


Figure 7. ODSRS launch configuration concept

Table 2. ODSRS conceptual design equipment mass and power list

Subsystem	Mass, kg		Power, W Avg	Peak
Structure		3658		
Bus and stiffeners	200			
Feed assembly support	50			
Subreflector support	50			
Subreflector	50			
KIPS support (including heat source support)	20			
HGA support	5			
Radiator support	10			
Propulsion support	25			
Peta/bus Interface structure	90			
Peta	1668			
Solid hex panels (84)	1490			
Computer command subsystem		23	20	
Telecommunications		606		
Feed assembly (including diplexing and microwave switching equipment)	120			
Masers and UP converters (2)	100			
Cooling units (2)	300		2500	
Ground link electronics	10		40	
HGA (2)	20			
Laser ranging cubes (400)	45			
Ranging transponder	11		14 or 21[a]	
Power		579		
KIPS (including heat source and fuel; less radiator)	431			
Redundant elements	148			
Temperature control		1757		
Blankets	10			
Louvers	7			
Radiators	50			
Insulation for PETA	1690			

[a]When both receivers are on, add one set of S/X-band transmitters.

Table 2. ODSRS conceptual design equipment mass and power list (Continuation 1)

Subsystem	Mass, kg		Power, W Avg	Peak
Attitude control		299		
Wheels (3)	204		45	300
Star trackers (STELLAR)	12		18	18
Actuators	50		10	50
DRIRU II	16		22	22
Electronics	5		25	
Coarse sun sensor (2)	3		0	0
Fine sun sensor (2)	9		5	10
Pyrotechnics		10		
Mechanical devices[a]		25		
Cabling		60		
RFI shield		275		
Propulsion		470		
Hydrazine: Stationkeeping	235			
Attitude Control	85			
Nonexpendables	150			51.5
Total ODSRS mass[b]		7762		
OTV adapter		50		
Contingency		631		
Total mass for OTV estimate		8443		

[a]See Table 17 (Section III).

[b]The total ODSRS mass will be divided between two Shuttle flights. In addition to the mass of the ODSRS itself, the mass of cradles to secure ODSRS parts to the Shuttle and of special assembly and test equipment will be charged to the payload. Since the mass of the ODSRS without OTV is much less than Shuttle capability, this is not expected to be a problem.

Table 2. ODSRS conceptual design equipment mass and power list (Continuation 2)

Subsystem	Mass, kg	Power, W Avg Peak
Orbit Transfer Vehicle (OTV)		
Initial mass	24,700	
Usable propellant	21,000	
Burnout mass	3700	
Shuttle capability available for cradles, tools, etc.	4700	

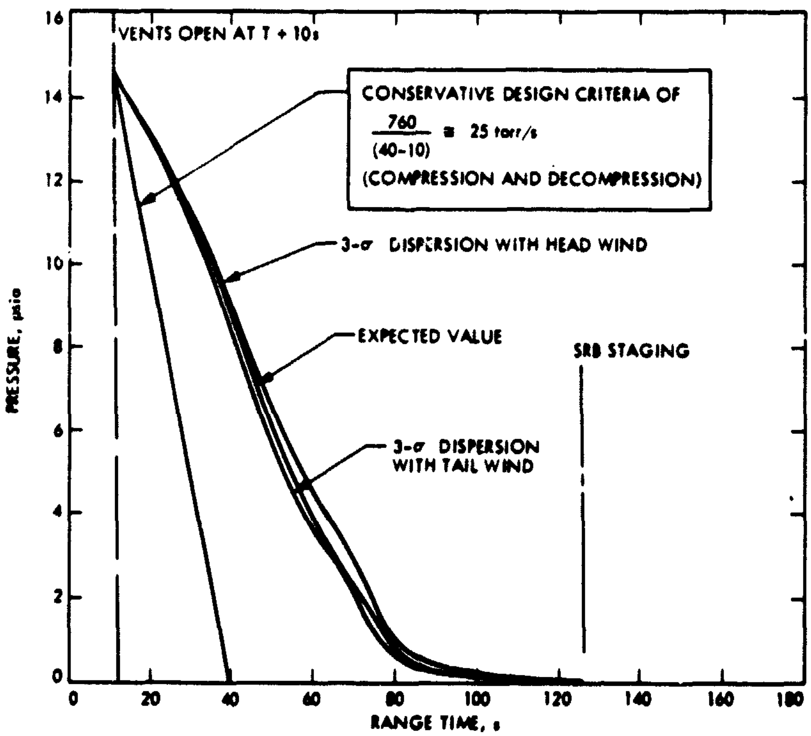


Figure 8. STS payload bay internal pressure histories during ascent and design criteria

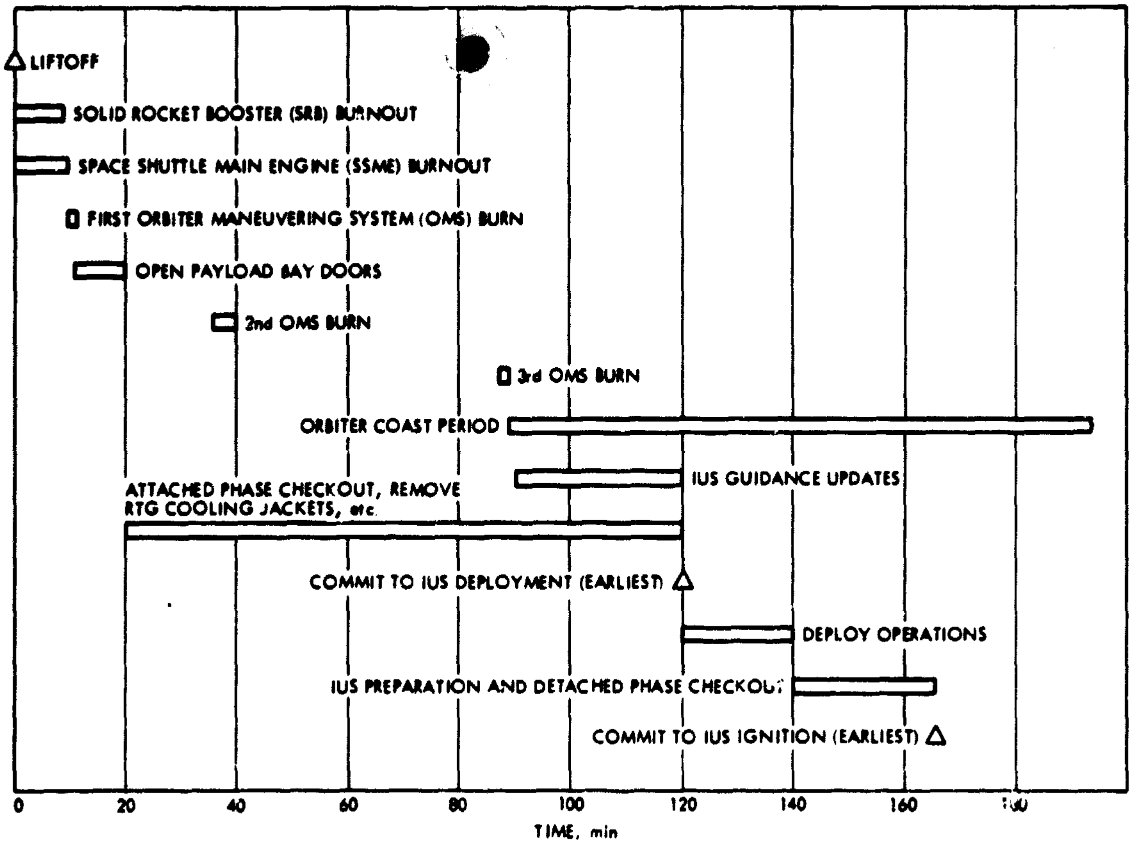


Figure 9. Generalized STS launch to IUS ignition sequence

a. Thermal Radiation. Exposed portions of the ODSRS and flight assemblies shall be designed to withstand the limiting thermal radiation design levels specified in Table 6.

b. Temperature. The flight assemblies shall be designed to withstand temperature requirements based on the type approval (TA) or protoflight (PF) test requirements. It is expected that most ODSRS electronics will have a TA test requirement of +20 to +75°C. The recommended design margin is 10°C in excess of the TA test requirements. For assemblies external to the ODSRS bus such as appendages and trusses, the assembly shall be designed to pass a TA test at levels ±25°C greater than flight allowables and that a 10°C design margin exist in excess of the TA test requirements. Temperature requirements for protoflight assemblies which will experience levels different than the above ranges will be specified by the Environmental requirements Engineer.

Table 3. Expected acoustic levels

Center frequency, Hz	Sound pressure level (dB ref. 20 $\mu N/m^2$)
One-third octave	One-third octave
32	126
40	128
50	130
63	131.5
80	133.5
100	134.5
125	136
160	137
200	137.5
250	138
315	138.5
400	138.5
500	138
630	137.5
800	137
1000	136
1250	135.5
1600	134
2000	133
2500	132
3150	130.5
4000	129
5000	128
6300	126.5
8000	125
10,000	124
Overall	149
Duration: 3 minutes	

Table 4. Expected sinusoidal vibration levels

Frequency, Hz	Vibration level
5 to 23	1.02 cm (0.4 in.) double amplitude
23 to 100	11.3 *g* peak
100 to 2000	6.4 *g* peak

Table 5. Expected random vibration levels

Frequency, Hz	PSD level
25 to 100	+6 dB/octave
100 to 1000	0.1 g^2/Hz
1000 to 2000	-12 dB/octave
Overall level: 11.1 g rms	Duration: 3 min/axis

Table 6. Expected thermal radiation levels

	Limiting thermal radiation levels	
	Design minimum flux, mW cm^{-2}	Design minimum flux, mW cm^{-2}
Direct solar radiation	0	163.0
Earth-reflected radiation	0	57.3
	Effective black body temperatures	
	Design minimum, Temperature ^{o}K	Design maximum, Temperature ^{o}K
Earth IR radiation	215	297

c. Vacuum. The design pressures for the mission will decrease from 1×10^5 N/m^2 (760 torr) to 1.3×10^{-12} N/m^2 (1×10^{14} torr) in space.

d. Radiation Pressure. The ODSRS spacecraft and its assemblies shall be designed to function within the radiation pressure, which will not exceed 10^{-5} N/m^2 on the sunlit side of the spacecraft.

e. Meteoroid Environment. This section contains a description of the meteoroid environment for the ODSRS assuming a 10-year mission in a circular Earth orbit at geosynchronous altitude. The 10-year integral fluence of meteoroids having mass greater than the mass specified in the table, is shown as a function of mass in Table 7. Assuming a 28-m-diameter antenna, Table 7 also provides the expected number of meteoroid impacts and the probability of no impacts, both of these quantities being given for meteoroids of mass greater than the specified mass. These quantities are described in more detail in the following paragraphs.

1) Meteoroid Flux. The meteoroid flux and the mass distribution are derived from the analysis of considerable experimental data accumulated in Earth orbit. This data has been analyzed in detail by Cour-Palais (NASA SP-8013) and Kessler (NASA SP-8038) to provide analytic models for the flux and mass distribution at Earth orbit.

The number of impacts per unit area per unit time (i.e., the flux) is sporadic in time, although a substantial increase occurs during the time when the Earth's orbit encounters meteoroid streams. This increase for streams is included by increasing the sporadic background by the stream flux averaged over a year.

The integral meteoroid mass distribution gives the flux of meteoroids having mass greater than the specified meteoroid mass given in the table. Hence, the number in a mass interval is obtained from the difference of the two integral flux (or fluence) values corresponding to the limits of the mass interval.

The meteoroid flux near a planet for orbital spacecraft is also affected by gravitation focusing and shielding by the planet. Gravitational focusing increases the meteoroid flux as the spacecraft orbital altitude decreases while planetary shielding decreases the meteoroid flux as the orbital altitude decreases. These effects are described in detail in NASA SP-8013 and have been taken into account in the evaluation of the meteoroids, assuming that the antenna is in a circular Earth orbit at synchronous altitude. The meteoroid flux and fluence is assumed to be isotropic.

2) Meteoroid Fluence. An important consideration for assessing damage produced by meteoroids is the fluence (i.e., the expected number of impacts per unit area), the meteoroid relative velocity, and the meteoroid mass density. The integral fluence which is the expected number

Table 7. Meteoroid environment

Particle mass M g	10-year meteoroid fluence (particles M^2 of mass greater than M)	Expected number of impacts by particles of mass greater than M on antenna	Probability of no impacts on the antenna by meteoroids of mass M or greater
10^{-10}	3.1×10^{3}	2.2×10^{6}	0
10^{-8}	1.1×10^{2}	7.8×10^{4}	0
10^{-6}	1.6×10^{1}	1.1×10^{4}	0
10^{-5}	1.0	7.1×10^{4}	0
10^{-4}	6.0×10^{-2}	4.2×10^{1}	0
10^{-3}	3.7×10^{-3}	2.6	0.07
10^{-2}	2.3×10^{-4}	0.16	0.85
10^{-1}	1.4×10^{-5}	9.9×10^{-3}	0.99
10^{0}	8.1×10^{-7}	5.7×10^{-4}	0.999
Mean relative velocity, km/s		14.5	
Particle mass density, g/cm^3		0.5	

of impacts by meteoroids having mass greater than a specified mass is the time integral of the integral meteoroid flux. The time interval is taken as 10 years for the ODSRS Mission. The resulting expected integral fluence, relative velocity, and meteoroid mass density are given in Table 7.

The expected number of impacts by meteoroids having mass greater than the mass specified in the table is the product of the integral fluence and the area of the exposed surface. The expected number of impacts on the antenna is shown in Table 7, assuming that the antenna is a circular disk 28 m in diameter.

Referring to Table 7, the expected number of impacts of meteoroids having mass greater than 10^{-10} g is large (2.2×10^6). The expected number decreases as the meteoroid mass increases. For small values of the expected number of impacts, the question becomes what is the probability of no impact by a meteoroid of this mass or greater. This probability is evaluated using a Poisson distribution having the specified expected value for the probability distribution. The probability of having no impacts by meteoroids of mass m or greater is also shown in Table 7. For the JPL flight projects, the value at 95% is used for design purposes.

3) <u>Damage Assessment</u>. Risk of damage to the antenna will depend on the antenna design, construction, and materials used. The available data indicate that the meteoroid environment poses no problem to the ODSRS antenna. It is recommended that any future study perform a detailed damage assessment of the antenna to verify this assumption.

f. <u>Radiation Environment</u>. An estimate of the average electron flux, average proton flux, electron fluence, and proton fluence has been made for the ODSRS mission at synchronous altitude, assuming a 10-year mission in the equatorial plane. The estimate is based on values computed by GSFC using the AE-4 electron model for inner zone electrons and the AE-5 electron model for outer zone electrons. The AE-4 electron model underestimates the number of electrons at high energy. GSFC is in the process of recomputing these values with a better model. Further detail ODSRS system design should use the revised model. The average proton flux and the mission proton fluence are given in Table 8 as a function of the proton energy. The values are integral values representing the values for protons having energy greater than the tabulated energy values. The average electron flux and the mission electron fluence are given in Table 9 as a function of the electron energy. Similarly, these values are integral values representing the values for electrons having energy greater than the tabulated electron energy. Since the values understate the electron environment at high energies (i.e., greater than about 2.5 MeV), they should be considered as a minimum for preliminary design and revised for detail design.

Table 8. Low-energy protons, synchronous orbit

Energy, MeV	Average flux, cm^{-2}-s^{-1}	Mission fluence, cm^{-2}
0.1	6.72×10^5	2.42×10^{14}
0.3	1.35×10^5	4.25×10^{13}
0.5	2.70×10^4	1.21×10^{13}
0.7	5.40×10^3	1.70×10^{12}
0.9	1.08×10^3	3.41×10^{11}
1.1	2.17×10^2	6.83×10^{10}
1.3	4.34×10^1	1.37×10^{10}
1.5	8.67	2.74×10^9
1.75	1.16	3.65×10^8

Table 9. Electrons, synchronous altitude

Energy, MeV	Average flux, cm^{-2}-s^{-1}	Mission fluence, cm^{-2}
0	3.67×10^7	1.16×10^{16}
0.25	6.89×10^6	2.17×10^{15}
0.50	2.09×10^6	6.60×10^{14}
0.75	8.32×10^5	2.63×10^{14}
1.00	3.31×10^5	1.04×10^{14}
1.25	1.55×10^5	4.89×10^{13}
1.50	7.25×10^4	2.29×10^{13}
1.75	3.39×10^4	1.07×10^{13}

Table 9. Electrons, synchronous altitude (continuation 1)

Energy, MeV	Average flux, cm^{-2}-s^{-1}	Mission fluence, cm^{-2}
2.00	1.59×10^4	5.01×10^{12}
2.50	3.38×10^3	1.07×10^{12}
3.00	6.94×10^2	2.19×10^{11}
3.50	6.69×10^1	2.11×10^{10}

E. Environmental Test Plan

A large precision orbital structure such as the ODSRS cannot practically be tested environmentally as a complete system on Earth. It is especially important that confidence in the capability of the structure to maintain its precision alignment in all orbital environments with varying sun angles be developed prior to launch. Confidence in the response of the structure to attitude control and propulsion also needs to be adequately developed.

To achieve this goal, system level environmental verification will be done in three parts, the assembled bus alone, the stowed system, and the deployed system.

1. Assembled Bus

The assembled ODSRS bus, consisting of electronics, propulsion unit, thermal control blankets and heaters, and the section of the structure that contains the bus will be tested in the JPL 25-ft STV facility to verify the thermal design integrity of the system and its thermal interfaces. The assembled bus will also undergo vibration and pyro shock.

2. System in Stowed Configuration

The ODSRS stowed configuration will require three shuttle bays to contain all bus and antenna hardware, assembly, alignment, and test equipment and the orbit transfer propulsion system. Each planned shuttle load will be made up in the stowed launch configuration including real or simulated shuttle attach points and mounting hardware. These stowed loads will go through shuttle level vibration and pyro shock tests. This is expected to be the greatest induced load that the ODSRS will see in flight.

The ODSRS orbit change propulsion system is expected to require a full shuttle payload bay, and will be vibration- and pyro-tested to the same levels as the rest of the stowed hardware. It will also require a qualification test in an altitude chamber.

3. System in Deployed Configuration

Qualification of the ODSRS in the deployed configuration for the space environment will be accomplished by a combination of testing, modeling, and analysis. A section of the structure and antenna will be tested for deflection and surface distortion induced by solar radiation from different positions, i.e., edge on, frontal, back side, etc. An analysis using deflection test data as an input to a thermal/structural computer program will predict the worst case RMS surface distortion and subsequent gain loss due to thermal distortions.

Qualification of the ODSRS in the deployed and assembled configuration while experiencing vibration loads from the LEO to GEO orbit transfer, stationkeeping propulsion, and attitude control will be done by a combination of analysis, modeling, and testing on a section of the antenna.

4. EMI

The ODSRS has an extremely sensitive low noise receiver, and EMI will be critical. System level EMI testing will be required at the assembled bus level and will also be required of the propulsion and attitude control systems during simulated operation.

F. Shuttle Interface Requirements

1. General Requirements

Design compatibility between the ODSRS and the Space Shuttle is a major requirement. The ODSRS system concept involves the use of the Space Shuttle as an orbital assembly facility and as a test and evaluation complex for the ODSRS. This section describes major Shuttle mechanical and electrical interfaces.

Two Shuttles will be required to transport the ODSRS hardware, assembly, and test equipment into low-Earth orbit, and a third Shuttle mission will be required to rendezvous the orbital transfer propulsion stage with the completed ODSRS.

2. Shuttle Payload Bay Requirements

a. <u>Shuttle Volume Constraints</u>. The Space Shuttle payload bay provides a cylindrical volume 18.28 m (60 ft) in length by 4.57 m (15 ft) in diameter. Depending upon mission requirements, portions of the bay may be occupied by payload chargeable items such as mission-dependent automatic assembly equipment and tooling. The remaining volume is available for storing the various components of the ODSRS spacecraft.

b. Shuttle-Payload Attachment. The payload bay provides a set of hard point attachment locations for payload articles. These hard points are the only planned points where lift off acceleration is coupled to the payload. All payload connections to these points must be regarded as thrust takeout structures. Figure 10 provides a schematic illustration of the locations of these points.

c. Payload Center of Gravity. The distribution of payload mass within the bay must fall within specified boundaries. These boundaries are determined by CG envelopes and total payload mass. CG envelopes are specified for the Shuttle payload along X, Y, and Z axes as defined in Figure 11. Figures 12-14 describe the payload mass distribution envelopes. Payload design must also consider the aborted mission case, where the entire payload may be brought back to Earth. The design must prevent payload breakup for loads defined by shuttle payload control documents.

d. Electrical Power. Average power consumption by the payload is not to exceed 7 kW when provided by the shuttle dedicated fuel cells. Up to 12 kW peak power may be available under certain conditions. Electrical power distribution is provided via power panels located in the payload bay. Available power consists of unregulated 28 Vdc and 400 Hz power.

e. Pressurized Gas. There is no ODSRS requirement to use the pressurized gas service available from the shuttle.

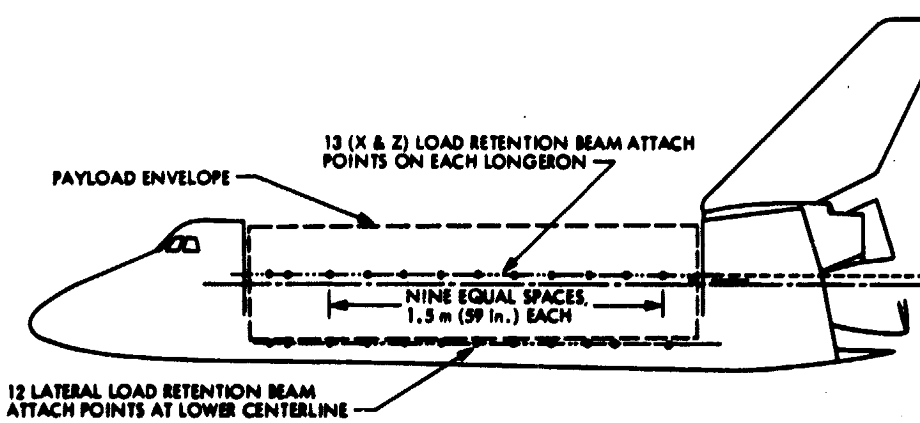
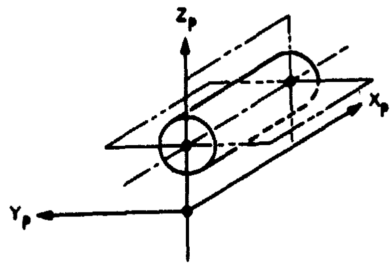


Figure 10. Payload primary attachment locations



TYPE: ROTATING PAYLOAD-REFERENCED COORDINATES
ORIGIN: 5 m (200 in.) BELOW THE CENTERLINE OF THE FORWARD END OF THE PAYLOAD
ORIENTATION AND LABELING:
X-AXIS IS NEGATIVE IN THE DIRECTION OF LAUNCH, PARALLEL TO THE ORBITER PAYLOAD BAY CENTERLINE
Z-AXIS IS POSITIVE UPWARD IN THE ORBITER LANDED POSITION, PARALLEL TO ORBITER Z-AXIS
Y-AXIS COMPLETES THE RIGHT-HANDED SYSTEM

Figure 11. Payload coordinate system

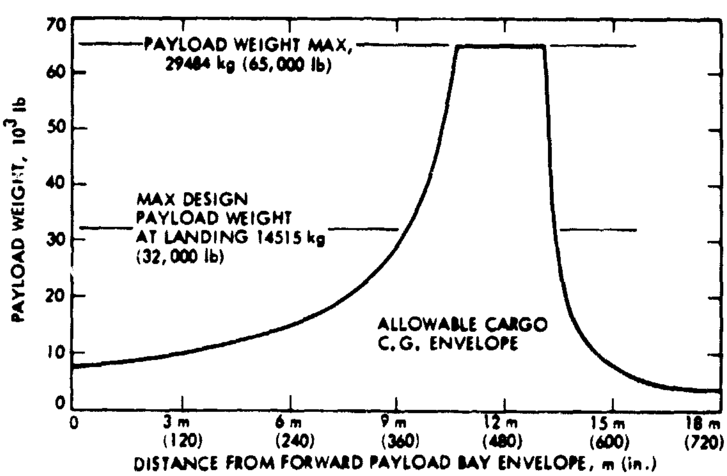


Figure 12. Cargo cg limits (along X axis)

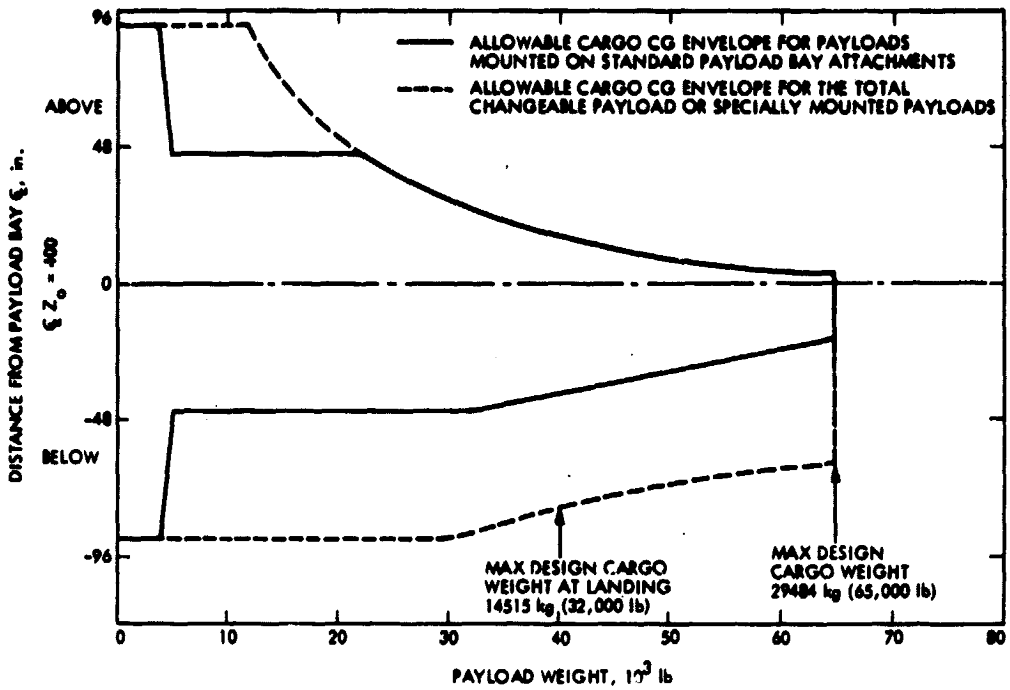


Figure 13. Cargo cg limits (along Z axis)

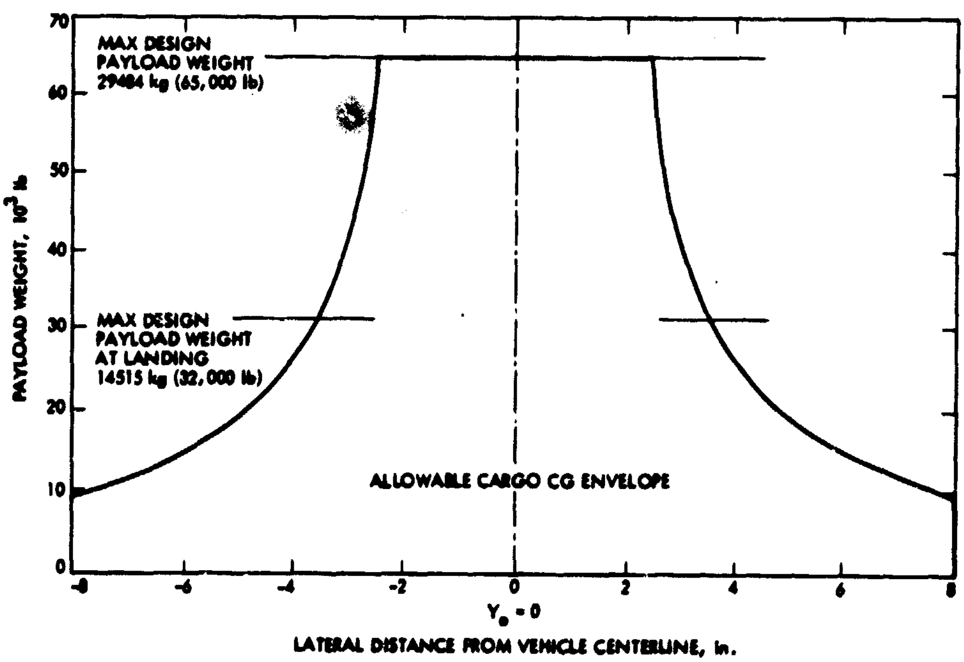


Figure 14. Cargo cg limits (along Y axis)

f. Propellant Dump and Purge Lines. There may be a requirement imposed by safety considerations to provide propellant and cryogen dump or purge on orbit. This requirement is subject to negotiation with JSC.

g. Telemetry and Onboard Data Display. The Shuttle provides interfaces for spacecraft (payload) telemetry and command. In addition, a third category, Caution and Warning, is a special case of telemetry service that provides the shuttle crew with information regarding potentially hazardous processes, operations, and subsystems.

h. Attach/Detach Mode of Operations. The Shuttle data system provides communications with the payload in both attached and detached operating modes. When the payload is attached to the Shuttle, command, telemetry, and caution/warning (C&W) signals are communicated via hardwire connection umbilical between the payload and the Shuttle information system.

G. Orbital Assembly and Checkout Plan

It is planned to use the STS as the orbital assembly and checkout facility. Some ODSRS unique, payload chargeable, assembly and test equipment will be required. While no detailed plan for the assembly and checkout phase has been developed, the following assumptions have been made for cost and schedule planning.

1. Assembly Configuration

Figure 15 shows a conceptual configuration that would work for ODSRS assembly. The expandable truss structure would be removed from the forward part of the cargo bay via the RMS and deployed. It would be attached to a turntable at the front of the cargo bay via four rigid assembly positioning struts. The turntable would rotate the antenna as required for access by the RMS. Precision panels for the antenna surface would be picked out of the cargo bay and attached to the structure. It is expected that attaching and adjusting these panels will require a special end tool for the RMS. Each precision surface panel will be adjustable during and after assembly. Some device for precision mechanical alignment of the surface panels will be required. It was assumed that a precision laser rangefinder was mounted in the center of the turntable for this purpose. This rangefinder would probably provide the input to a computer to control the adjustment mechanism on the panel installation tool.

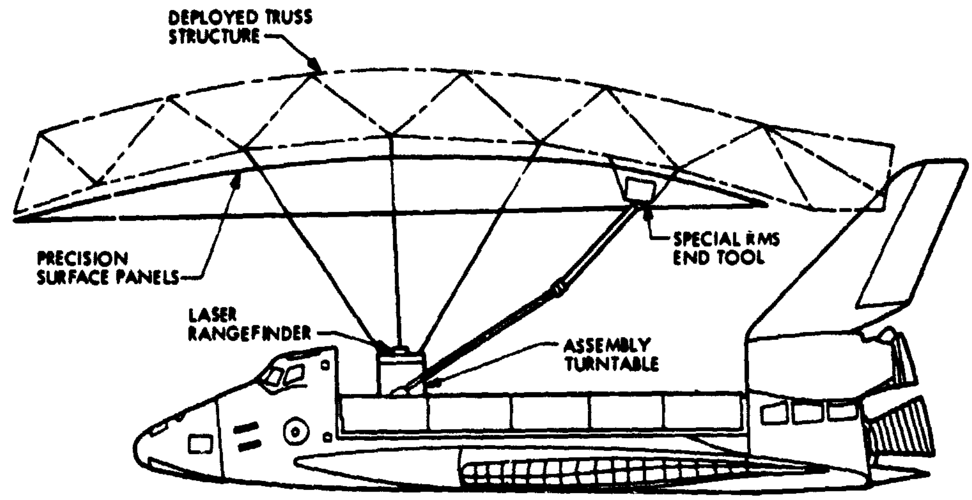


Figure 15. ODSRS assembly concept

2. RF Electrical Checkout

After mechanical assembly and alignment is completed, the ODSRS would be rotated so that it pointed away from the shuttle for electrical checkout. Electrical checkout would be accomplished by pointing at an external source such as a radio star or spacecraft. It is planned that very little (or no) realignment of the antenna surface will be required as a result of the electrical check. Position of the subreflector may require some fine adjustment at this time. Verification of low noise receiver performance and bent pipe link performance will also be accomplished.

3. ODSRS System Checkout

Test and verification of the remainder of the ODSRS system will be accomplished after the RF electrical checks are complete. This will include a "free flying" test to verify attitude control, power, and temperature control functions. After completion of all system tests, it is expected that a "pre boost" review will be held to determine readiness of the ODSRS system for transfer from shuttle orbit to geosynchronous orbit.

4. Orbit Transfer Vehicle Attachment

The orbit transfer vehicle will be brought up in a third shuttle. It will probably have a limited stay time in orbit due to propellant boiloff. After it is attached to the ODSRS, a final check of the attitude control ability to control the ODSRS with OTV attached will be made.

5. ODSRS Assembly and Test Scenario

The following scenarios have been assumed for schedule and cost analysis in this study.

STS Launch 1: Erection of truss structure, attachment of electronics, and partial assembly of antenna surface panels in low earth orbit.

Estimated orbit stay time: 30 days maximum.

EVA activity: 45 hours maximum.

Objective: To establish a Shuttle-based assembly and test facility in low-Earth orbit and to begin assembly of the ODSRS.

STS Launch 2: Rendezvous and docking of second STS with first STS and completion of assembly and test.

Estimated orbit stay time: 30 days maximum.

EVA Activity: 45 hours maximum.

Objectives: To complete assembly of the ODSRS system and to complete mechanical and electrical alignment and testing. A review of this activity will be held prior to launch of the third shuttle.

STS Launch 3: Rendezvous and docking of OTV stage to ODSRS.

Estimated orbit stay time: 3 - 5 days.

EVA activity: Less than 45 hours.

Objectives: To attach OTV to ODSRS and prepare for orbit change maneuver.

H. Relay Telemetry Link Design Requirements

1. Requirements

a. Telemetry. The ODSRS is required to receive telemetry data from a deep space probe and to relay it to a receiving station on Earth. This must be accomplished with an acceptably low degradation of the spacecraft telemetry data stream error rate.

b. International Agreements. The United States is bound by international agreements that limit the amount of signal power per unit bandwidth per unit area that can be received at Earth from a satellite. The ODSRS to Earth link must meet these requirements.

2. Design Assumptions

a. Telemetry Relay Concept. The ODSRS telemetry function will be performed by a feedthrough link, commonly known as "bent pipe." In this method, no demodulation or processing of telemetry data is required on the ODSRS. The composite signal from the deep space probe, including carrier, telemetry, and ranging, is first received by the ODSRS low noise receiver. This composite signal, combined with the ODSRS receiving system noise, is then translated in frequency to the ODSRS to Earth channel frequency, amplified and transmitted to Earth. This method has the advantage of minimizing the operational complexity and hardware requirements on the ODSRS. Its disadvantage is in more complex analysis to predict the net effect of the ODSRS on the total spacecraft to ODSRS to Earth telecomunications link. Koerner (Ref. 3) has analyzed the ODSRS bent pipe link in detail. The results of that analysis will be summarized in this report.

A functional block diagram of the ODSRS "bent pipe" feedthrough channel is shown in Figure 16. The receiver consists of a bandpass filter, linear amplifier, and frequency translator. A power-controlled AGC system adjusts the gain of the linear amplifier to hold the power level at the receiver output at a constant value. The transmitter consists of a linear power amplifier whose input power level can be controlled by a variable attenuator.

b. ODSRS to Earth Link Parameters.

1) Frequency. Possible frequency allocations for the ODSRS to Earth link have been reviewed with the frequency allocation group. Until agreement is reached with WARC, we will not have a specific assignment. However, the most likely frequencies appear to be around 14 GHz. It is desirable from the ODSRS viewpoint to keep the frequency low to reduce weather effects. It is desirable from the allocation standpoint to keep the frequency high to reduce crowding.

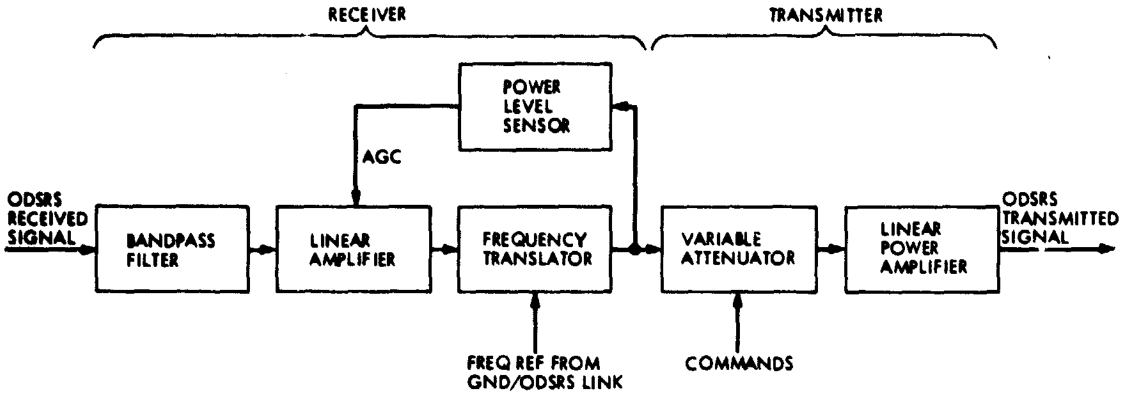


Figure 16. ODSRS feedthrough channel functional block diagram

Our preliminary analysis (Ref. 3) assumed 14 GHz as a ODSRS to Earth frequency. This will be considered representative of performance at other possible frequencies, and no further detailed analysis will be done until a specific allocation is made.

2) <u>Bit Rate</u>. Maximum bit rate design points will be 25 Mbps for SAR data and 250 kbps for digital TV data.

3) <u>Rainfall Degradation</u>. The link will be designed to provide less than 0.2 dB of degradation at 25 Mbps for 99.99% of the statistical weather at the prime receiving station.

4) <u>Antenna Size</u>. The ODSRS relay link antenna will be 2 m in diameter. This will provide a beamwidth on Earth that is expected to be acceptable to WARC and requires about 3 W maximum ODSRS transmitter power to meet the degradation requirements with a 5-m ground antenna. These antenna sizes are easy to handle and are not critical to point. (We have been advised by the frequency allocation group that to avoid interference with other orbiters it may be necessary to use larger antennas with smaller beamwidths).

3. Telemetry Performance Analysis

The degradation in spacecraft-to-Earth telemetry performance due to having an ODSRS in between the spacecraft and the Earth is the major consideration in the ODSRS bent pipe link analysis. Reference 3 has shown that this degradation is a function of the signal power received at the ODSRS, the bandwidth of the feedthrough channel, the ODSRS receiver noise spectral density, the signal power received at the ground station, and the ground station noise spectral density.

Figure 17 shows this degradation vs ODSRS transmitter power for the conceptual ODSRS-to-Earth link design. Note that for relatively modest ODSRS transmitter power levels, the link degradation can be limited to 0.1 to 0.2 dB. The curve gets very steep at this point, and for 0 dB degradation, the ODSRS transmitter power required is infinity. Reference 1 shows that a degradation in telemetry performance can be directly made up by an indentical increase in spacecraft-to-ODSRS link performance. Thus an increase of 0.2 dB in spacecraft transmitter power or antenna gain would overcome a 0.2 dB degradation due to the ODSRS being in the link. The recommended design philosophy for a deep space mission using an ODSRS is to assume 0.2 dB worst case degradation at threshold as part of the telemetry design control table.

A simplified design control table showing the significant parameters of the ODSRS-to-Earth relay link is shown in Table 10.

4. International Agreements

There is a complex set of international agreements regulating the power levels that a satellite can radiate onto the Earth's surface. Parameters that are controlled include frequency, bandwidth, power per unit area, power per unit bandwidth, and angle of arrival of the signal. For purposes of this report, the known limits at 12.5 to 12.75 GHz will be assumed to be typical of those which would be imposed on a K_u band ODSRS-to-Earth link. To simplify matters the following assumptions and approximations have been used.

(1) The allowable power flux density that can be received at any point on the Earth's surface is -118 dBm/m^2.

(2) The minimum elevation angle from the ground station to the ODSRS will be 30 deg.

(3) For other ground points where the ODSRS elevation angle is greater than that of the ground station, the range differential is more than offset by the ODSRS antenna pointing loss. For example, the space loss for the sub-ODSRS point on the Earth would be 0.27 dB less than that for a ground station where the ODSRS elevation angle was 30 deg. However, assuming the ODSRS antenna is pointed at the ground station, the ODSRS antenna pointing error would be 8.7 deg or 13 ODSRS antenna beamwidths.

(4) The maximum power flux density, neglecting atmospheric attenuation, will occur at the point on the Earth's surface where the ODSRS antenna is pointed. If the maximum atmospheric attenuation occurred on the ODSRS-to-ground-station path while clear sky attenuation occurred along the ray path to a ground point nearby the ODSRS ground station, the power flux density at that point could exceed the power flux density at the ground station. For a station where the

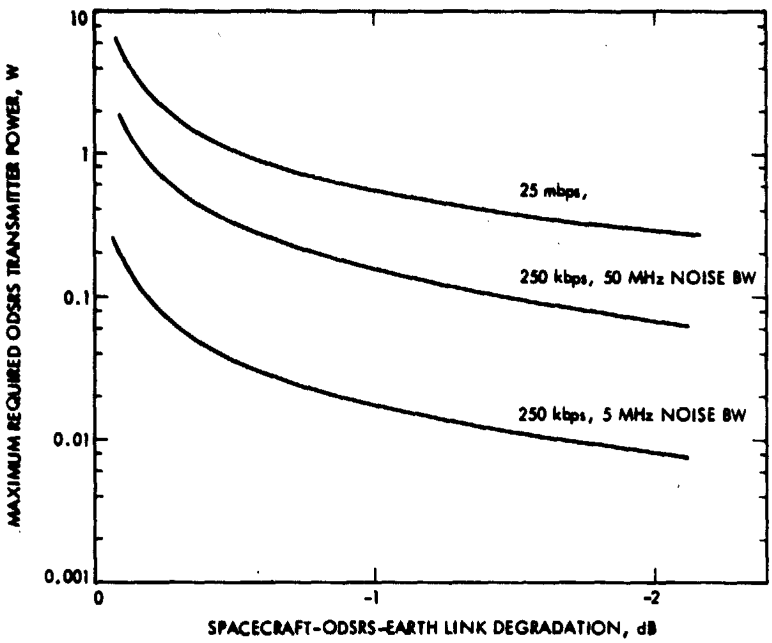


Figure 17. ODSRS earth link degradation vs maximum required ODSRS transmitter power

ODSRS elevation angle is 30 deg, the worst case atmospheric attenuation difference is 6.45 dB. The allowance for ODSRS antenna pointing loss is 0.5 dB. Thus, if the maximum power flux density at the ground station with worst-case atmospheric attenuation is constrained to be -118.00 - 0.50 -6.45 = -124.95 dBm/m^2, the power flux density cannot exceed -118.0 dBm/m^2 at any other point on the Earth's surface.

Reference 3 has analyzed the maximum received power flux density at the ground station for ODSRS feedthrough noise bandwidths of 5 and 50 MHz with telemetry data rates of 250 kbps and 25 mbps. The results show that the ODSRS-to-Earth telemetry channel can be designed to meet expected international agreements. However, it will be necessary to vary the ODSRS transmitter power output over a range of about 1 mW to 3 W, depending on the weather, the telemetry data rate from the spacecraft, and the power level received at the ODSRS from the spacecraft. Setting the ODSRS transmitter power level requires knowledge of the received signal level and noise spectral density at the ODSRS receiver. Provision for this data must be made in the ODSRS stationkeeping telemetry.

Table 10. ODSRS/ground link communication system performance estimate

Transmitting system parameters	
(1) RF power output (1 W)	30.00 dBm
(2) Circuit loss	-1.00 dB
(3) Antenna gain (2 m dia., 70% eff.)	47.79 dB
(4) Antenna pointing loss	-0.50 dB
Path Parameters	
(5) Space loss Frequency = 14 GHz Range = 38611.91 km	-207.11 dB
(6) Atmospheric attenuation	-6.72 dB
Receiving System parameters	
(7) Polarization loss	0.00 dB
(8) Antenna gain (5 m dia., 70% eff.)	55.76 dB
(9) Antenna pointing loss	-0.10 dB
(10) Circuit loss	0.00 dB
(11) Noise spectral density System noise temperature = 366.1 K 30 deg elevation angle, rain (31 mm/h)	-172.95 dBm/Hz
(12) Received signal power	81.88 dBm
(13) Received signal power/receiving system Noise spectral density	91.07 dB·Hz

I. Stationkeeping Telecommunications Link Design Requirements

The stationkeeping telecommunications link provides for operations and control of the ODSRS by the ODSRS control center.

1. Requirements

a. <u>Telemetry</u>. Operational data from the ODSRS will be required to monitor the status of the ODSRS, to verify the results of command activity, and to troubleshoot problems during the ODSRS lifetime.

No telemetry requirements are being defined for science data from the ODSRS. It is not expected that additional science data requirements would be a problem, since the ODSRS-to-Earth stationkeeping telemetry link is not a technically difficult design.

The operational telemetry link should not depend on precise pointing of the ODSRS or its articulating antennas. This is to provide telemetry data for analysis in case of attitude control malfunction on the ODSRS.

b. Command. A command link will be required to provide instructions to the ODSRS for pointing, frequency selection, relay transmitter power levels, and other normal operational instructions. Command capability will also be required in case of ODSRS problems to analyze and resolve these problems. The command link should not depend on precise pointing of the ODSRS or its articulating antenna. This is to provide reliable command capability in case of attitude control malfunction.

c. Ranging. A ranging system will be required that will provide for determination of the ODSRS position to 1 m in 3 axes relative to the Earth center. This implies that the accuracy of the ranging system itself must be ~10 cm.

d. International Agreements. All ODSRS stationkeeping telecommunications links must meet applicable international agreements on spectrum utilization.

2. Design Assumptions

a. Telemetry Bit Rate. An ODSRS-to-Earth telemetry bit rate of 1200 bps has been assumed for engineering data. This requires only 0.125 W of ODSRS transmitter power at S-band and appears to satisfy all potential telemetry users.

b. Command Bit Rate. An Earth-to-ODSRS command bit rate of 125 bps has been assumed. This provides adequate capability for updating the pointing and other day-to-day operational activities of the ODSRS and provides adequate margin for troubleshooting in case of ODSRS attitude control malfunction.

c. ODSRS Stationkeeping Antennas. The ODSRS has two stationkeeping antennas that each provide a minimum of -4 dB gain over a hemisphere. They are mounted on opposite corners of the bus, pointing into the Earth-favored hemisphere, but skewed in opposite directions. This skew extends the area of coverage to nearly the entire sphere of the ODSRS in case of attitude control malfunction.

d. Ground Station Antenna. The 5-m ground station antenna that is used by the K_u band relay telemetry link will have S- and X-band feeds to service the stationkeeping link.

e. Ground Station Transmitter. The ODSRS ground station has a 100-W S-band transmitter for stationkeeping command and ranging.

f. Ground Station Receiver. The ODSRS ground station has an uncooled paramp front end followed by a GASFET second stage.

g. ODSRS Stationkeeping Transponder. The NASA standard transponder will be used in an Earth orbital version with a noise bandwidth of 200 Hz. This transponder has a receive capability on S-band and a transmit capability on S- and X-band.

h. ODSRS Transmitter. The ODSRS will have a transmitted power of 0.125 W at S-band and 16 mW at X-band.

3. Stationkeeping Telecommunications Performance Analysis

a. S-Band Command and Telemetry Links. Table 11 contains a performance estimate for an S-band 125-bps command link. Table 12 contains a performance estimate for an S-band 1200-bps telemetry link. For each of these links the ODSRS is assumed to be located at an elevation angle of 30 deg with respect to the ground station. At this point the ODSRS/ground station range is 38612 km. In each case the spacecraft antenna gain is assumed to be a low-gain antenna with a minimum gain of -4 dB. The peak gain of this antenna would be about +4 dB and the net gain of the antenna would exceed the -4 dB value over about one hemisphere.

For the command link the command channel performance margin is 17.79 dB. Assuming that, with the exception of the ODSRS antenna, design value performance is achieved, command capability could be maintained with an ODSRS antenna gain of -21.79 dB relative to isotropic. If additional link capability is needed in some emergency, a DSN 20-kW/26-m station command capability could be maintained with an ODSRS antenna gain of -59.47 dB relative to isotropic.

The telemetry performance margin is 3.05 dB for the 5-m station. The performance estimate in Table 12 assumes that Viterbi (rate 1/2) coding is used and the required bit error probability is 5×10^{-5}. Assuming that, with the exception of the spacecraft antenna, design value performance is achieved, the 1200-bps telemetry rate could be maintained with an ODSRS antenna gain of -7.05 dB relative to isotropic using the 5-m ground station. If additional link capability is needed in some emergency, a DSN 26-m station could be used, increasing link performance by 20.33 dB. Using the 26-m antenna, the 1200-bps telemetry rate could be maintained with an ODSRS antenna gain of -27.38 dB relative to isotropic.

The incident power flux density at the receiving station is also calculated in Table 12. Note that, if the peak of the ODSRS antenna pattern was pointed at the receiving station, the received power flux density would not increase more than 8 dB. Hence, the ODSRS telemetry link should meet the CCIR requirements for all orientations of the ODSRS when the ODSRS is located in geosynchronous orbit.

Table 11. Communication system performance estimate, ODSRS S-band command link, 5-m station

Transmitting system parameters	
(1) RF power output (100 W)	50.00 dBm
(2) Circuit loss	-1.00 dB
(3) Antenna gain (2 m diameter)	38.13 dB
(4) Antenna pointing loss	-0.10 dB
Path parameters	
(5) Space loss Frequency = 2113 MHz Range = 38612 km (ELE = 30 deg)	-190.68 dB
(6) Atmospheric attenuation	-0.12 dB
Receiving system parameters	
(7) Polarization loss	-
(8) Antenna gain	-4.00 dB
(9) Antenna pointing loss	-
(10) Circuit loss	-2.00 dB
(11) Noise spectral density NF = 5.5 dB	-169.32 dBm/Hz
(12) Received signal power	-109.77 dBm
(13) Received signal power/receiving system noise spectral density	59.55 dB·Hz
Carrier channel	
(1) P(carrier)/P(total)	-0.55 dB
(2) Design point noise bandwidth (100 Hz)[a]	20.00 dB·Hz
(3) Design point SNR	3.01 dB
(4) Margin above design point	35.99 dB
Command channel	
(1) P(command)/P(total) RMS phase deviation = 0.354 rad	-9.29 dB
(2) Bit rate (125 bps)	20.97 dB·Hz
(3) Demodulation loss (from carrier)	-1.00 db
(4) Required E_B/N_0	10.50 dB
(5) Performance margin	17.79 dB

[a]One-sided noise bandwidth.

Table 12. Communication system performance estimate, ODSRS S-band telemetry link, 5-m station

Transmitting system parameters	
(1) RF power output (0.125 W)	20.97 dBm
(2) Circuit loss	-1.00 dB
(3) Antenna gain	-4.00 dB
(4) Antenna pointing loss	-
Path parameters	
(5) Space loss Frequency = 2295 MHz Range = 38612 km (ELE = 30 deg)	-191.40 dB
(6) Atmospheric attenuation	-0.12 dB
Receiving system parameters	
(7) Polarization loss	-
(8) Antenna gain (5M diameter)	39.13 dB
(9) Antenna pointing loss	-0.10 dB
(10) Circuit loss	-0.85 dB
(11) Noise spectral density T_{ANT} = 35.3 K, ΔT_{ATM} = 2.7 K @ ELE = 30 deg T_{AMP} = 60 K	-177.04 dBm/Hz
(12) Received signal power	-137.37 dBm
(13) Received signal power/receiving system noise spectral density	39.67 dB·Hz
Carrier channel	
(1) P(carrier)/P(total) β_{TLM} = 70 deg	-9.32 dB
(2) Design point noise bandwidth (5.4 Hz)[a]	7.32 dB·Hz
(3) Design point SNR	3.01 dB
(4) Margin above design point	20.02 dB
Telemetry channel	
(1) Required P_T/N_0 for 1200 bps @ $P_E = 5 \times 10^{-5}$	36.62 dB·Hz
(2) Performance margin	3.05 dB
Power flux density	
(1) Received signal power neglecting atmospheric attenuation and receiving system polarization, antenna pointing, and circuit losses	-136.30 dBm
(2) Effective area of receiving antenna Area efficiency = 0.566	10.46 dB·m^2

Table 12. Communication system performance estimate, ODSRS S-band telemetry link, 5-m station (Continuation 1)

(3) Maximum fraction of signal power in any 4 kHz band	-4.95 dB
(4) Received power flux density	-151.71 dBm/m^2
(5) Allowed power flux density	-124.00 dBm/m^2
(6) Margin	27.71 dB

[a]One-sided noise bandwidth.

b. Stationkeeping Ranging Links. For stationkeeping the ODSRS will require the capability of ranging to the ODSRS from three widely spaced ground stations. Tables 13-15 contain link performance estimates for this system. Table 13 is a performance estimate for the S-band uplink. Table 14 is a performance estimate for the S-band downlink. Table 15 is a performance estimate for the X-band downlink. The dual frequency downlink permits calibration of the effect of the ionosphere on the range measurements.

Ranging performance margins are calculated for an RMS range error of 1 m and for a measurement time of 2 min. Of this 2 min, 100 s would be used for the first code component, 1 s for each of the 10 ambiguity resolving components, and 1 s per component for the required time interval between components. The ambiguity range would be 298 km. For the S-band range measurement the ranging performance margins are 15.44 dB for the first code component and 21.18 dB for the ambiguity resolving code components. For the X-band range measurement the ranging performance margins are 3.99 dB for the first code component and 9.73 dB for the ambiguity resolving code components.

The range measuring system for which link performance estimates are shown will not meet the radio metric requirements of 0.1 m accuracy. Even with the improvements expected to be available by 1985, range measurement accuracy with the present 0.5 MHz clock frequency probably will not be better than 1 to 2 m. To achieve the 0.1-m accuracy, the ranging clock frequency must be increased from 0.5 to 20 MHz. This increase in ranging clock frequency will entail substantial modification to both the ground station and the spacecraft transponders.

Table 13. Communication system performance estimate, Ground/ODSRS ranging link, 5-m station

Transmitting system parameters	
(1) RF power output (100 W)	50.00 dBm
(2) Circuit loss	-1.00 dB
(3) Antenna gain	38.13 dB
(4) Antenna pointing loss	-0.10 dB
Path parameters	
(5) Space loss	-191.00 dB
Frequency = 2113 MHz	
Range = 40061 km (ELE = 15 deg)	
(6) Atmospheric attenuation	-0.22 dB
Receiving system parameters	
(7) Polarization loss	-
(8) Antenna gain	-4.00 dB
(9) Antenna pointing loss	-
(10) Circuit loss	-2.00 dB
(11) Noise spectral density	-169.32 dBm/Hz
NF = 5.5 dB	
(12) Received signal power	-110.19 dBm
(13) Received signal power/receiving system noise spectral density	59.13 dB·Hz
Carrier channel	
(1) P(carrier)/P(total)	-10.00 dB
(2) Design point noise bandwidth (100 Hz)[a]	20.00 dB·Hz
(3) Design point SNR	3.01 dB
(4) Margin above design point	26.12 dB
Ranging channel	
(1) P(ranging)/P(total)	-0.46 dB
(2) Noise bandwidth (2 MHz)	63.01 dB·Hz
(3) Ranging SNR	-4.34 dB

[a]One-sided noise bandwidth.

Table 14. Communication system performance estimate, ODSRS/Ground S-band ranging link, 5-m station

Transmitting system parameters	
(1) RF power output (0.125 W)	20.97 dBm
(2) Circuit loss	-1.00 dB
(3) Antenna gain	-4.00 dB
(4) Antenna pointing loss	-
Path parameters	
(5) Space loss Frequency = 2295 MHz Range = 40061 km (ELE = 15 deg)	-191.72 dB
(6) Atmospheric attenuation	-0.22 dB
Receiving system parameters	
(7) Polarization loss	-
(8) Antenna gain	39.13 dB
(9) Antenna pointing loss	-0.10 dB
(10) Circuit loss	-0.85 dB
(11) Noise spectral density T_{ANT} = 35.3 K, ΔT_{ATM} = 5.1 K T_{AMP} = 60 K	-176.98 dBm/Hz
(12) Received signal power	-137.79 dBm
(13) Received signal power/receiving system noise spectral density	39.19 dB·Hz
Carrier channel	
(1) P(carrier)/P(total)	-4.44 dB
(2) Design point noise bandwidth (5 Hz)[a]	6.99 dB·Hz
(3) Design point SNR	3.01 dB
(4) Margin above design point	24.75 dB
Ranging channel (first code component)	
(1) P(ranging)/P(total)	-9.26 dB
(2) Integration Time (100 s)	20.00 dB
(3) Required $P_R T_I / N_0$ (σ_R = 1 m)	34.49 dB
(4) Performance margin	15.44 dB
Ranging channel (ambiguity resolution)	
(1) P(ranging)/P(total)	-9.26 dB
(2) Integration time (1 s)	0.00 dB s
(3) Required $P_R T_I / N_0$ (P_E = 0.001)	8.75 dB
(4) Performance margin	21.18 dB

Table 14. Communication system performance estimate, ODSRS/Ground S-band ranging link, 5-m station

Power flux density	
(1) Received signal power Neglecting atmospheric attenuation and receiving system polarization, antenna pointing, and circuit losses	-136.62 dBm
(2) Effective area of receiving antenna, area efficiency = 0.566	10.46 dB m^2
(3) Maximum fraction of signal power in any 4-kHz band	-4.44 dB
(4) Received power flux density	-151.52 dBm/m^2
(5) Allowed power flux density	-124.00 dBm/m^2
(6) Margin	27.52 dB

[a]One-sided noise bandwidth.

Table 15. Communication system performance estimate, ODSRS/Ground X-band ranging link, 5-m station

Transmitting system parameters	
(1) RF power output (16 MW)	12.04 dBm
(2) Circuit loss	-1.00 dB
(3) Antenna gain	-4.00 dB
(4) Antenna pointing loss	-
Path parameters	
(5) Space loss Frequency = 8415 MHz Range = 40061 km (ELE = 15 deg)	-203.00 dB
(6) Atmospheric attenuation	-1.33 dB
Receiving system parameters	
(7) Polarization loss	-
(8) Antenna gain	50.42
(9) Antenna pointing loss	-0.10 dB
(10) Circuit loss	-0.35 dB
(11) Noise spectral density T_{ANT} = 52.9 K, ΔT_{ATM} = 58.6 K @ ELE = 15 deg T_{AMP} = 100 K	-175.06 dBm/Hz

Table 15. Communication system performance estimate, ODSRS/Ground X-band ranging link, 5-m station (Continuation 1)

(12) Received signal power	-147.32 dBm
(13) Received signal power/receiving system noise spectral density	27.74 dB·Hz
Carrier channel	
(1) P(carrier)/P(total)	-4.44 dB
(2) Design point noise bandwidth (5. Hz)[a]	6.99 dB·Hz
(3) Design point SNR	3.01 dB
(4) Margin above design point	13.30 dB
Ranging channel (first code component)	
(1) P(ranging)/P(total)	-9.26 dB
(2) Integration Time (100 s)	20.00 dB·s
(3) Required $P_R T_I / N_0$ (σ_R = 1 m)	34.49 dB
(4) Performance margin	3.99 dB
Ranging channel (ambiguity resolution)	
(1) P(ranging)/P(total)	-9.26 dB
(2) Integration time (1 s)	0.00 dB·s
(3) Required $P_R T_I / N_0$ (P_E = 0.001)	8.75 dB
(4) Performance margin	9.73 dB
Power flux density	
(1) Received signal power Neglecting atmospheric attenuation and receiving system polarization, antenna pointing, and circuit losses	-145.54 dBm
(2) Effective area of receiving antenna, area efficiency = 0.566	10.46 dB·m^2
(3) Maximum fraction of signal power in any 4-kHz band	-4.44 dB
(4) Received power flux density	-160.44 dBm/m^2
(5) Allowed power flux density	-120.00 dBm/m^2
(6) Margin	40.44 dB

[a]One-sided noise bandwidth.

J. Radiometric Requirements

Radiometric requirements on the ODSRS are imposed by navigation and by radio science. These requirements are primarily accuracy and stability requirements on the ground-spacecraft-ODSRS-ground relay communications system design. Total system requirements have been assessed, and the ODSRS contribution to these requirements will be summarized in this section.

1. Spacecraft Navigation

a. Ranging Accuracy. The overall accuracy with which the range to a deep space probe can be determined shall be 1 meter. This implies that the ODSRS location in 3 axes relative to the Earth center must be known to 1 m. The existing DSN ranging system cannot achieve this accuracy for the ODSRS location. A new ranging system development is required. Three widely spaced ground stations will likely be required to "triangulate" ODSRS range to this accuracy.

b. Doppler Accuracy. The overall accuracy with which the doppler shift of a deep space probe can be determined shall be 0.1 mm/s. This implies that the end-to-end phase stability of the communications link including spacecraft, ODSRS, and transmitting and receiving ground stations is 1 mm (for a 10-s averaging time) or 10 mm (for a 100-s averaging time). To meet this requirement will require stable spacecraft and ODSRS temperatures over the data tracking period, knowledge of the ODSRS velocity components to 0.1 mm/s, and modeling of the spacecraft and ODSRS motion during the data tracking period.

c. Angle Accuracy. The overall accuracy with which the angle from the Earth to the spacecraft can be determined is 0.05 rad. This requirement implies the use of either wideband differential ranging or ΔVLBI techniques. The ODSRS would be a good tool for VLBI, since its orbital position would yield a longer baseline and greater angle accuracy.

d. Two-Way Data at Long Round Trip Light Times (RTLT). In order to use the ODSRS in support of two-way data needs (ranging and doppler), a ground station in view of the ODSRS will be required. This is because the ODSRS has no transmitter. The ODSRS is of benefit in this configuration when the RTLT becomes long with respect to the length of a station pass and the station would set before the two-way signal returned. The signal could be relayed to the ground station through the ODSRS. This implies a ground station, such as Goldstone, located in the same general area as the relay telemetry receiving station.

e. Two Station Difference Doppler Data. For some missions (VOIR is an example) there is a tracking degeneracy that is resolved by using two widely separated Earth stations and using the "differenced" data between them. The wider the station separation or baseline, the more accurate this technique is. An ODSRS at 6.6 Earth radii would provide a significantly larger baseline than any two ground stations. Note that the ODSRS location would need to be known to 1 m in 3 axes for this advantage to hold.

f. Navigation Near the Sun. Within ±30 deg of the Sun, doppler navigation requires a 2-frequency, 2-way capability to eliminate solar effects. Solar effects are also reduced at higher frequencies, such as the ODSRS maximum frequency of 32 GHz. No quantitative conclusion as to the value of the ODSRS in this situation exists, but it has the potential for improved navigation accuracy.

2. Radio Science

Radio science acquires data from two types of sources: coherent sources, such as a spacecraft; and natural sources, such as a radio star. Radio science requirements are generally much more stringent than navigation requirements. However, they are also less firm, i.e., if the requirement is not met, less data will be obtained but it will still be useful.

For the ODSRS study, the decision has been made to emphasize the type of radio science for which the ODSRS can provide a new or unique capability. Radio science experiments that can be conducted from ground stations generally require special setups, state-of-the-art techniques, and real-time, hands-on operation. These types of experiments will likely be best handled at ground stations.

a. Potential Radio Science Uses for ODSRS.

1) ΔVLBI. For mapping natural radio sources, the ODSRS provides a longer baseline, and hence a potential for more accuracy.

2) Gravity Wave Detection. Gravity wave detection experiments have been proposed with varying degrees of practicality (Refs. 4, 5). These proposals appear to be evolving toward a credible experiment in the future. A major error source for this experiment will be the Earth's troposphere and ionosphere. The ODSRS appears to be a potentially useful tool for detecting data above the troposphere and ionosphere and helping to reduce this error source.

3) Existing Radio Science Experiments. Experiments such as relativity and planetary occultations that are currently carried out by ground stations are perturbed by the Earth's troposphere and ionosphere. Detecting data above these disturbances will improve the quality of these experiments.

4) Far Field Calibrations. Radio science requirements place extremely tight requirements on the entire communication systems. An important element of meeting these requirements is testing and calibration. The ODSRS would provide a tool for far field calibration that would allow more accurate ranging, timing, polarization, gain, and pattern calibration (Ref. 6).

5) Troposphere/Ionosphere/Atmosphere Calibrations. With a two-way link to the ODSRS and the use of higher frequencies than S- and X-band, there is the possibility to study the variations and general characteristics of the Earth's troposphere, ionosphere and atmosphere and their effects on radio signals.

K. Orbit Design Requirements

The design of the ODSRS orbit is constrained by communication requirements, navigation requirements, radio science, and the capability of the orbit transfer vehicle to boost the ODSRS from shuttle orbit to geosynchronous orbit.

1. Communications Requirements

a. Ground Station View. The ODSRS must be in continuous view of its ground stations throughout its orbit. This is to provide the advantages of 24-h tracking of a spacecraft by the ODSRS with no ground station handovers required.

b. United States View. The ODSRS orbit must be in continuous view of a ground station in the continental United States for relay telemetry and radiometrics. This is to provide the capability for 24-h tracking of a spacecraft using stations located only in the United States.

c. Spacecraft View. The ODSRS orbit must have an inclination relative to the ecliptic large enough to minimize Earth occultations of spacecraft in or near the ecliptic plane. An angle of 17.5 deg to the ecliptic will be satisfactory for all planets except Pluto, which has an inclination of 17.1 deg. A geostationary orbit would have an inclination relative to the ecliptic of 23.5 deg.

d. Minimum Elevation Angle. The minimum elevation angle from the ground station to the ODSRS shall be 30 deg at the southernmost point in its orbit. This is to insure the capability of the relay telemetry link to meet its performance requirements without violating international communications agreements (see Relay Telemetry Link, Section II-H). A geosynchronous orbit with an inclination of <17.2 deg will meet this constraint.

2. Navigation Requirements: Doppler

The inclination of the ODSRS orbit relative to the ecliptic must be low enough to provide a receiving station velocity signature in the doppler data of spacecraft in or near the ecliptic plane. This is an important source of navigation information in doppler data.

3. Radio Science

Very Long Baseline Interferometry (VLBI) investigations prefer large orbital inclinations. However, much useful data can be obtained from low inclination orbits.

4. Orbit Transfer Vehicle (OTV)

The size of an OTV required to move the ODSRS from shuttle orbit to geosynchronous orbit is a strong function of the ODSRS mass and the inclination change required. For the ODSRS design, the OTV size has been limited to one shuttle payload. The ODSRS size and the inclination change required will be traded off to meet this constraint.

L. Radio Frequency Interference Requirements

The ODSRS is uniquely susceptible to RFI-induced performance degradation because of its orbital location combined with its requirement for processing of very weak signals (compared to a communications satellite, for example). The RFI problem can conveniently be divided into three categories: (1) the effect of a given RFI waveform on a given signal waveform, (2) the expected/possible rejection of RFI by the ODSRS antenna (side lobe characteristics) and (3) the expected RFI environment. Of these, the first two are subject to standard analytical techniques, but their complexity makes the analysis a major task. The expected RFI environment is a difficult problem because of the multiplicity of existing signal sources on the Earth, the difficulty of obtaining information on U.S. military and foreign signal sources and, probably most important, the difficulty of extrapolating knowledge of the 1978 RFI environment to the expected RFI environment in the late 1980's.

1. Effect of an Interfering Signal

The mission of the ODSRS is such that it can have only limited control over the modulation of the signal it receives from a deep space probe. Thus both the desired signal and the interfering signal waveforms are essentially uncontrolled. The worst case is when the waveforms are similar and are hence difficult to distinguish even in principle. Analysis of the general case is a formidable task which is important but which has not yet been undertaken. A special case has been examined by M. Koerner in order to "get a feel for the problem." This special case is that of a sine wave interfering with an uncoded binary PSK channel. The parameters involved in Koerner's interference calculation are given in Table 16. Figure 18 is a plot of the allowable effective radiated power (EIRP) in dBm for a 0.2-dB degradation, as a function of the bit rate. As displayed in Figure 18 the RFI problem becomes increasingly less severe with increasing bit rates because the signal bandwidth increases and hence the receiver sensitivity decreases. Figure 19 is a plot of the probability of observing a given RFI source antenna gain for a randomly oriented RFI source antenna; for example, a 20-dB gain "hit" has a probability of about .005. For a 10^3 bps link to the ODSRS, a -20 db (relative to isotropic) ODSRS sidelobe level and a hit probability of 0.01, an RFI source power of approximately +37 dBm (5 W) will produce a 0.2-db degradation. Alternately, a 0-dB RFI source antenna gain and a 25-W power level[1] (a defective home microwave oven, for example) will produce 0.2-dB degradation. These examples indicate the severity of the RFI problem and the necessity for control of the wide-angle ODSRS sidelobe structure.

2. Control of the ODSRS Wide-Angle Sidelobe Structure

Figure 20 shows the DSN 64-m antenna sidelobe envelope measured by Bathker (Ref. 7) for the azimuth plane. Also shown are the sidelobe envelopes associated with a uniformly illuminated circular aperture and a circular aperture with a $1-R^2$ tapered illumination (Ref. 8). The latter involves a gain loss of 1.25 dB, but serves to illustrate that very low wide-angle sidelobe envelopes are theoretically possible. A general study of wide-angle paraboloidal antenna sidelobe response using Keller's geometric theory of diffraction (GTD) was performed in 1970 (Ref. 9). This study showed good agreement with experiment and showed that GTD is a reliable technique for wide-angle sidelobe prediction as a function of antenna feed/configuration parameters. By sacrificing some antenna aperture efficiency it appears possible to design a large offset-fed (unblocked) reflector antenna for very low wide-angle sidelobes. Use of shielding techniques has also been reviewed and will be used for ODSRS antenna design.

[1]For this case the required EIRP is decreased 11 dB to account for the fact that microwave ovens are S-band and Table 16 assumes X-band. There is 11 db less space loss to the ODSRS at S-band than there is at X-band.

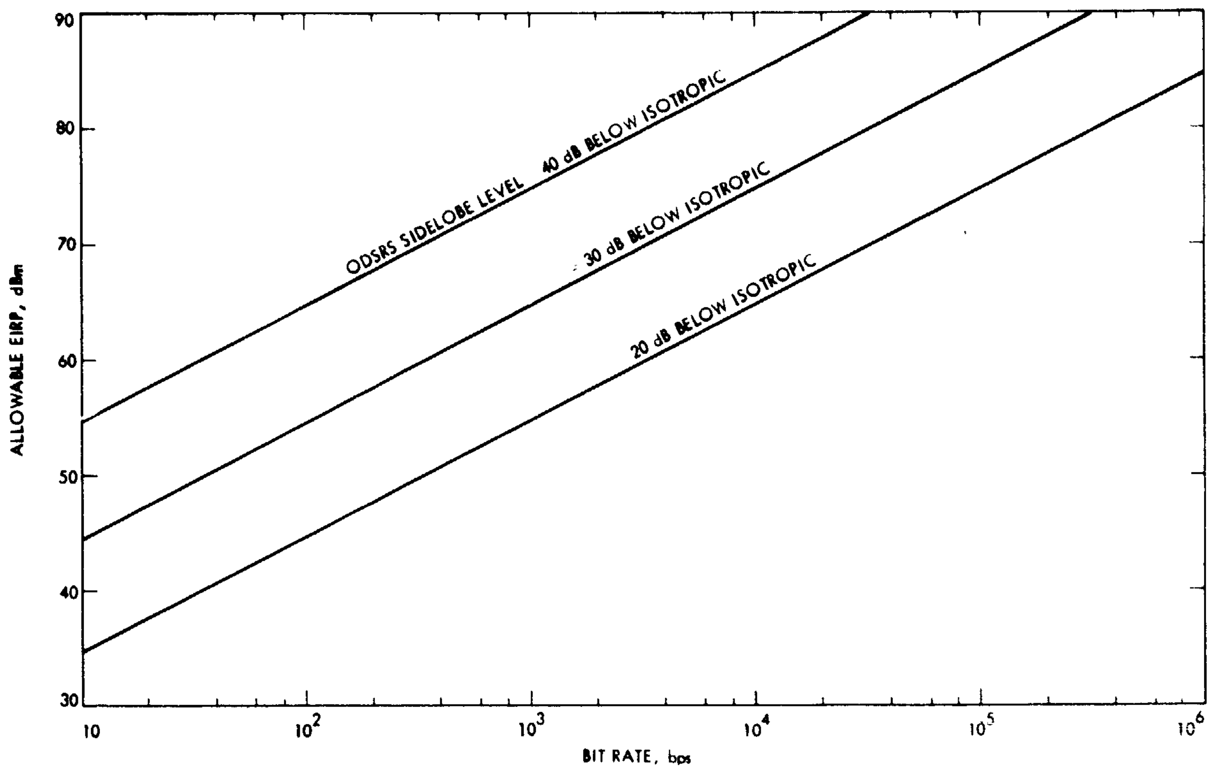


Figure 18. Allowable EIRP for a 2 dB degradation as a function of bit rate

3. RFI Technology Requirements

The ODSRS will require advances in RFI technology to enable its implementation. Three specific areas in which this technology is needed have been identified as follows:

(1) Development of fundamental analysis and designs for antennas with adequate sidelobe control. This will consider both antenna design and shield design.

(2) Development of analysis techniques for predicting the effect of RFI on a wide range of complex signal waveforms. Techniques are specifically needed to handle the large number of combinations of RFI waveforms and signal waveforms.

(3) Development of techniques for estimating and bounding the RFI environment in a geosynchronous orbit.

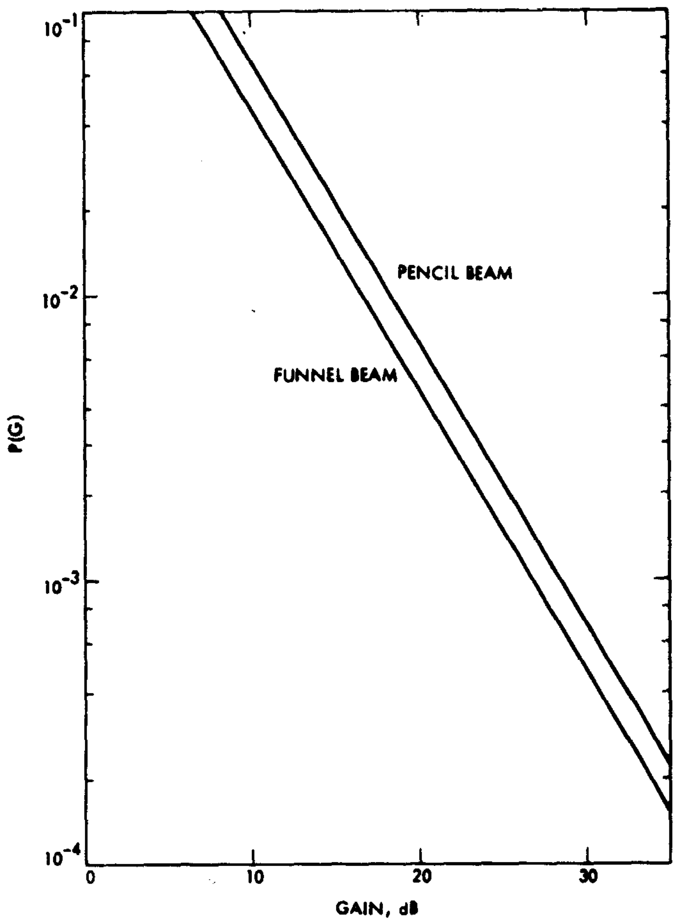


Figure 19. Probability of observing the specified gain for a randomly oriented antenna

M. ODSRS Operations Requirements

The ODSRS will be an entirely new operations concept. It is expected to ultimately reduce the day-to-day operations personnel support required to track a deep space probe. This plan summarizes the operations philosophy that has been assumed for purposes of life cycle cost estimates for the ODSRS.

1. Operations Requirements

The following functions will be performed by the ODSRS operations organization:

(1) ODSRS Stationkeeping Operations

(a) Monitor the ODSRS performance and status. Detect problems in a timely manner and take action for their resolution.

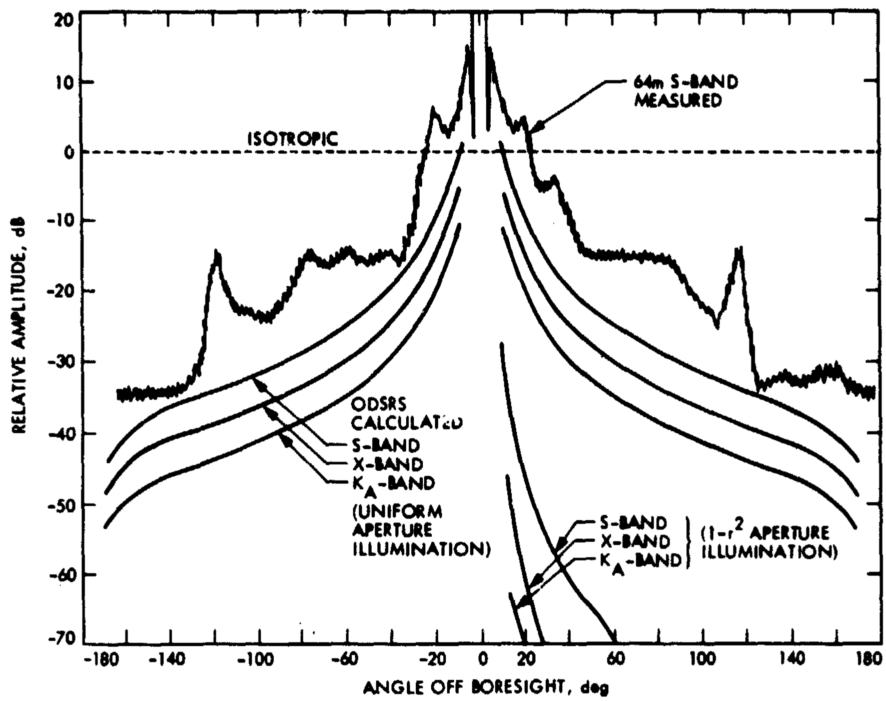


Figure 20. Possible ODSRS wide-angle sidelobe envelopes

(b) Monitor the ODSRS orbit and generate commands to the station-keeping propulsion system as required to maintain the ODSRS orbit within specification.

(2) Spacecraft Project Support Operations

(a) Generate ODSRS pointing and articulation control commands from project supplied spacecraft ephemeris data.

(b) Generate ODSRS relay telemetry state control commands from spacecraft project supplied received power and frequency predicts.

(c) Determine ODSRS orbit position from stationkeeping ranging data and furnish to the spacecraft project for navigation and radio science.

(d) Relay spacecraft telemetry, navigation, and radio science data from the ODSRS ground station to the project mission control center.

Table 16. Communication system performance estimate ground/ODSRS Interference link

Transmitting system parameters	
(1) Effective radiated power	54.72 dBM
Path parameters	
(2) Space loss Frequency = 8415 MHz Range = 35786.2 km	-202.02 dB
(3) Atmosphere attenuation	-
Receiving system parameters	
(4) Antenna gain	-20.00 dB
(5) Noise spectral density (System noise temperature = 11.6 K)	-187.95 dBm/Hz
Interference level	
(6) Received interference power	-167.30 dBm
(7) Interference reduction (In coherent demodulation, 2 stages)	-6.93 dB
(8) Interference power at bit detector	-174.23
Noise level	
(9) Noise bandwidth of bit detection (Bit rate = 1000 bps)	26.99 dB/Hz
(10) Noise power in bit detector bandwidth	-160.96 dBm
(11) Interference to noise ratio at bit detector	-13.27 dB
(12) Allowable interference to noise ratio at bit detector for 0.2-dB degradation	-13.27 dB
(13) Margin	0.00 dB

(3) ODSRS-DSN-PROJECT Interface: Insure that the status and capabilities of the ODSRS are known by the DSN scheduling office and the flight projects being supported.

(4) ODSRS Ground Station Maintenance: Insure that the ODSRS ground stations are properly maintained and ready to meet project support commitments.

2. Operations Concepts

The ODSRS is designed for a 10-year nonmaintained lifetime. It is also designed for reliable day-to-day operations with minimum intervention by an operations team. To obtain maximum benefit from this design, an operations philosophy of minimum support to do the job will be needed. The following concepts are suggested:

(1) ODSRS Control Center Staffing. The ODSRS will likely be operated 24 hours per day. During routine operations the activity related to this will involve occasional repointing and setting up for different spacecraft tracking. This activity should be manageable by one person per shift. It is expected that the ODSRS stationkeeping ranging activity and the generation of stationkeeping propulsion commands will require two or three 8-hour shifts per week. A base of talented engineers will be needed to handle occasional panics, and some means will be needed to insure the existence of this base.

(2) ODSRS Ground Station Support. ODSRS ground stations will be designed for a once-a-year maintenance cycle. They will not be technically unique, and regular DSN station personnel should be able to handle this task. Operations of the ground stations will be completely remote, and will consist largely of insuring that they are properly configured and that their antenna is pointed at the ODSRS. It is expected that this function can be performed by the same personnel operating the ODSRS control center.

III. ODSRS SUBSYSTEMS DESIGN

A. Structure/Mechanical Devices (SMD)

1. Requirements

a. <u>General Configuration Requirements</u>.

(1) Antenna surface, subreflector, and feed assembly geometry is per subsections III-B and III-C.

(2) Masers must be rigidly attached to feed assembly.

(3) Cooling compressors must be within 1 m of masers.

(4) A radio interference shield must encircle the antenna, subreflector, and feedhorn, leaving an unshielded opening for the antenna sighting axis (see Fig. 21).

(5) The Earth vector, during tracking operations, will be in the hemisphere of the ODSRS containing the feed assembly.

(6) The two relay link antennas must be pointable at an Earth station during tracking operations.

(7) The heat rejection radiators must always be oriented away from the Sun.

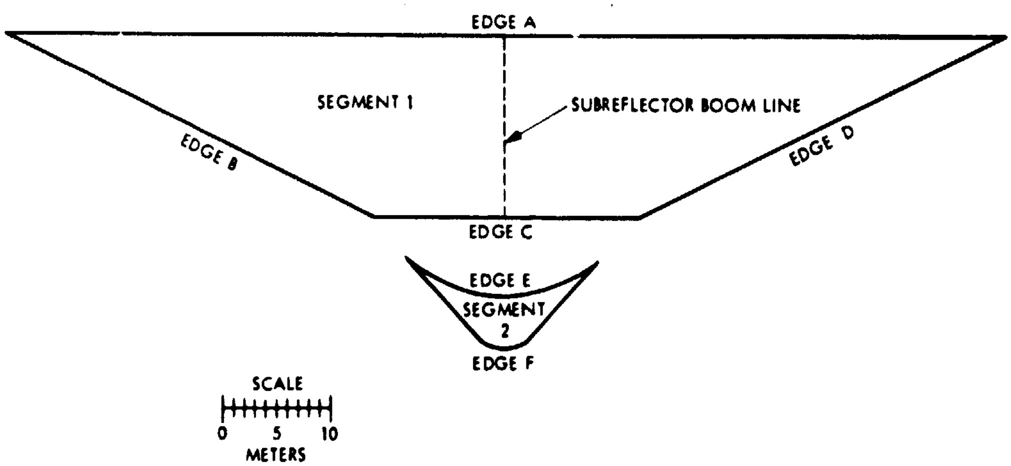


Figure 21. 28-m ODSRS radio interference shield

(8) Star trackers must be provided with their required fields of view.

(9) Orbit transfer propulsion and stationkeeping propulsion must thrust through the center of mass.

(10) The isotopic heat source must be kept a safe distance from sensitive electronics.

(11) The design must be consistent with projected orbital assembly capabilities.

(12) Where practical, deployment should be remote/automatic, rather than manual.

b. Launch Requirements.

(1) Stow all elements of the ODSRS within the shuttle prescribed dynamic envelope in handling fixtures compatible with shuttle attach points.

(2) Provide for adequate structural support of all stowed appendages during launch-induced vibrations.

(3) Design launch configuration such that the center of mass of the elements in the shuttle cargo bay is within the prescribed limits.

(4) Design launch configuration to facilitate removal of the spacecraft elements on orbit in a manner consistent with assembly operations.

c. Orbit Transfer Requirements.

(1) The ODSRS in its deployed, operational state must withstand the accelerations encountered during orbit transfer.

(2) The ODSRS structure and bus will have the necessary facilities to dock with the orbit transfer stage(s) and jettison the stage(s) after reaching geosynchronous orbit.

2. Conceptual Design

a. General Description. The deployed 28-m ODSRS without its radio interference shield is depicted in Fig. 4. The four-sided bus is the primary structural platform to which spacecraft elements are attached. The feed assembly, radiators, relay link antennas, and the isotopic heat source are attached to the bus, stowed, and latched for launch in the shuttle. After being released from the orbiter, these elements are remotely unlatched and deployed. The antenna surface panels, the expandable truss, and the subreflector are stowed in the shuttle separately from the bus and are deployed on-orbit and attached to the bus either manually or by the Remote Manipulator System (RMS). The radio interference shield is constructed on-orbit either manually or by the RMS. When checkout of the assembled system is complete, the orbit transfer stage is docked to the bus and boosts the spacecraft to geosynchronous orbit. When the orbit transfer is complete, the propulsion system is jettisoned.

b. Bus. The bus consists of two electronics compartments, an attitude control compartment, and a compartment containing two cooling systems for the masers. These compartments are joined to form a four-sided bus with a rectangular inner cavity. This structure serves as the primary platform to which all other spacecraft components are attached. During launch the bus is secured to its support cradle in the orbiter cargo bay.

c. Expandable Truss Structure. For launch, the expandable truss structure is collapsed and constrained in its launch support cradle in the shuttle cargo bay. For on-orbit assembly, it is removed from its cradle, deployed, and attached to the spacecraft bus with a three-bipod truss.

d. Solid Panel Antenna Surface. The antenna surface is formed by 48 hexagonal solid panels and 36 panels which are segments of hexagons. For launch, the 84 panels are stacked on top of each other between two bulkheads which serve as the support cradles in the shuttle cargo bay. A shock-absorbing, compressive blocking material individually contoured to fill the space between and provide support to two specific adjacent panels in the stack is placed between each of the panels. The stack of panels and blocking is loaded in compression between the two bulkheads by putting in tension the 18 beams which connect the two bulkheads. These 18 beams outline the hexagonal cross-section of the stack of panels and serve to take out horizontal motion in the stack of panels. For on-orbit assembly, the stack of panels is unloaded from compression and one of the bulkheads is removed. The panels can then be removed in sequence from the open-ended container formed by the remaining bulkhead and the 18 beams. The panels are described in more detail in subsection III-B, Antenna Mechanical.

e. Propulsion Support. The 1-meter-diameter, spherical hydrazine tank is supported inside the central cavity of the bus by eight bipods. Thruster locations and support is TBD.

f. Kilowatt Isotope Power System (KIPS) Support. The Rankine cycle engine is mounted outside the bus to the top plate of the attitude control compartment. The isotopic heat source is supported from the attitude control compartment of the bus on a boom so that its radiation field will not harm sensitive equipment. During launch, the boom is folded and latched in a stowed position inside the launch envelope. For on-orbit deployment, the boom is unlatched, a hinge-line actuator swings the boom out, and a folding strut locks to its deployed position. Heat rejection for the system is provided by two planar radiating surfaces extending symmetrically from opposite sides of the bus. The radiators are articulated with one degree of freedom so that they are always edge on to the sun. These same radiators also provide heat rejection for the maser cooling systems. For launch, the radiators are stowed and latched. For on-orbit deployment, pinpullers unlatch the radiators and hingeline actuators swing them to their deployed position.

g. Feed Assembly Support. The feed assembly is an integral structure containing the feed horn, the two masers and upconverters, and waveguides. It is supported from the bus by two tripods and provided with one-degree-of-freedom articulation for pointing and for deployment. Flexible hoses provide coolant circulation between the masers in the feed assembly and the cooling system in the bus. During launch, the feed assembly is latched in a position where the feed horn is oriented perpendicular to the bus. For on-orbit operation, the assembly is unlatched and deployed to its proper orientation with articulation capability for making adjustments in its orientation.

h. Subreflector. The subreflector is a hyperboloid section constructed of graphite epoxy composite material. For launch, this structure is dismantled into four sections and secured to one of the bulkheads in the antenna surface panels assembly. These sections are assembled on-orbit and attached to the ODSRS either manually or with the RMS.

i. Subreflector Support. The subreflector is supported from the feed assembly by a three-section boom. For launch, the boom is folded on two hingelines and latched to the feed assembly. For on-orbit operation, pinpullers unlatch the boom, and hingeline actuators and pushoff springs deploy the assembly to its final position.

j. Relay Link Antenna Support. Each of the two relay link antennas (RLAs) is supported from the bottom of the bus by a boom so that it can be pointed continuously at Earth ground stations. Each RLA can be articulated with two degrees of freedom. For launch, the booms are latched to the bus. For on-orbit operation, pinpullers unlatch the booms, and hingeline actuators and pushoff springs deploy the RLA's to their final position.

k. Radio Interference Shield. The radio interference shield is formed with two segments of some thin, flexible, metallic film (see Fig. 21). Edge A is attached to a structural hoop which is mounted on the subreflector boom and the edge of the antenna structure opposite the boom. It is supported by several structural members running from the edge of the antenna to the hoop. Edges B and D attach to the edge of the antenna surface, and the "subreflector boom" line attaches to the subreflector boom. Shield segment 2 fills the gap left between segment 1 and the antenna surface on the side of the feed assembly. Edge E attaches to the edge of the antenna surface, and Edge F attaches to Edge C. Particulars of the RFI shield design, launch accommodation, and deployment are TBD. The ODSRS with assembled RFI shield is depicted in Fig. 22. The RFI shield will accommodate the repositioning of the subreflector boom associated with feed assembly allignment.

3. Mass Estimates

Table 17 presents mass estimates.

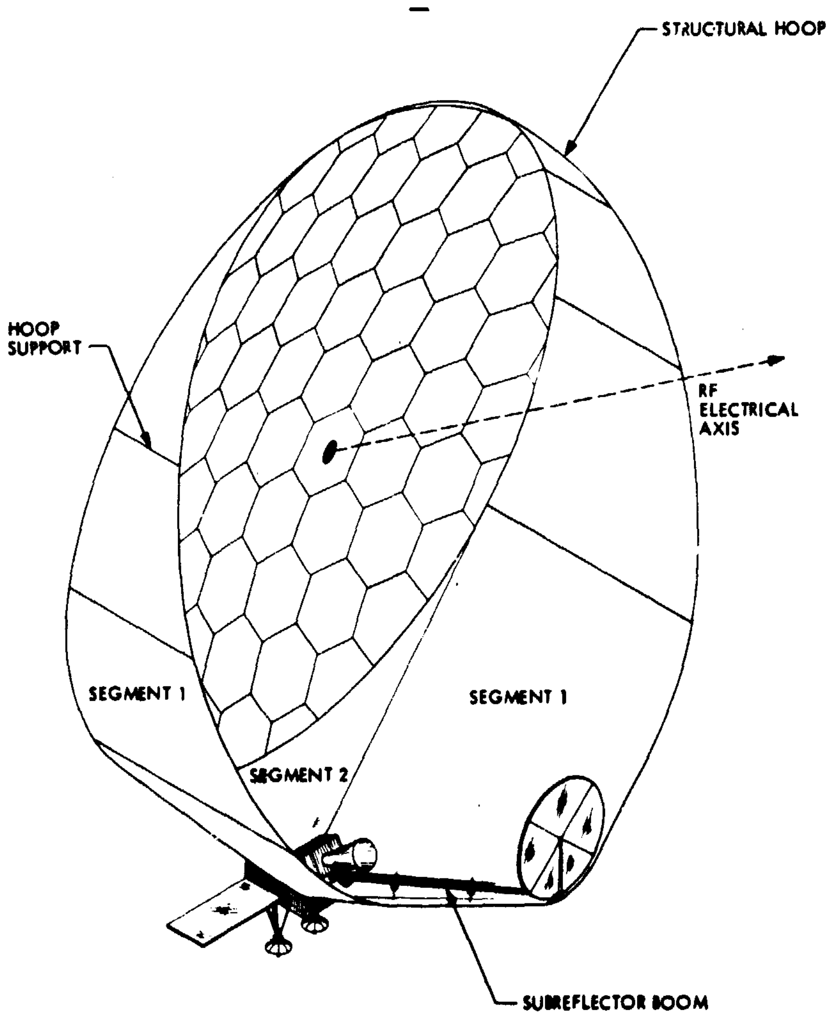


Figure 22. 28-m ODSRS with RFI shield

Table 17. Structure and Mechanical devices mass estimates

Structure		
Component	Mass, kg	Tolerance %
Bus and stiffeners	200	+50; -25
Feed assembly support	50	+50; -25
Subreflector support	50	+50; -25
Subreflector (4 sections)	50	TBD
Radiator support	10	+50; -25
RLA support	5	+50; -25
Propulsion support	25	+50; -25
KIPS support	10	+50; -25
KIPS heat source support	10	+50; -25
Bus interface structure	90	+50; -25
Expandable Truss	1668	TBD
Hexagonal antenna surface panels (84)	1490	TBD
Structure Total	3658	
Mechanical Devices		
HGA Deployment		
2 hingeline actuators	2.0	±10
2 pinpullers w/brackets	0.3	±10
2 pushoff springs	0.10	±10
Subreflector boom deployment		
2 hingeline actuators	2.0	±10
2 cam latches	0.8	±10
2 pinpullers w/brackets	0.3	±10
2 pushoff springs	0.1	±10
Feed assembly deployment		
2 ball-lock devices	0.6	±10
Radiator deployment		
2 hingeline actuators	2.0	±10
4 pinpullers w/brackets	0.7	±10
2 pushoff springs	0.1	±10
2 hinges (4 monoballs)	1.4	±10
Radiator articulation		
2 scan-type bearing assemblies	0.4	±20

Table 17. Structure and Mechanical devices mass estimates (Continuation 1)

Mechanical Devices		
Component	Mass, kg	Tolerance %
Isotopic heat source deployment		
1 hingeline actuator	1.0	±10
1 pinpuller w/brackets	0.2	±10
1 folding strut w/brackets	1.5	±10
1 pushoff spring	0.05	±10
1 hinge (2 monoballs)	0.7	±10
Launch tug separation devices		
Separation and umbilical covers	3.0	±20
Separation pushoff springs	2.0	±10
Separation latches	4.0	±20
Subreflector boom deployment		
2 hinges (4 monoballs)	1.4	±10
Mechanical Devices Total	25.0	

B. Antenna Mechanical Subsystem

1. Requirements

The Antenna Mechanical Subsystem (AMS) consists of the structure and panels that form the large antenna. Functionally, the mechanical portion of the antenna must provide a sufficiently precise structure, under all orbital environments, to meet the performance reouirements of the antenna electrical subsystem. The following functions shall be provided:

(1) Capability to verify structural design prior to launch. This does not reouire a complete environmental and electrical test on Earth prior to launch. It does require sufficient demonstration of structural design, electrical performance, assembly repeatability, and alignment capability that NASA can commit to launch with confidence.

(2) The design shall provide for repeatability of assembly and alignment on Earth and in orbit. This is to allow as much alignment as possible to be completed on Earth prior to launch to minimize in-orbit alignment time.

(3) The assembled antenna mechanical subsystem shall maintain its final alignment to satisfactory tolerances over all environmental conditions, including incident angles of solar radiation and attitude control dynamics. It shall have the structural strength to withstand up to 0.2 *g* acceleration during boost from LEO to GEO.

The major performance parameter the antenna mechanical subsystem must meet is to achieve and maintain surface accuracy and stability such that a maximum gain degradation of 1 dB will not be exceeded for any operating frequency or condition. This degradation is as defined by the RUZE equation and is shown in Fig. 23 as a function of allowable RMS surface distortion. Figure 23 is calculated at 32 GHz, which is the worst case for the ODSRS design.

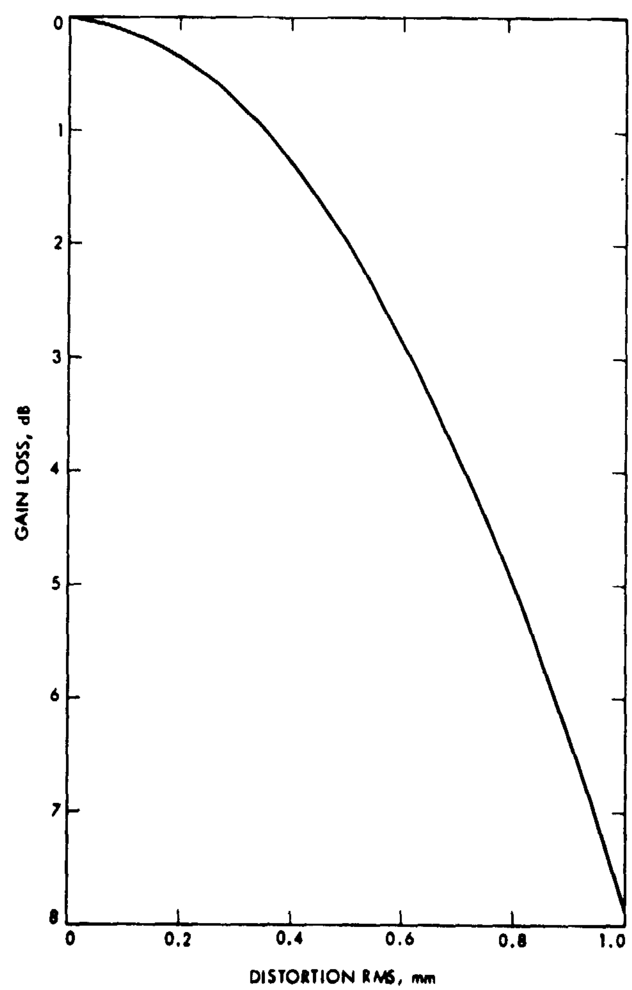


Figure 23. Ruze gain loss, 32-GHz frequency

2. Implementation Options

Mechanical implementation options for the ODSRS antenna were studied for the RF reflective surface and for the backup structure that supports the reflective surface.

a. Reflective Surface. Implementation options for the ODSRS antenna were the choice between a deployable and an erectible antenna surface. These options are described in detail in Ref. 10. The main selection criterion was surface quality adequate for 32 GHz with a 28-m antenna.

Current deployable antenna technology does not meet ODSRS frequency and size requirements. The precision deployable concept (solid panels that deploy like a flower petal) looks promising. The mesh deployable concept is further away in demonstrated capability at 32 GHz. Deployable antennas have one large advantage over erectible antennas in space. That is in reduction of in-orbit assembly and alignment time. Their disadvantage is the uncertainty in technology readiness to provide adequate surface quality at 32 GHz.

A precision erectible surface concept has been demonstrated by Dr. Robert Leighton of Caltech that meets ODSRS surface quality requirements at a smaller size on Earth (Fig. 24). This concept was selected as the basis for the ODSRS surface panel design. It appears that with a reasonable development program this concept could be extended to meet ODSRS requirements for manufacturing surface quality, repeatability of surface quality after disassembly and reassembly, and thermal stability. The baseline ODSRS surface is a set of shaped hexagonal panels that are each supported by three standoffs from the joints of the backup structure. Owing to the immaturity of space erection technology, a major unknown at this time is whether the assembly precision can be maintained in orbit.

b. Backup Structure. The ODSRS antenna requires a rigid structural platform on which to assemble the precision surface. Because of the large number of joints associated with the backup structure concepts considered, it was very desirable to select a concept that did not require these joints to be assembled and aligned in orbit. This is due to the expected time and cost of making a joint in orbit. The Parabolic Erectable Truss Antenna (PETA) being developed by General Dynamics is a deployable antenna structure concept that already has considerable technology development in process. The PETA concept (Fig. 25) uses basic deployable tetrahedral elements to form a large, stiff truss. It was originally developed to support a mesh antenna surface, and with further development appears to meet ODSRS requirements. The PETA concept was selected as the baseline ODSRS antenna backup structure.

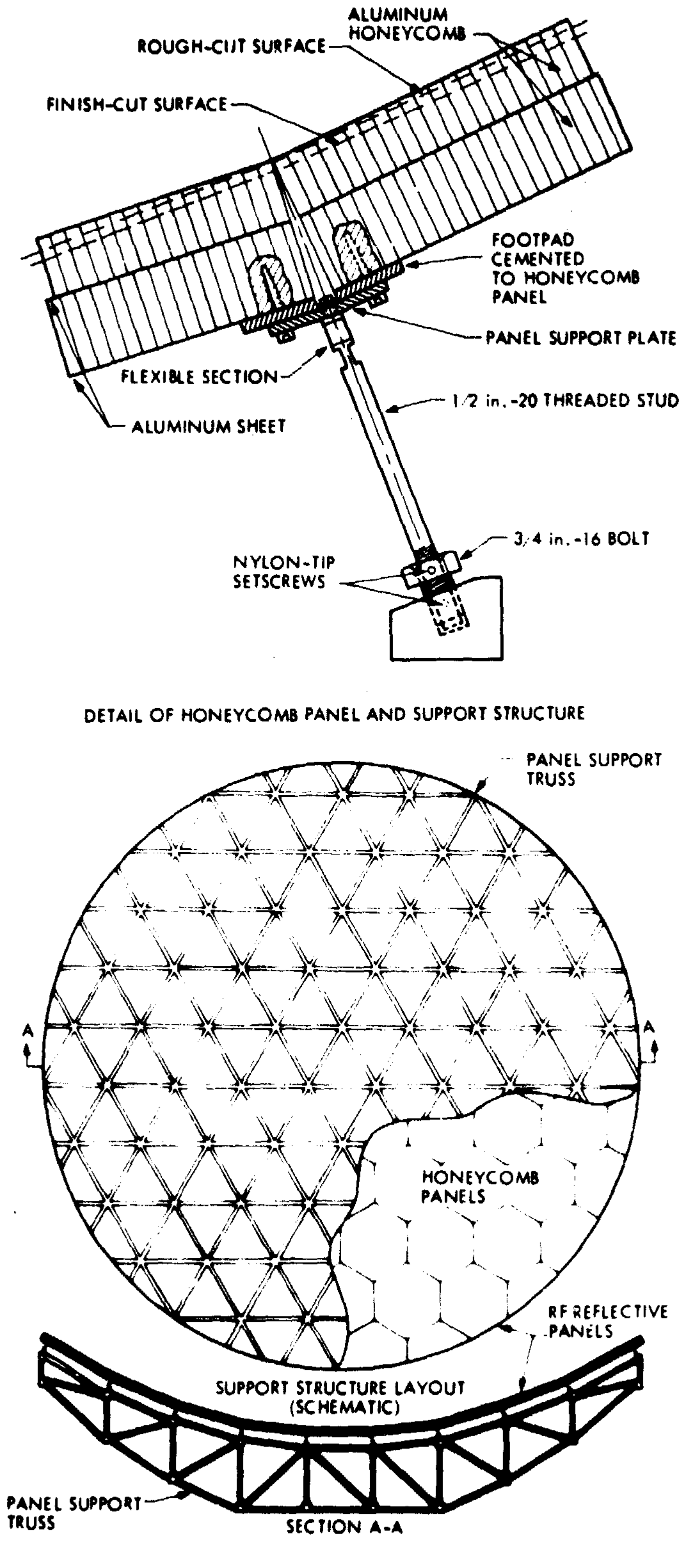
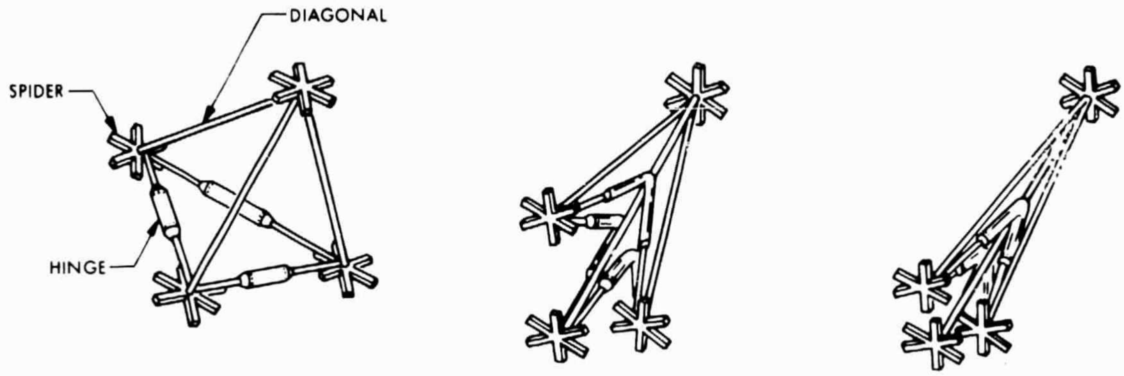


Figure 24. Caltech configuration of 10-m millimeter-wave antenna



TETRAHEDRON TRUSS FOR PETA ANTENNA

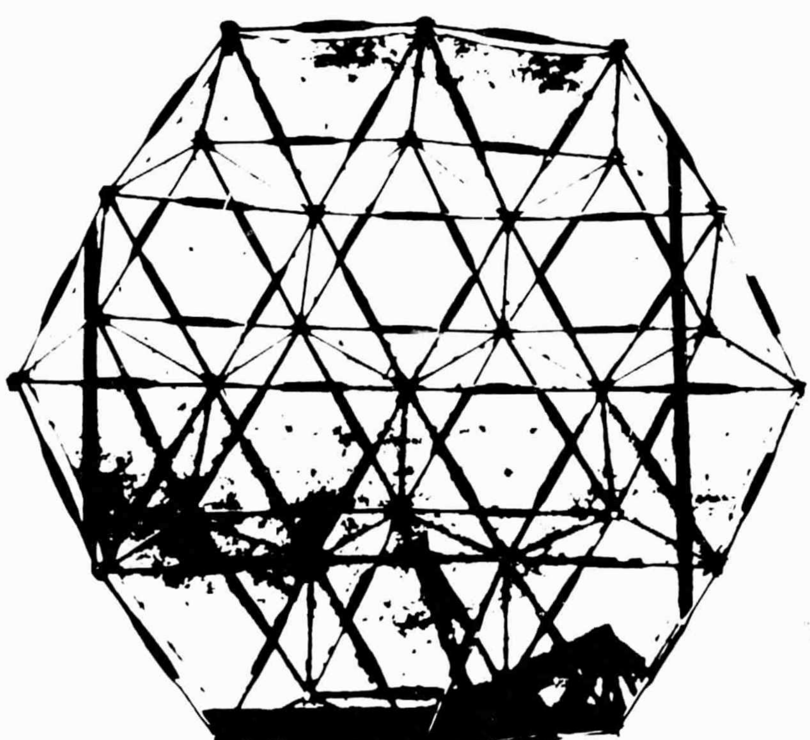


Figure 25. Truss configuration for General Dynamics PETA antenna

3. Conceptual Design

The ODSRS antenna will be an erectible antenna formed of hexagon-shaped precision solid surface panels, or segments thereof. These hexagons will be precision formed of a graphite composite material with a small temperature coefficient of expansion. One of the major problems faced by the ODSRS structure is distortion of the reflecting surface by temperature gradients due to varying solar radiation angles. The following approaches to temperature control have been chosen.

(1) The structural truss assembly will be shielded from solar radiation by thermal blankets to minimize temperature differences throughout the structure itself.

(2) The structure will be formed of graphite composite tubes with a small negative coefficient of expansion, and these will be joined by carpenter hinges with a small positive coefficient of expansion.

(3). The surface panels of the paraboloid will be coated to minimize the temperature difference between the sunlit and sun shaded surfaces. It is estimated that about 200°F difference can occur.

(4) To minimize the distortion from this large temperature difference which can occur on the hexagon shaped surface panel, the reflective surface will consist of a thin (1/32 in.) graphite composite sheet supported every 6 to 12 in. by flexure supports to a supporting structure which in turn will be firmly attached at three points to the truss structure.

A trial thermal loading analysis was made using the NASTRAN program to model a thin graphite composite panel supported laterally in the center and at alternate nodes by constraints normal to the surface to simulate the flexural supports. The results were encouraging, with the maximum displacement due to thermal loading being very small compared to surface accuracy requirements.

Another source of gain loss for the ODSRS is through displacement of the subreflector surface with respect to the main reflector surface. This type of displacement can occur due to dynamic response of the subreflector boom truss to attitude control or to temperature changes on the subreflector, the main reflector, or the subreflector boom truss. The initial assembly misalignment is also a possible source of error. Figure 26 shows this gain loss vs offset for the ODSRS antenna configuration. The subreflector location will be made adjustable to compensate for these errors during assembly. Table 18 shows expected surface errors for the ODSRS.

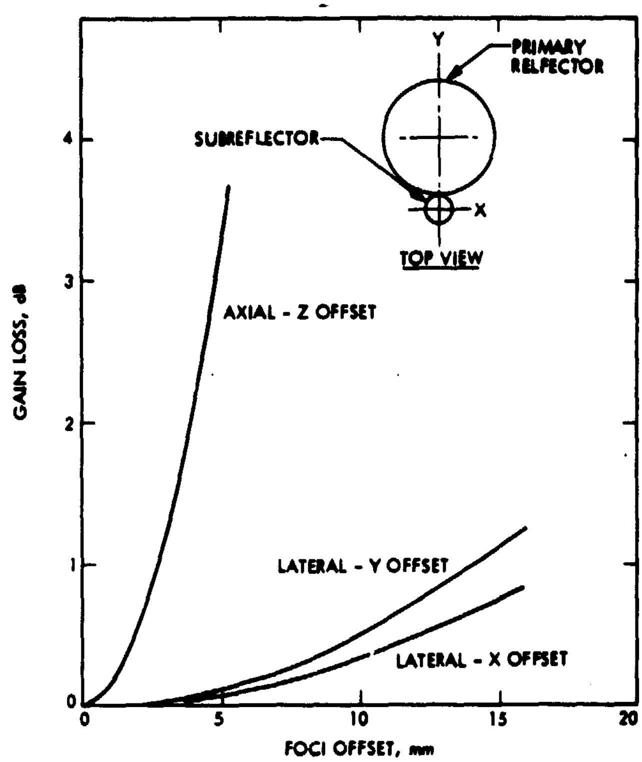


Figure 26. Offset antenna gain loss vs foci offset

Table 18. 28 m ODSRS surface errors[a]

Error source		Error, mm
Main reflector panel manufacturing		0.13
Main reflector panel setting		0.20
Subreflector manufacturing		0.13
Thermal distortion		0.20
	RMS Total	0.34

[a]No error for subreflector setting accuracy was included, and it was assumed that this would be a very small contributor to performance degradation, see Fig. 26.

C. Antenna Electrical Subsystem

1. Functional Requirements

The Antenna Electrical Subsystem (AES) is the microwave performance-oriented portion of the large antenna. The antenna must be designed to reliably provide microwave performance at a specified level over an extended lifetime (10 years) in the expected orbital environment. The approach selected for fulfillment of this requirement must be compatible with possible future requirements for an improved performance level. As a desired (but not required) feature of the antenna, the selected approach should be compatible with other Earth-orbital missions, in order to maximize the potential usefulness of ODSRS technology.

2. Performance Requirements

a. Telemetry. An improvement of 6.0 dB in the antenna gain divided by system noise temperature for the ODSRS relative to the 1985 ground-based DSN 64-m X-band capability was selected as the ODSRS performance level. This 6-dB improvement represents a compromise between the minimum improvement which would be worthwhile, and a large improvement which would be technologically and/or economically impractical. It is also similar to the improvement planned for the Large Advanced Antenna (LAAS) for tradeoff and comparison purposes. In specifying telemetry link improvement in terms of gain to system noise temperature ratio, the frequency of maximum performance is left as an open parameter, subject to broad constraints such as spacecraft transmitter technology and available bands. Implicit in this way of specifying link performance is the assumption that the user spacecraft antenna aperture is held constant; hence the spacecraft gain increases with frequency and the spacecraft beamwidth decreases inversely with increasing frequency.

b. Radiometric Navigation. The antenna must provide a level of performance at S-(2.3 GHz) and X-(8.4 GHz) bands which is compatible with desired navigation performance. This requirement does not appear to be a determinant in sizing the ODSRS antenna, but does result in requiring an ODSRS antenna feeding system which can handle at least S- and X-bands, in addition to any higher frequency telemetry band that may be selected. The antenna must be stable in phase and frequency for all operating conditions.

c. Antenna Polarization. Right-hand and left-hand circular polarization capability is required for the large antenna in all of its frequency bands of operation. Ability to determine linear polarization parameters is also required for radio science applications. Gain and noise temperature performance for linear polarization parameter determination may be lower than that required for circular polarization.

d. Radio Frequency Interference (RFI) Rejection. Through use of sidelobe control, the large antenna must provide sufficient RFI rejection that the ODSRS can be expected to operate in the orbital RFI environment.

e. Antenna Pointing. In conjunction with the attitude control subsystem and the antenna structure subsystem the antenna beam must be pointed with an accuracy such that the 6 dB performance improvement is obtained during the tracking periods. To achieve this objective the antenna, in concert with other parts of the relay radio subsystem, must provide beam pointing error signals to the attitude control system to be used as a fine pointing control.

f. Science Applications. The selected antenna approach should provide as much flexibility as possible in terms of supporting unplanned radio science experiments after deployment in orbit.

g. Performance Analysis and Prediction. The selected large antenna configuration must be such that performance parameters may be quantitatively predicted by accepted techniques.

h. Compatibility with Existing and Planned Deep Space Missions. The ODSRS antenna design must provide for support of ongoing deep space missions in the existing frequency bands. The S- and X-band ODSRS performance should be at least comparable to that expected for the planned DSN 34-m antenna network.

3. Interfaces

a. General. The selected large antenna approach must be compatible with other subsystem designs, shuttle packaging considerations, reasonable space assembly techniques and low Earth orbit checkout.

b. Antenna Mechanical Subsystem. The antenna structural subsystem must maintain sufficient physical stability of the antenna in the expected ODSRS environment that a maximum antenna gain degradation of less than 1 dB occurs in all of the selected frequency bands.

c. Attitude Control Subsystem

1) Antenna Beam Pointing. The antenna feed and its associated monopulse electronics will supply RF beam pointing error signals to the attitude control subsystem. The attitude control subsystem must, in turn, use this to maintain ODSRS beam pointing to one-tenth of the antenna beamwidth.

2) Antenna Roll Maneuver. It is expected that the antenna will use shielding and/or other techniques to control the wide-angle sidelobe structure over the Earth-facing hemisphere in order to provide RFI protection for the ODSRS. Because the ODSRS tracking direction (beam pointing for a given mission) will be almost constant in inertial space, it will be necessary to roll the ODSRS about the antenna beam axis during tracking. In this way the Earth will remain in the angular region of low sidelobe structure, thus minimizing the susceptibility to RFI. The roll period is 24 hours.

4. Implementation Options

a. Results of Previous Studies. For deep space communications, the question of the appropriate antenna type for use in ground stations was studied in detail by JPL In the early 1960's (Ref. 11) and led to the implementation of the DSN 64-m-diameter steerable paraboloids presently used in the DSN. The conclusion of these studies, which has not been altered by time, is that the paraboloidal (or quasiparaboloidal) reflector has no serious competitors for the deep space communications ground station application.

More recently, the characteristics and appropriate applications for large space antennas have been studied by JPL (Ref. 12). This study examined the various characteristics of reflectors, lenses and phased arrays. The study clearly showed that for applications such as the ODSRS for which antenna gains in excess of 10^5 are required, the large steerable reflector has no serious competitors. Arrays of low-gain elements (slots, dipoles, etc.) contain an impractical number of elements (i.e., 10^5 or more). In addition to problems with bulkiness and complexity, lenses have severe bandwidth problems. The present ODSRS study has not attempted to reexamine the conclusions of this study, but has instead attempted to optimize reflector antenna configurations.

b. Configurations Studied

1) 28 Meter-Diameter Offset-Fed Two-Reflector Antenna. The existing DSN antennas, most large ground antennas and many spacecraft antennas (e.g., Voyager) are symmetrically fed two-reflector cassegrain or modified cassegrain antennas. The wide-angle sidelobe performance of such designs is severely limited, however, by subreflector/support scattering and aperture blockage. The near-in sidelobe structure is also severely degraded by the aperture blocking, resulting in high effective antenna noise temperatures when tracking spacecraft near the Sun. Finally, the aperture blockage inherent in a symmetrically fed reflector degrades the aperture efficiency, resulting in a significant gain loss, typically about 1 dB.

The offset-fed paraboloid is a viable approach to elimination of aperture blockage. There has been recent renewed interest in offset-fed paraboloids, leading to extensive analytical and experimental work in the U.S. (Refs. 13, 14) and in the USSR (Ref. 15).

The ODSRS is not as susceptible to thermal noise radiated by the Earth's surface as is a ground-based antenna, but the problem of RFI is much worse because topographical shielding is not possible. Simple calculations show that for the wide-angle sidelobe levels normally obtained with well-designed symmetrically fed reflector antennas (Ref. 16), common uncontrollable RFI sources such as defective home microwave ovens, radar sets, etc., could completely jam out an ODSRS. For this reason a shielded, offset-fed dual reflector antenna with an unblocked aperture was chosen as one of the ODSRS configurations studied. For the required 6-dB telemetry link improvement an aperture diameter of 28 m at an operating frequency of 32 GHz is required. For S-(2.3 GHz) and X-(8.4 GHz) bands, this size yields performance comparable to the DSN 34-m-diameter antenna network.

Figures 3 and 4 show an artist's conception of the 28-m offset-fed antenna. A multifrequency-band (2.3, 8.4, and 32 GHz) hybrid-mode (corrugated) horn feed illuminates a quasi-hyperboloidal subreflector, which in turn illuminates the unblocked quasi-paraboloidal main reflector. Two of the major sidelobe sources, forward and rear spillover, occur primarily in one hemisphere of space which is kept away from the Earth by a 24-hour roll maneuver (Section III-C-3). A cylindrical shroud protects the "quiet" hemisphere from small scattering effects, rear spillover and, to some extent, rearward aperture radiation. The focal length of the paraboloid is 16.8 m and the diameter of the parent paraboloid is 67.2 m, yielding an F/D ratio of 0.25. Although this is a deep paraboloid (selected for weight/physical configuration reasons), calculations indicate that the offset cassegrain optics could also provide excellent multiple beam/beam scanning capability. Monopulse capability is provided at X- and K_A-bands by excitation of suitable higher- order (modes) in the hybrid mode horn.

2) <u>Array of Three Adaptively-Phased 17-Meter-Diameter Offset-Fed Two-Reflector Antennas</u>. The technology of adaptively phasing antenna apertures prior to signal combining is mature and experimentally demonstrated (Ref. 17). Recently a detailed study was performed to assess the performance of such systems with DSN-type receiver block diagrams (Ref. 18). The adaptive phasing allows the antenna apertures to bear an unknown physical relationship to each other. The performance of a 28-m-diameter single aperture may be achieved by adaptively combining the outputs of three 17-m-diameter antennas. The 17-m antenna size is attractive in terms of surface accuracy, ease of orbital erection, multiple target capability and "soft" failure. The antenna apertures need not be physically connected or even placed into service at the same time. Signal combining can be done on Earth.

Two immediately apparent problems with the three-element adaptive array are (1) the necessity for three low-noise receiver front ends (in each frequency band) and cryogenic systems and (2) the necessity for increased ODSRS-Earth downlink bandwidth if combining is done on the Earth. Orbital combining appears to be inconsistent with the ODSRS "bent pipe" concept.

3) Non-Adaptive Array of Small Reflector Antennas. Both of the problems described above for the adaptive array are eliminated by requiring that the correct array phasing is held sufficiently constant (in time) by structural/mechanical means. That is, the array elements are rigidly held in place by a mechanical framework with orbital structural stability comparable to the surface accuracy required for a single 26-m antenna.

The array element combiners (presumably one for each frequency band) are low-noise passive microwave devices which input signals to each of three low-noise receiver front ends (S-, X-, and K_A-bands). To avoid large degradations of the system noise temperatures, the combiners and interconnecting transmission lines must have exceedingly small losses. Presumably, equal length transmission lines can be utilized to provide an inherently broadband system.

Under contract to JPL, the Harris Corporation performed a study of this concept for the ODSRS application (Ref. 19). This study was highly constrained by JPL. An array was to be conceptually designed whose system performance (gain divided by system noise temperature) was equivalent to a single 30-m-diameter antenna/receiver system with the performance parameters shown in Table 19.

Study of the array element was specifically excluded from the contract. Three cases were to be studied with specified array element parameters as shown in Table 20.

Table 19. 30-m antenna/receiver performance parameters

Parameter	Frequency band		
	S-band	X-band	K_A-band
Frequency range	2.265-2.305 GHz	8.40-8.50 GHz	3.18-32.3 GHz
Aperture efficiency	0.75	0.70	0.60
Receiver noise temperature	2.0 K	4.0 K 15.0 K	
System noise	9.7 K	11.7 K 22.7 K	

Table 20. Array element parameters

Characteristic	Value
Element size	5 m, 10 m, 15 m
Element aperture efficiency	0.75
Element noise contribution due to losses	5 K

The rationale behind the element diameter selection is as follows. The largest size, 15 m, is similar to the 17-m adaptive array size and involves only a small number of elements (4). The smallest size, 5 m, can be preconstructed on Earth and loaded into the shuttle preassembled. This is also roughly the smallest size for which a high-performance cassegrain feed system can be used for X- and K_A-band coverage. This size also represents a rough upper limit on array complexity (30-40 elements). The 10-m case is simply an interpolation point between 5 m and 15 m.

The results of the Harris study are encouraging and show that this approach is a viable alternative to either the 28-m single antenna or the three-element adaptively phased array. One item not covered in the Harris study is the initial phase alignment of the array after assembly in orbit. An orderly procedure, phasing one element at a time against the sum phase with a receiver phase detector appears straightforward.

c. Tradeoff Criteria. Criteria which are relevant to the selection of a particular antenna electrical design approach include the following:

(1) Performance.

(2) RFI minimization.

(3) Performance predictability.

(4) Technology development required.

(5) Performance growth potential.

(6) Versatility with respect to mission definition/redefinition.

(7) Compatibility with radiometric applications.

(8) Ease of orbital assembly and checkout.

(9) Shuttle packaging compatibility.

(10) Weight, reliability, and cost.

d. Results of Tradeoff. Each of the configurations discussed is considered a viable approach. The area of greatest uncertainty at present, is the low-Earth-orbit assembly of the antenna. Providing suitable space assembly techniques can be devised, it is felt that the single 28-m-diameter shielded offset-fed dual-reflector antenna offers the greatest potential with respect to the tradeoff criteria. The nonadaptive array of approximately 5-m diameter reflector antennas minimizes the space assembly problem but is expected to provide poorer RFI rejection and a somewhat greater weight and cost. The array of three adaptively phased 17-m offset-fed shielded dual-reflector antennas is primarily attractive if the three elements are separately launched and checked out. This approach minimizes initial cost and also provides for more mission flexibility (each unit can operate separately).

5. Conceptual Design

This section discusses the antenna electrical aspects of the 28-m-diameter configuration. The antenna electrical aspects of the 17-m array element are essentially identical.

a. General Description. Figure 27 shows the selected feed geometry of the 28-m-diameter dual-reflector offset-fed antenna. A multiband (S, X, K_A) hybrid mode horn illuminates a hyperboloidal subreflector, which in turn illuminates a paraboloidal main reflector. Use of shaped reflector techniques (i.e., quasi-hyperboloidal and quasi-paraboloidal) to increase aperture efficiency is under intensive study at JPL (Ref. 14) and has been demonstrated in the USSR (Ref. 15); gain performance of the 28-m configuration was evaluated without shaping, for the purposes of this study.

A cylindrical metallic shield is placed around the aperture to reduce sidelobe levels for Earth RFI rejection in one hemisphere. The quantitative performance of this shield has not yet been evaluated, but calculations published by Ford Aerospace and Communications Corporation show promising results for cylindrical metallic shrouds on symmetrical paraboloids (Ref. 20).

The hybrid mode feedhorn is an extension of a dual frequency band (S- and X-bands) hybrid mode feedhorn developed at JPL for possible future DSN ground station use (Ref. 21). This type of horn not only exhibits high performance, but is also subject to exact analysis and performance prediction. Based on previous work by Williams (Ref. 21) a preliminary design for a three frequency band ODSRS feedhorn was performed. The horn configuration selected has a diameter of 1.14 m, a half flare angle of 10 deg and a groove depth of 5.0927 cm.

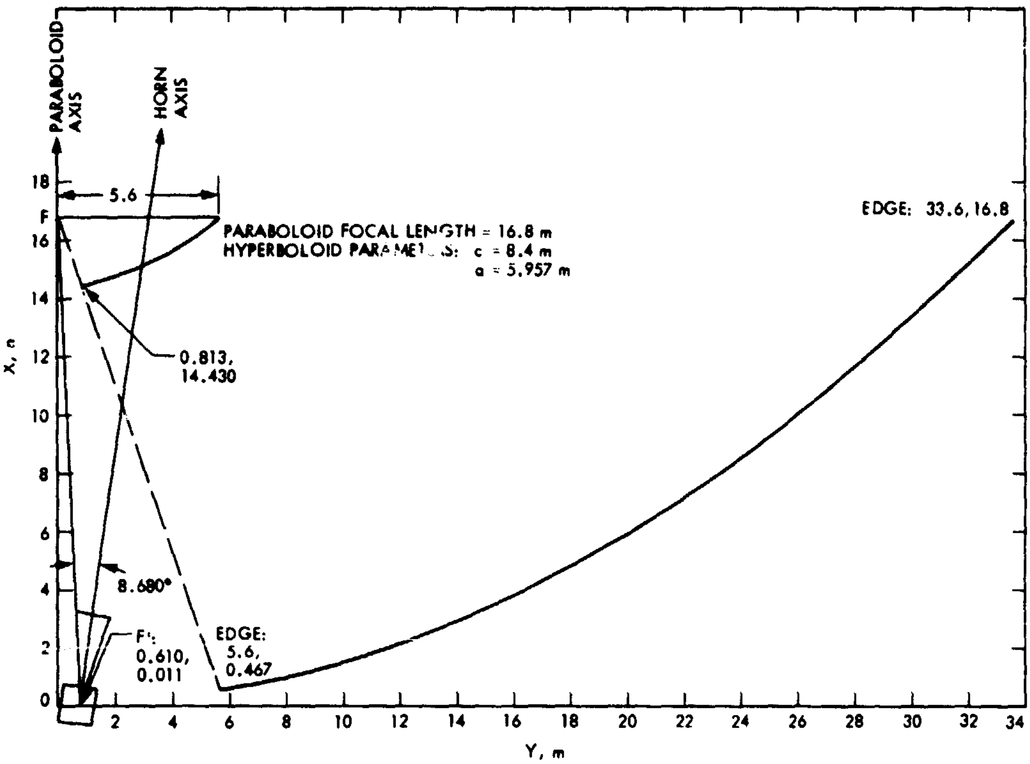


Figure 27. 28-m offset antenna feed geometry

JPL antenna analysis software was used to scatter the hybrid mode horn fields off the offset hyperboloid and to calculate the antenna aperture fields. The latter were then integrated to determine the aperture efficiency components. Table 21 below compares the ODSRS result with the corresponding numbers published (Ref. 22) for the DSN 64-m antenna at X-band.

Some (perhaps half) of the offset-fed ODSRS amplitude illumination loss should be recoverable by use of shaping techniques (Ref. 14, 15), but this possibility was not included in sizing the ODSRS antenna (i.e., an efficiency of 0.75 was selected). Note that efficiency losses due to sidelobe reduction for RFI may require increasing the antenna size.

b. <u>Monopulse Antenna Pointing Error Detection System</u>. It is expected that monopulse capability will be required at both X- and K_A-bands. A monopulse electronic system has been conceptually designed. At each of the two frequency bands it would consist of a three-channel superheterodyne system with error/reference channel cross-correlators and integrators. The reference channel input would be obtained from the low-noise front end output and the error channel inputs would be derived from medium-noise front ends such as radiation-cooled paramps.

Table 21. DSN 64-meter and ODSRS offset-fed antenna aperture efficiencies[a]

Factor	DSN 64 m, dB @ 8.4 GHz	ODSRS offset-fed, dB @ 32 GHz
Forward spillover	-0.247	-258
Rear spillover	-0.006	-0.008
Amplitude illumination	-0.719	-0.945
Phase error	-0.124	-0.004
Cross polarization	-0.0003	-0.00008
Aperture blockage	-0.830	-0.0
Totals	-1.928 dB = 0.641	-1.215 dB = 0.756

[a]Losses due to surface inaccuracy not included.

A brief analysis was performed to derive typical integration times for the angle error channels. As a ground rule, it is assumed that no signal demodulation can be used and, in fact, that the monopulse system has to work satisfactorily when tracking a random noise signal such as that from a radio source. This assumption is compatible with the ODSRS "bent pipe" concept and is also compatible with the requirement to support radio science observations.

When a spacecraft signal is being tracked, the worst case will be a weak narrowband signal. As a worst-case numerical example, assume that a 0.1-dB rms pointing signal loss is desired. This corresponds to a required integration time of about 2 seconds, a bandwidth of 1 kHz, and an SNR of 0.1.

c. Antenna Scan/Multiple Beam Capability. Although the ODSRS does not require multiple beam capability, many other Earth orbital applications do. It is desirable that the ODSRS antenna have good multiple beam capability in order to maximize the versatility of the ODSRS design. Wong (Ref. 23) studied the beam scanning performance of symmetrical cassegrain systems and showed that a deep paraboloid (e.g., 0.25 F/D ratio) can provide excellent scan/multiple beam capability if a cassegrain feed system is used.

The scan properties of the offset-fed cassegrain ODSRS antenna have been briefly investigated using a raytrace technique. It has been found that the offset cassegrain feed has superior scan capability compared to the symmetrical configuration investigated by Wong (Ref. 23).

d. Technology Level. The selected antenna electrical configuration makes use of the latest available techniques, but does not assume new technology. The problem of sidelobe control for RFI rejection has not yet been adequately analyzed and new technology for RFI analysis and control will be required. A detailed analysis of the overall antenna beam pointing system needs to be performed.

e. Redundancy. There is no redundancy planned for the selected configuration.

f. Mass Requirements. The antenna feedhorn, diplexing and microwave switching equipment is expected to involve a mass of 120 kg.

g. Power Requirements. The antenna electrical subsystem will require occasional peak powers of approximately 100 W to activate microwave waveguide switches. There will be no quiescent power requirements.

D. Cryogenic Receiver Subsystem

1. Requirements

a. Functional. The Cryogenic Receiver Subsystem (CRS) shall meet the following functional requirements:

(1) Receive radio signals at S-band (2.3 GHz), X-band (8.4 - 8.5 GHz), and K_A-band (31.8 - 32.3 GHz) from deep space probes or natural radio sources. Simultaneous reception shall be limited to any two of the three frequency bands.

(2) Provide cryogenic cooling for the low noise portion of the receiver assembly.

(3) Translate the received signal in frequency as required. This frequency translation shall be made using a coherent reference from the stationkeeping telecommunications subsystem or an onboard stable oscillator and shall preserve phase and frequency information needed by navigation and radio science.

(4) No demodulation or processing of the received signal shall be required of the CRS.

(5) The CRS shall be designed for a non-refurbished lifetime of 10 years.

b. Performance. The CRS shall have performance characteristics as shown in Table 22.

Table 22. Cryogenic receiver subsystem performance requirements

Parameter / Frequency band	S-band	X-band	K_A-band
Frequency range, GHz	2.265-2.305	8.40-8.50	31.8-32.3
Noise temperature, K	2.0	4.0	15.0

c. Interfaces. The CRS will have the following interfaces:

Interface	Interface function
CCS-CRS	Mode and state change commands Failure detection data
AES-CRS-RRS	Received RF signals from the antenna electrical subsystem are received at a low noise temperature, translated in frequency, amplified and sent to the RRS
STS-CRS	Frequency translation reference signal
PWR-CRS	28 ± 7 Vdc power to operate the up converters, masers, and cryogenic refrigerators
SDH-CRS	CRS housekeeping telemetry data is sent to SDH
CRS-Temperature Control	Thermal loads from the cryogenic refrigerator must be radiated away from the ODSRS

2. Implementation Options

a. Cryogenic vs Non-Cryogenic Low Noise Receiver. The cryogenic low noise receiver is a major development to operate reliably in a space environment for 10 years. Also, the likely power consumption of the cryogenic refrigerator even after an extensive development program will be the major driver on ODSRS power subsystem size.

Candidates for noncryogenic receivers were radiation cooling with paramps, tunnel diode amps, or FET amps. Best expected system noise temperature for these devices is about 200 K at 32 GHz. This would require an antenna size of 85 m to meet the ODSRS system performance goals. An 85-m antenna at 32 GHz would be very difficult to manufacture, assemble, and align, and would probably require active surface control to compensate for thermal effects. Also, it would have a beamwidth of 0.008 deg, which would quire a significant increase in attitude control pointing capability.

The cryogenic low noise receiver was chosen.

b. Cryogenic Refrigerator vs Expandable Cryogenic Fluid Cooling. It would be desirable to cool the low noise receiver by some simpler means than a mechanical refrigerator. The use of an expendable coolant was reviewed and discarded because of the total mass of coolant required for 10 years' operation and the difficulty of cryogenically storing this much fluid for 10 years.

3. Conceptual Design

The cryogenically cooled portion of the receiver is required to receive two out of three possible incoming frequencies simultaneously. Figure 28 shows the upconverter and maser configuration selected. Note that all incoming frequencies are upconverted to 32 GHz prior to the masers so that all masers operate at the same frequency. This greatly simplifies superconducting magnet design and fabrication. Operating the masers at K_A-band also provides minimum size and mass, which yields the highest possible cryogenic efficiency.

Technologies required by the CRS have been demonstrated in ground-based laboratory configurations. However, a major development effort is required to space-qualify this technology and to provide for 10 years' operation without operator maintenance.

In order to achieve confidence in a 10-year lifetime, it is recommended that two identical receiver and cryogenic systems be flown. There is some merit to operating both systems continuously, and switching RF inputs from one to the other in case of failure. However, since each system consumes about 2.5 kW continuously, it is recommended that the ODSRS design assume only one cryogenic low noise receiver assembly operated at a time.

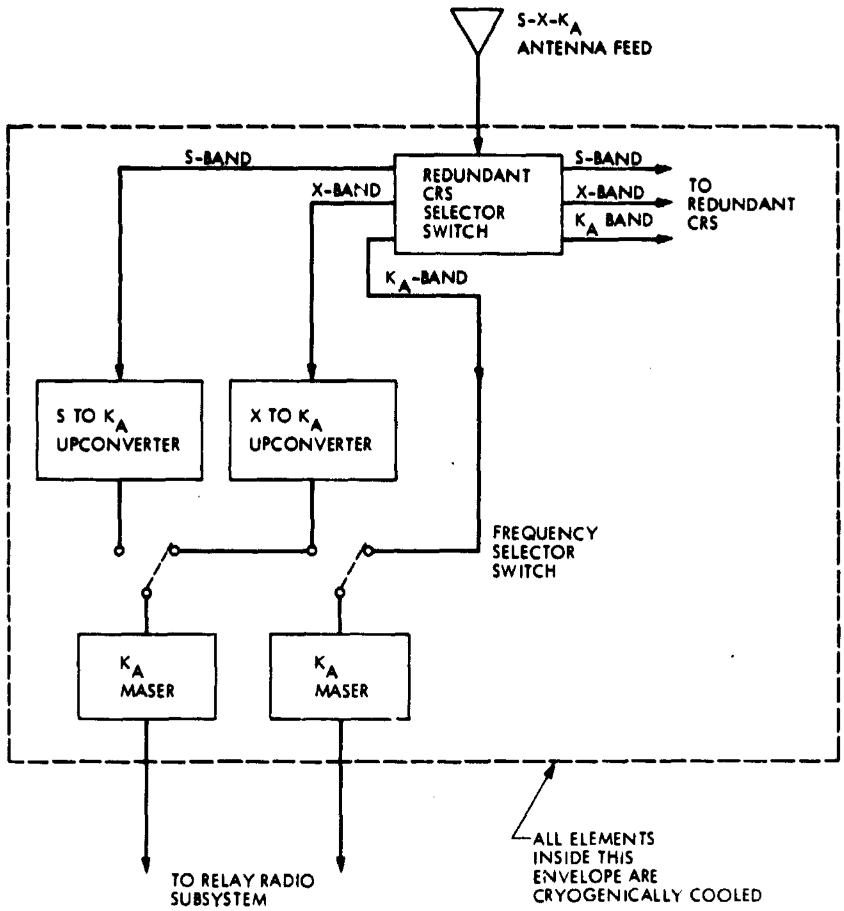


Figure 28. ODSRS low noise receiver configuration

Mass, size, and power requirements for the CRS are shown in Table 23.

E. Relay Radio Subsystem

1. Requirements

a. Functional. The Relay Radio Subsystem (RRS) shall perform the following functions:

(1) Translate the frequency of the signals received from the low noise receiver to the K-band relay link frequency.

(2) Linearly amplify the signals to the level required for ODSRS-to-Earth signal-to-noise ratio and compliance with anticipated CCIR requirements.

(3) Frequency translation and amplification shall be sufficiently stable to support radiometric requirements.

Table 23. CRS mass, size, and power requirements

Parameter	Value	Notes
Mass	150 kg 300 kg	Single subsystem Redundant configuration
Size	3 m^3	Redundant configuration
Power required		
Cryogenic Refrigerator	2 kW	Assumes one subsystem operating at a time
Maser and Electronics	500 W	
Duty cycle	Continuous	
Thermal load	2.5 kW	Needs to be radiated from ODSRS

(4) Adjust the K-band downlink power level, or turn on and off the K-band amplifiers upon receipt of commands from the ODSRS CCS.

(5) In the absence of a ground signal to ODSRS or upon receipt of a command from the CCS, the K-band frequencies will be controlled by an ultrastable oscillator onboard ODSRS.

(6) Provide the capability of deriving the K-band frequencies from a pilot tone or a carrier transmitted from the ground to ODSRS.

(7) Operate over either of two redundant channels.

b. Performance. The Relay Radio Subsystem shall meet the following performance requirements:

Parameter	Requirement
Received frequency range	31.8 to 32.3 GHz
Feedthrough bandwidth (each channel)	50 MHz, 5 MHz

Parameter	Requirement
Transmitted frequency range	Approximately 13.8 to 14.3 GHz
Transmitter power output range	3 W to 1 mW
Transmitting antenna gain	47.8 dB
Raw power input voltage	28 $\pm$ 7 V

c. <u>Interfaces</u>. The Relay Radio Subsystem will have the following interfaces:

Interface	Interface function
AACS-RRS	Signals to control the RRS K-band antenna positioning actuators
CCS-RRS	a) Commands to change RRS mode or state b) Failure detection information
CRS-RRS	Spacecraft signals to RRS for frequency translation and transmission to ground
PWR-RRS	Raw power (i.e., 28 $\pm$ 7 V) to the RRS power converters
STS-RRS	Pilot tone reference sent from ground to the RRS frequency synthesizer
RRS-SDH	a) The composite ODSRS housekeeping telemetry subcarrier from SDH to RRS for transmission to ground b) The RRS housekeeping telemetry data to SDH

2. Implementation Options

Implementation options for the RRS were confined to the following items:

(1) Antenna size.

(2) ODSRS to earth frequency.

(3) Transmitter power output.

(4) Type of power amplifier devices.

The selection of antenna size of 2 m, frequency of 14 GHz and transmitter power output of 3 W maximum is discussed in Section II-A-7, Relay Telemetry System. For 14-GHz power amplifiers, TWTs, GaAs FETs and Impatt devices were considered from the standpoint of reliability, lifetime, cost, efficiency, and mass. GaAs FETs appear to be the best choice for implementing a 3-W linear transmitter at 14 GHz in the mid 1980s. This is based on assumptions that planned technology developments will achieve projected improvements and that no unexpected failure mechanisms develop which would substantially reduce expected lifetimes of the devices. This conclusion was reached in a study which is documented in Ref. 24.

Impatt devices are expected to be favored over GaAs FETs above 30 GHz, but are less efficient than FETs at 14 GHz. At 3 W and 14 GHz, linear TWTA and GaAs FET amplifiers are expected to require 25 and 30 W of raw power respectively. This small power disadvantage is outweighed by the following advantages for the GaAs FET:

(1) Mass.

(2) Expected cost.

(3) Expected device lifetime.

(4) Graceful degradation when used in series/parallel combinations.

3. Conceptual Design

a. General Description. The RRS is composed of dual-channel frequency translators, frequency synthesizers, transmitters and antennas. The frequency translator operates independently on each of two 32-GHz signals received from the maser outputs. A maser signal is mixed with a reference frequency to down-convert it to a fixed IF frequency (probably in the 0.3 to 1-GHz region). Here it is amplified and filtered to reject noise outside the required information passband. The final IF stage employs envelope AGC to provide low distortion, low phase shift amplitude limiting under strong received signal conditions. The IF signal is then mixed with another reference to obtain the proper K-band frequency (nominally 14 GHz) to drive the transmitter chain.

Each of the two translated maser signals (and the ODSPS housekeeping composite telemetry modulation if desired) are combined to form the K-band downlink signal. This signal drives four parallel linear amplifier chains each consisting of three to four transistors. The outputs of the four amplifier channels are added in a power combiner and routed to the antenna for transmission to Earth. A block diagram of this conceptual design in shown in Fig. 29.

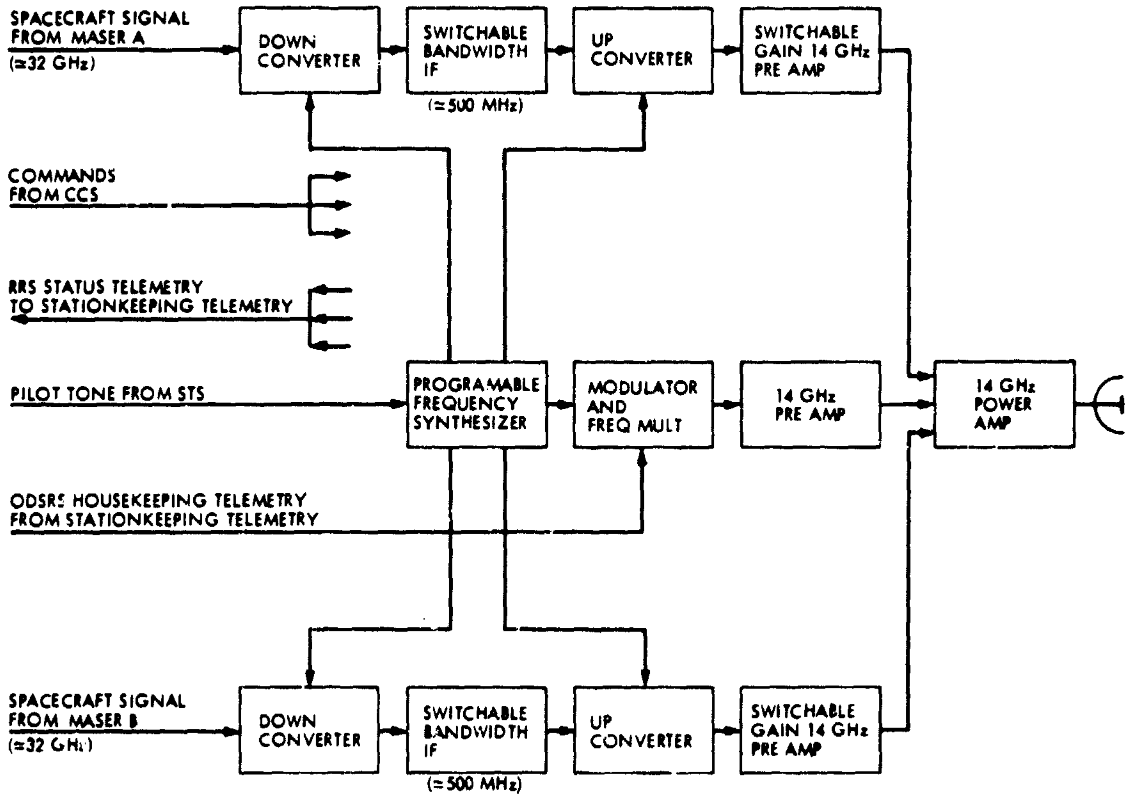


Figure 29. ODSRS relay radio subsystem functional block diagram

There are two 2-m antennas. Each is supported from the bus by a two-tube, two-rotary-joint system that allows Earth pointing by at least one antenna in all orientations except for a small portion of the sphere blocked by the spacecraft receiving antenna reflector. For normal tracking, both antennas will be in continuous view of the Earth.

The reference frequencies for the up and down converters in the frequency translator channels are supplied by a frequency synthesizer. The synthesizer operates from its own stable oscillator or is synchronized upon command by a pilot tone received from a ground station through the STS. The reference signals are programmable by command in order to provide required channel separation and frequency for reception and transmissions to Earth.

b. Operating Modes. Modes, states, and parameter variations required of the RRS are summarized in Table 24.

Table 24. Operating modes or variables

Item	Variation
Number of transmitted signals	Simultaneously transmit one housekeeping telemetry signal and 0, 1 or 2 translated planetary spacecraft signals
Transmitter power	Select power outputs in several steps from a maximum of 3 W to a minimum of 1 mW or turn transmitter off
Frequency	Translate each maser signal (at 31.8 to 32.3 GHz) to any of several selected frequencies in a 500-MHz band located at approximately 14 GHz
Feedthrough bandwidth	Select 50 or 5 Mhz
K-band-to-Earth antenna orientation	Two degrees of freedom
Active unit	Operate over either the prime system or the standby redundant system.

c. Technology. The circuits at frequencies between a few GHz and 32 GHz will utilize GaAs FETs as the active devices for amplification frequency multiplication, mixing, etc. The narrow bandwidth filtering in the IF strips will be accomplished with surface acoustic wave filters

(SAW's). Bandwidth switching can be done using solid state switches that actuate the desired path in a parallel bank of channels. Power output can be adjusted by activating selected patterns of diode or other types of solid state switches in a series/parallel combination of fixed attenuators in several IF stages.

The possibility of varying transmitter power by varying transistor supply voltages should be examined during the detailed design phase.

Available technology is adequate to meet the 14-GHz 2-m antenna requirements. The reflector is a sandwich construction of aluminum honeycomb core and graphite epoxy skins. The reflector and feed support tubes are tridirectional fiberglass. The feeds and rotary joints are scaled versions of the X-band portion of the VO S/X-band hardware designs.

d. Redundancy. The series/parallel combination of power transistors in the transmitter is a form of redundancy in that "graceful" degradation results from single stage failures. The rest of the radio, however, is not so tolerant. Standby redundancy for each RRS component is recommended. Two complete single string systems, from frequency translator through K-band antenna, have been assumed for mass and cost estimates. Power estimates assume only one system is activated.

The subject of cross strapping between prime and standby components should be addressed during the detailed design phase, when more is known about this technology and about ODSRS requirements.

e. Mass, Size and Power Requirements. The requirements are given as follows:

	Mass, kg	Size, cm^3	Power, W
Electronics	10	12,000	40
Antennas and cables	20	N/A	N/A
Total	30		40

F. Stationkeeping Telecommunications Subsystem

1. Requirements

a. Functional. The Stationkeeping Telecommunications Subsystem (STS) shall perform the following functions:

(1) Acquire and lock on to the S-band signal sent from the ground.

(2) Detect the command message bit stream from the received S-band signals and provide it to the CCS.

(3) Transmit to the ground S- and X-band carriers, derived from the received S-band signal in the ratios of 240/221 and 880/221, respectively. In absence of a received signal or upon receipt of a suitable command, the transmitted signals will be derived from a selfcontained ultrastable oscillator onboard the ODSRS.

(4) Demodulate the ranging signal from the received signal and modulate the transmitted carriers with the ranging signal.

(5) Provide a pilot tone derived from the received S-band signal to the frequency translator in the RRS.

(6) Modulate the transmitted signals with the composite ODSRS stationkeeping telemetry signal.

(7) Operate over either of two redundant channels.

b. Performance. The stationkeeping telecommunications subsystem shall meet the following performance requirements:

Parameter	Requirements
Received frequency range	2110 to 2120 MHz
Transmitted frequency range	2290 to 2300 MHz and 8402 to 8440 MHz
S-band power output	125 mW
X-band power output	16 mW
Contribution to ranging uncertainty	1 m[1]
Tracking loop noise bandwidth	200 Hz
S- and X-band antenna gains	-4dB minimum over the Earth-favored hemisphere
Raw power input voltage	28 ±7 V

[1] 1-m ranging accuracy is possible with the baseline transponder design. A requirement for 10-cm accuracy has been identified. The technology development necessary to provide this accuracy will be described in the technology section of this report.

c. Interfaces. The stationkeeping telecommunications subsystem will have the following interfaces.

Interface	Interface function
STS-CCS	Supply commands to change STS mode or state. Accept the command message bit stream detected in the STS receiver.
STS-PWR	Supply raw power (28 ±7 V) to the STS power converters.
STS-RRS	Accept from STS the pilot tone for reference in the RRS frequency synthesizer.
STS-SDH	Supply the composite ODSRS housekeeping telemetry signal from the SDH to STS for transmission to ground. Supply STS housekeeping telemetry data to the SDH.

2. Implementation Options

It was assumed early in the study effort that the NASA Standard Transponder (NST) and spacecraft low-gain antennas that are available today would meet the STS requirements. Subsequent analysis indicates that only minor modifications to the existing NST and low-gain antenna designs are needed to meet specific ODSRS requirements. Thus, no other options have been considered at this time.

3. Conceptual Design

a. General Description. The STS is composed of two S/X-band transponders (S-band up and S/X-band down) and two S/X-band antennas. A transponder contains an S-band diplexer, a command receiver, an S-band transmitter and an X-band transmitter. The diplexer connects the receiver and the S-band transmitter to a single port which feeds an S-band antenna. A block diagram of this configuration is shown in Fig. 30.

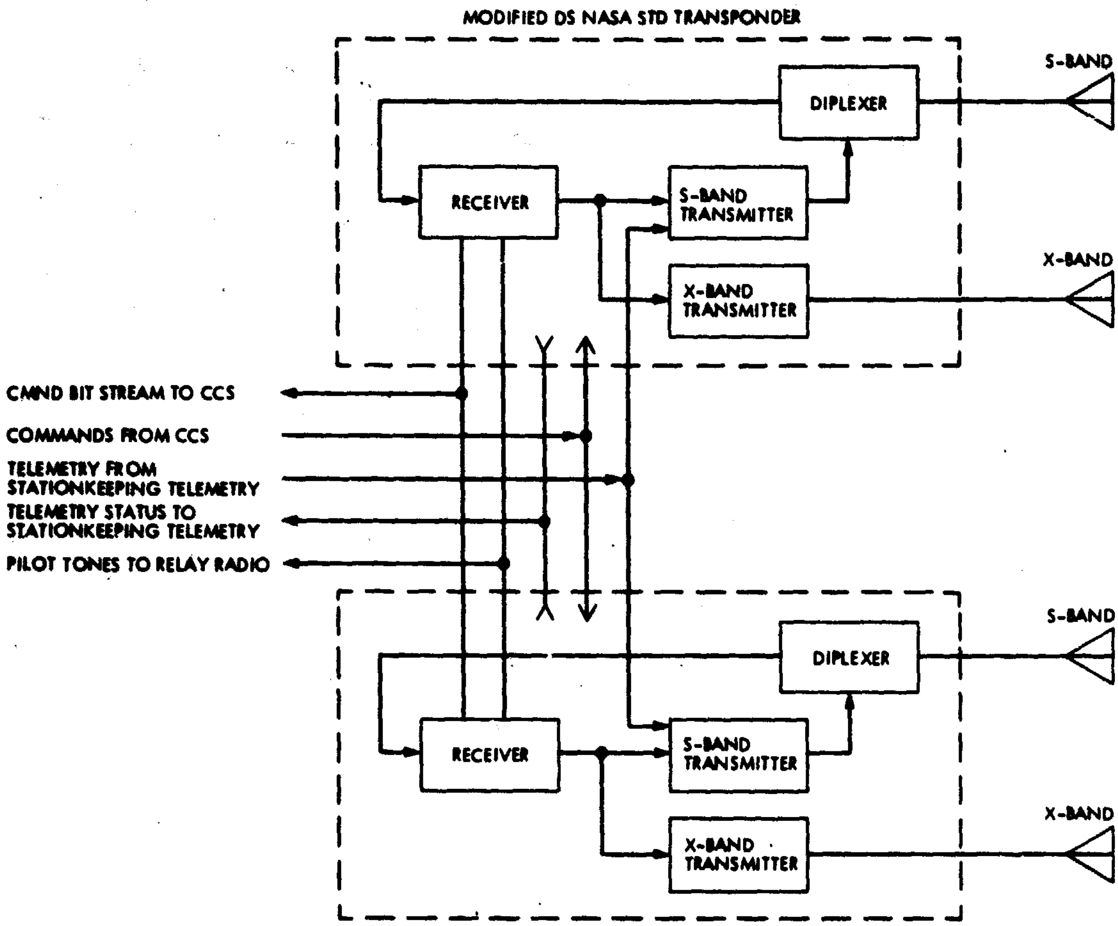


Figure 30. ODSRS Stationkeeping Telecommunication Subsystem Functional Block Diagram

The command message bit stream is detected in the receiver and sent to the CCS. The receiver detects the ranging baseband signal sent from the ground and sends it to the S- and X-band transmitters for turnaround transmission to ground. The receiver also supplies frequency references derived from the S-band uplink to the RRS frequency synthesizer. The ODSRS composite telemetry information from the SDH modulates the transmitter signal for transmission to Earth.

The antennas are dual-frequency (S/X-band) antennas that each provide at least -4 dB gain over a hemisphere. They are mounted at diagonally opposite corners of the bus, pointing into the Earth's hemisphere but skewed in opposite directions. This skew will allow extended coverage, possibly of the entire sphere of the ODSRS for command traffic in case of ODSRS attitude control malfunction. The amount of skew will depend on the link margins.

b. Operating Modes of Variables. Modes, states and parameter variations required of the STS are summarized below:

Item	Variation
Command data rates	Select any $2000/2^n$ bps rate Where n = 0,1,2, ... 8
Transmitters activated	S- and X-band transmitters can be turned on or off independently
Receivers activated	Unit 1 or 2 on, or both on
Ranging channel	On or off
Tracking	Downlink driven from internal oscillator if RCVR is not locked. If RCVR is locked to uplink signal, downlinks can be commanded to either noncoherent (internal oscillator) or coherent (driven by RCVR VCO) mode.

c. Technology. Available technology is adequate to meet the baseline requirements. The Viking Orbiter S/X HGA feed design (which is used as the STS antenna) requires only minor modifications to meet ODSRS peculiar mechanical and pattern requirements. The NST's are modified versions of today's deep space (DS) model. The modifications are (1) changes the 18-Hz PLL to a 200-Hz loop to allow operation in low Earth orbit and (2) provide a pilot tone output from the receiver detector module.

In our study effort, a requirement for 10-cm ranging accuracy was identified (see Technology Development Descriptions for more discussions). Information on what the ranging transponder to meet this requirement might look like is not detailed at this time. Briefly, to implement this high-accuracy ranging system on ODSRS would require at least an X-band turnaround system with a 30- to 45-MHz ranging channel bandwidth. This X-up, X-down wideband transponder might be 30 to 40% heavier and draw 20% more power than the baseline design (S-up and S/X-downlink) transponders. If S- and X-band uplink and downlink are required simultaneously, the baseline mass and power estimates would have to be increased by between 200 and 240%.

d. Redundancy. Standby redundancy for components of the STS is recommended. Two single-string systems have been budgeted. The subject of cross strapping between prime and standby components was not considered in this study. It should be addressed in the detailed design phase, when a reliability analysis can be made.

e. Mass, Volume and Power Requirements. These requirements are as follows:

Mass, kg	Size, cm^3	Power, W
11	18,000	14 or 21[a]

[a]One transponder draws 14 W. The 21-W results when both receivers are on, in addition to one set of S- and X-band transmitters.

G. Attitude and Articulation Control Subsystem

1. Requirements

a. Functional. The Attitude and Articulation Control Subsystem (AACS) is primarily responsible for maintaining attitude control of the ODSRS. In addition, the AACS controls the articulation of any solar arrays, high-gain antenna, radiators, and sensor platforms mounted on the spacecraft. The AACS shall:

(1) Maintain its pointing accuracy toward target spacecraft by compensating for any disturbance torques (e.g., solar pressure, gravity gradient).

(2) Perform commanded turns of the ODSRS as are required for retargeting and stationkeeping maneuvers.

(3) Provide attitude stabilization during on-orbit assembly of the spacecraft.

(4) Provide attitude stabilization during stationkeeping maneuvers.

(5) Provide articulation and pointing control of sensor platforms, solar arrays, radiator panels, and high-gain antennas.

(6) Provide sufficient engineering data in the telemetry stream to accommodate ground support operations.

b. Performance. In order that the ODSRS be capable of meeting its mission requirements, several key performance requirements have been specified:

(1) Total antenna electrical line-of-sight (LOS) pointing error shall not exceed 0.002 deg (7.2 arc sec).

(2) The antenna shall be capable of retargeting 90 deg for both axes in one hour.

(3) The AACS shall be designed for a 10-year operational life.

(4) In order that the RFI from the Earth be kept to a minimum, it is desirable to point the shielded hemisphere of the 28-m antenna at the Earth during tracking operations. As the pointing accuracy must be maintained during tracking, a continuous roll maneuver about the electrical LOS is required. Preliminary analysis of this maneuver has revealed that it may be difficult to maintain the required pointing accuracy due to the spin dynamics of the ODSRS. A detailed simulation of the ODSRS dynamics will be necessary to determine what constraints must be levied on the configuration to accommodate the roll maneuver. Finally, a tradeoff study of the RFI benefits realized from the maneuver vs the spacecraft design necessary to provide it is needed to develop the optimal approach.

c. Interfaces. As part of its normal operation, the AACS will interact with several of the other ODSRS subsystems as follows:

(1) SMD. Dynamic interaction between flexible members of the ODSRS structure and attitude control actuators will seriously affect pointing accuracy. Of particular concern will be the flexibility of the parabolic extendible truss antenna (PETA) assembly. Mechanical alignment of the AACS sensors will also be a critical area.

(2) AES. The AACS will utilize a tracking error signal generated by the antenna electrical subsystem and based upon the received signal from the target spacecraft. This direct measurement of the antenna pointing error will allow for the precise pointing of the antenna by the AACS.

(3) SDH. The AACS will supply telemetry data for ground analysis to the SDH.

(4) PWR. The AACS components shall receive their power from the power subsystem.

(5) SPS. Chemical thrusters in the ODSRS design will be jointly shared by the attitude control and stationkeeping propulsion subsystem. Definition of specific control responsibilities between the two subsystems has not been determined.

(6) CCS. The AACS will receive control commands from the CCS and will feed back status data. This will be a complex interface due to the interaction between the AACS and CCS for pointing, articulation, etc.

(7) SPS. The AACS will deliver valve commands to the SPS.

2. Implementation Options

Based upon the performance requirements and mission constraints, a conceptual design for the AACS was formulated centering around the use of reaction wheels as the primary torquers. Reaction wheels have the advantages of smooth, precise torquing with no expendables. They do involve more mass and power than other attitude control systems, but these were not significant constraints relative to the rest of the ODSRS system size. Attitude determination will be accomplished using celestial, inertial, and antenna beam error sensors.

The only significant tradeoff study involved the means for desaturating (unloading) the reaction wheels. Reaction wheels provide torque by changing rotational speed. As they have a peak operating speed, it is necessary to periodically unload their stored momentum by torquing the spacecraft. Possible schemes for momentum dumping include magnetic torques (using the Earth's magnetic field), propulsive thrusters (electric and chemical), gravity gradient control (utilizing active control of spacecraft inertias), and solar pressure control (utilizing active control of the spacecraft surface area).

The criteria chosen for evaluating the relative merit of the various desaturation schemes were, in descending importance: feasibility, simplicity/reliability, power and mass.

Feasibility for the ODSRS required consideration of the operating environment and mission constraints. Simplicity and reliability are significant because of the autonomous, 10-year nonrefurbished operation required. The power and mass constraints are not as significant as might typically be expected. Relative to the rest of the ODSRS, the AACS will not contribute a significant amount of mass and power.

The selection of the desaturation scheme for the reaction wheels was quickly narrowed down to a choice of propulsive thrusters. Magnetic torquing, while frequently used by small satellites at low orbits, proved to be infeasible for the ODSRS. Because the Earth's magnetic field is small (0.001 gauss) at GEO, the size of torquer bars required (10^8 pole-cm per axis) is beyond the foreseeable state-of-the-art. Furthermore, the ability of magnetometers to differentiate between the torquer's magnetic field and the Earth's field is questionable.

Gravity gradient and solar pressure control were eliminated because of the complex and unanalyzable nature of their mechanizations. Active inertia/surface area control is difficult for small, Earth-oriented satellites. Considering the size of the ODSRS and the fact that it must be capable of operating in any arbitrary orientation relative to the Sun, these desaturation schemes were considered unacceptable.

Two possible thruster designs were considered. One called for using low thrust, pulsed-plasma electric thrusters. The other concept utilized chemical hydrazine thrusters.

Pulsed-plasma thrusters have been used for many years on Earth orbiters because of the high specific impulse of the fuel (usually solid Teflon, $I_{sp} = 1700$ s) and their mechanical simplicity (no valves, fuel lines, etc.). They provide thrust by pulsing for short periods (~30 µs) at a fixed rate (~1 pulse every 6 s). The electric thrusters would have a slight mass advantage over a hydrazine system. The disadvantages of the electric thrusters involve high peak power consumptions, antenna RFI from the electric arc, possible contamination of antenna surfaces by the expelled Teflon, and the long periods required for momentum dumping.

Hydrazine thrusters are common to Earth orbiters and deep space probes alike. While more mechanically complex than the electric thrusters, chemical thrusters require low power, do not present significant contamination problems, and are capable of higher thrust levels than the electric thruster.

Since the ODSRS must be capable of tracking deep space probes over an extended period of time, the pointing stability of the antenna while desaturating the wheels must be considered. While the low thrust level of the electric thruster would allow for precise pointing during unloading, the high thrust of the hydrazine system would probably perturb the spacecraft in excess of the pointing requirement. A rough analysis of the environmental torques on the spacecraft reveals that hydrazine thrusters with a 0.01 lb average thrust would be required to unload the wheels for about 30 min per week. This was assumed to be an acceptable period for a planned loss of communications with the target spacecraft.

A summary of the tradeoffs between the electrical and chemical thrusters is shown in Table 25. The hydrazine thrusters have been chosen as the baseline design for wheel unloading.

Table 25. Summary of advantages and disadvantages of electrical and chemical stationkeeping and attitude control

Parameter	Electric	Chemical
1. System mass	220 kg	234 kg
2. Power consumption	1550 peak/35 W avg.	Approx. 20 W peak
3. Interaction with spacecraft dynamics	30-s pulses of 5.5 lbf at 6 pps or slower	Steady state (0.2-5 lbf)

Table 25. Summary of advantages and disadvantages of electrical and chemical stationkeeping and attitude control (contd)

Parameter	Electric	Chemical
4. Contamination	Teflon can expand in directions and coat optics or thermal control surfaces	Ammonia absorption all on cryogenic surfaces
5. Interference with reception	Electric arc discharge Emits plasma (1 m max. diam) opaque to RF $\leq 10^{10}$ Hz	Electromagnetically actuated solenoid valves
6. Safety in crash situation	No combustible or liquids	Flammable liquids
7. Reliability	No significant moving parts or contamination	Close tolerance moving parts in valves. Hydrazine is contamination-and temperature-sensitive
8. Component availability	Off shelf	Off shelf
9. Fabrication cost	Wiring and mounting only	Welded lines, thermal blankets and heaters, passivation, etc.
10. Command/control required	On/off only	On/off; temperature control, pressure sensor(s), latch pyro valves
11. Redundancy	22-kg mass penalty for each redundant thruster	Minor mass penalty for redundant thrusters

3. Conceptual Design

a. General Description. The ODSRS will be three-axis stabilized with reaction wheels as the primary attitude control torquers. A hydrazine thruster system, which will also be employed for station keeping, will be used to unload the stored momentum from the wheels. The thrusters will also serve as a backup to the reaction wheels for coarse attitude control of a reduced mission.

The AACS will employ three types of attitude sensors. For initial acquisition of a target and for nontracking periods, gyros, sun sensors, and star trackers will provide the reference signals. In order that the spacecraft be capable of operating in any attitude relative to its celestial references, the sun sensors and star trackers will be mounted on gimballed platforms which will provide 4 steradian coverage. Once the RF signal from a target space probe has been acquired, the AACS will utilize an RF monopulse tracking loop, which gives a direct measurement of the beam pointing error based upon the received signal. The inertial and celestial sensors will serve as a backup to the monopulse system.

The AACS will also provide articulation of gimballed appendages, such as radiators, high-gain antennas, and solar panels (if included). High-resolution encoders and brushless dc motors will provide precise articulation of these components.

b. Operating Modes. There are four basic operating modes associated with the attitude control of the ODSRS: cruise, retarget, acquire and track.

In the cruise mode, the ODSRS is oriented in a desired attitude relative to its celestial references (Sun and selected stars). Using the star trackers and sun sensors, the AACS will maintain three-axis control by employing the reaction wheels to counteract any environmental torques. This mode is not intended for precise pointing of the antenna, but is a standby mode of operation.

The retarget mode is used to reposition the antenna line-of-sight (LOS) toward a new target (either radio source or deep space probe). Based upon ephemeris data and target position predicts, the ground will command the ODSRS to assume a new inertial attitude. The AACS, using its high-resolution gyros, will then command the reaction wheels to turn the spacecraft to its new position. The celestial sensors will be used to update the gyro information and confirm proper spacecraft orientation.

Upon completion of a retargeting maneuver, the AACS enters a vernier pointing mode, wherein the received signal from the target source will be used to complete acquisition. A preprogrammed search about the new pointing direction will be used to locate the target signal. Again the gyros, with updates from the celestial sensors, will provide primary attitude reference.

Having acquired a signal from the target source, the AACS will then enter a track mode. In this mode, a closed-loop RF monopulse system is employed to give direct sensing of the antenna electrical sensing LOS pointing error. The AACS will command the reaction wheels to maintain the pointing accuracy within the required 0.002 deg. This pointing accuracy will not be met during momentum unloading of the wheels, but the time required for unloading (~30 min/week) is assumed to be acceptable.

c. Technology. The components of the AACS represent state-of-the-art technology which is either off-the-shelf or will be available in the near future. None of the technology requires a massive new development effort. A description of the thruster system is included in the section on the Propulsion Subsystem.

1) Reaction Wheels. The baseline design for ODSRS utilizes the AFML reaction wheel under development by Sperry Flight Systems for the Air Force. Performance characteristics for these wheels are given in Table 26.

Table 26. AFML characteristics

Angular momentum	674 to 1350 N-m-s (500 to 1000 ft-lb-s)
Maximum torque	.636 N-m (90 oz.-in.)
Rotational speed (max.)	10,000 rpm
Weight	62 kg (136 lb)
Envelope	69 cm (27 in.) diameter maximum 76 cm (30 in.) height maximum
Power (avg./peak)	17/110 W
Bearings	3 loop magnetic suspension
Run-up time	8.4 h
Operational life	10 years, no single point failure

As these wheels are fully redundant, one wheel per axis will suffice for the ODSRS attitude control. The 10-year operational life is aided by the use of magnetic suspension bearings.

2) Sensors. A three-axis gyro package provides inertial reference, sun and star trackers provide celestial reference, and a monopulse system

provides a target reference. The gyro package will be the DRIRU II, which is a dry, tuned-rotor inertial reference unit under development by Teledyne for JPL. The DRIRU II has three channels which provide fully redundant three-axis inertial information. This package is intended to become a NASA standard.

Celestial reference is provided by combining measurements from sun and star trackers. These sensors will be mounted on separate gimballed platforms in order that they may view their celestial references. The sun sensors will be composed of both coarse and fine sensors, using the NASA standard units.

The coarse sensor is used to acquire the Sun, while the fine sensor provides precision position information about two axes. The STELLAR star tracker, which has the capability to track 10 stars at a time, will provide another two axes of attitude information. This advanced design tracker employs a charge-coupled device (CCD) image sensor for very high resolution tracking.

The monopulse system will be described in more detail in the Antenna Electrical Subsystem section. Basically, the monopulse uses the received signal strength to determine the error in the antenna electrical line-of-sight. This provides a direct measurement of the beam pointing error for the AACS.

3) Actuators. The articulation of sensor platforms, radiation panels, high-gain antennas, and solar arrays (if used) will be provided by brushless dc motor actuators. These actuators will employ direct drive of the gimballed appendages in order to eliminate backlash. High-resolution, optical shaft encoders will be integrally mounted with the actuators to measure their relative position to the spacecraft.

d. Redundancy. The basic philosophy of redundancy employed in the design of the AACS was to not allow any single point failures to prevent satisfactory completion of the ODSRS mission. The reaction wheels are designed with full redundancy in each unit (dual motors, drives, magnetic suspension coils, etc.). Therefore, the baseline design employs one wheel assembly per axis. The DRIRU II also contains built-in redundancy. With three channels providing two-axis information, there are redundant measurements for each axis. One DRIRU II package will be employed.

Redundant units will be used to prevent celestial sensor single point failure. There will be dual coarse sun sensors, dual fine sun sensors, and dual STELLAR star trackers. The platform actuators for the sensors will also be redundant in the motors, drive circuits, and encoders.

e. Physical Characteristics. Table 27 summarizes the mass, size, and power requirements for the AACS components. These estimates include the redundancy outlined in the previous section.

Table 27. AACS physical characteristics

Component	Size	Mass, kg	Power, W	
			Avg	Peak
Reaction wheels (3)	27 in. dia x 30 in. height	204	45	300
DRIRU II	12.5 x 10 x 10 in.	16	22	22
STELLAR star tracker	7 in. dia x 12 in.	12	18	18
Coarse sun sensor (2)	5 x 5 x 2 in.	3	0	0
Fine sun sensor (2)	TBD	9	5	10
Actuators	TBD	50	10	50
	Total[a]	288	100	400

[a]Estimates for hydrazine thrusters are not included. They are discussed in the Propulsion Subsystem Section.

H. Power Subsystem

1. Requirements

a. Functional. The Power Subsystem (PWR) shall perform the following functions:

(1) Provide sufficient power for satisfactory operation of all ODSRS electrical equipment.

(2) Provide required power switching and control functions.

b. Performance. The power subsystem must provide 5.5 kW of continuous power for a period of 10 years in a geosynchronous orbit. This includes a sun occultation period which may range from 0 to 1.2 h in a 24-h orbit and occurs about 90 orbits per year. The power subsystem must provide a main electrical bus voltage of 28 ±7 Vdc.

c. Interface. Power bus interfaces exist between all using ODSRS subsystems and the power subsystem. Also, there is a control and feedback interface between the computer and control subsystem and the power subsystem.

There is an interface between the shuttle and the power subsystem. With the selection of the isotopic dynamic system as the primary power source for the 28-m ODSRS, cooling of the isotope heat source/system may be required in the shuttle. In addition, if this system is inoperative within the shuttle until deployed after assembly in orbit, the shuttle must provide power to the ODSRS for assembly and initial test.

2. Implementation Options

Several candidate power sources have been reviewed for applicability to the 28-m ODSRS. Radioisotope thermoelectric generators (RTG), articulating solar arrays and batteries, and isotopic-fueled dynamic power conversion systems were the candidate systems considered.

The use of RTGs would require 11 500-We units. Each unit would have an envelope dimension of 114 by 122 cm. The total mass of RTGs required is about 910 kg, which is about twice that of competing systems. In addition, cooling of the eleven RTGs within the shuttle would become a significant problem. There is one advantage of RTGs over solar panels. Batteries would not be required for providing energy during sun occultation periods.

Articulating (3-degree-of-freedom) solar cell arrays and rechargeable batteries sized for 10 years of operation have also been reviewed. Significant shadowing of the 85-m^2 array, due to the size of the 28-m-diameter antenna, would require heavy usage of the battery system. The amount of this shadowing would be dependent on the actual missions that the ODSRS would track, and is difficult to evaluate at this time. Without the shadowing penalty, battery capacity required for sun occultation usage would be about 500 AH at 50% depth of discharge. Battery mass has been estimated to be about 300 kg. Both the advanced nickel cadmium rechargeable batteries (44 Wh/kg) and rechargeable nickel hydrogen batteries (50 Wh/kg) were reviewed as the secondary power source. The advanced nickel cadmium type was selected because of volume, which is about 3 times less than the nickel hydrogen type. The small mass difference was not considered to be a significant disadvantage.

Isotopic-fueled dynamic power conversion systems such as the Brayton (BIPS) and the organic Rankine cycle (KIPS) have also been reviewed. Because of severe shadowing of the candidate solar arrays by the 28-m ODSRS, isotopic-fueled dynamic power conversion systems were an attractive candidate, although significant technology development was required. The advantage of isotopic dynamic power conversion is that is does not require the use of rechargeable secondary batteries for sun occultation operation. In addition, attitude control requirements for optimum solar array usage are relaxed. Although the mass of the basic KIPS is only about 13 kg less than the solar array/battery system, the mass of additional batteries to supplement solar array power output and additional solar array area (for battery charging) to provide for the shadowing problem would significantly increase this difference. Further development of the BIPS has been cancelled by DOE because of major technology problems. KIPS is the only isotopic dynamic power conversion system presently planned for further development.

3. Conceptual Design

A candidate power system that can provide power without problems of antenna shadowing, special sun occultation requirements, low Earth orbit checkout etc., is an isotopic-fueled dynamic power conversion system. This system, known as "KIPS" (Kilowatt Isotope Power System) is presently being funded by DOE for availability in the 1982 time period, and has been selected for the 28-m ODSRS. KIPS can be developed to provide power output of 5.5 kW for 10 years and can provide either direct or alternating current at several different voltage levels. KIPS produces electric power by use of a Sundstrand organic Rankine cycle power conversion system with a new design plutonium oxide heat source (GPHSA) which results in a power supply exhibiting high efficiency at low peak temperature (Refs. 25-27). Low peak temperature permits use of conventional materials for construction and results in a system with higher reliability.

A simplified block diagram of the KIPS electrical power system is shown in Fig. 31. The alternator electrical output of 110 Vac may be rectified to dc for the ODSRS. The voltage regulator controls the alternator field and output to provide a voltage of 28 Vdc ±2%. Constant speed control is provided by an electronic speed control system which senses alternator frequency and applies electrical load to a dissipative load bank to maintain constant turboalternator speed at various user load demands.

KIPS dimensions are 61 cm in diameter by 112 cm long. A summary of the KIPS characteristics is shown in Table 28. The overall efficiency is 20.4% at 28 Vdc ±2%. The efficiency can be increased to about 22% by using the basic 100-Vac output and thereby eliminating the transformer rectifier function. The mass of the 5.5-kWe configuration which includes the plutonium 238 isotopic fuel but not the radiator is 422 kg. The radiator area required for the KIPS is about 21 m^2 and is estimated to weigh approximately 82 kg. Present KIPS design uses a cylindrical radiator configuration. The disadvantage of this radiator is the lack of space within the shuttle launch vehicle. A panel-type radiator that could be "folded" up similar to solar panels could be developed and used.

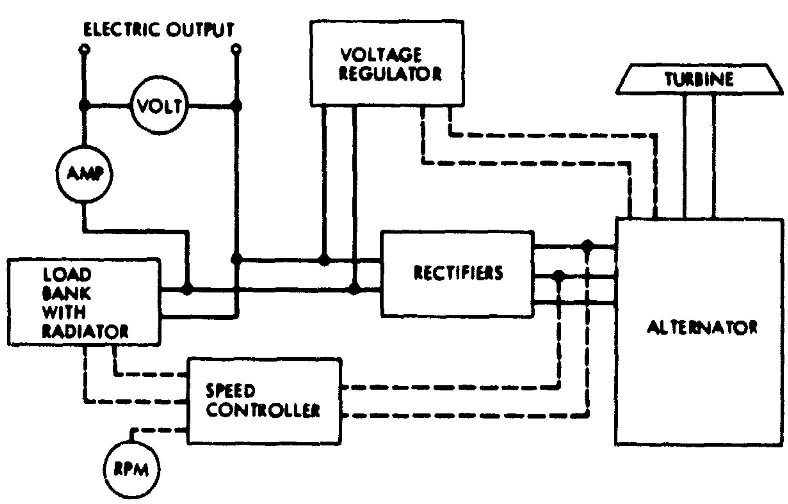


Figure 31. Simplified block diagram of KIPS electrical power system

A block diagram of the ODSRS power subsystem is shown in Fig. 32. Power from the KIPS is delivered to the using subsystems via the power control and distribution unit, where power can be commanded on or off. The PC&D unit contains telemetry transducers, load relay modules, load disconnects, redundant coded command, etc. The estimated mass is 5.0 kg.

The dc-dc converter is provided for converting the bus voltage of 28 Vdc to other voltages that may be required. The efficiency is assumed to be about 80%. The dc-dc converter is block-redundant and consists of dual and quad relays. Transformers, regulators, and miscellaneous components are included. The estimated mass is 4 kg. The total mass of the complete 5.5-kW system less radiator and redundancy is 431 kg.

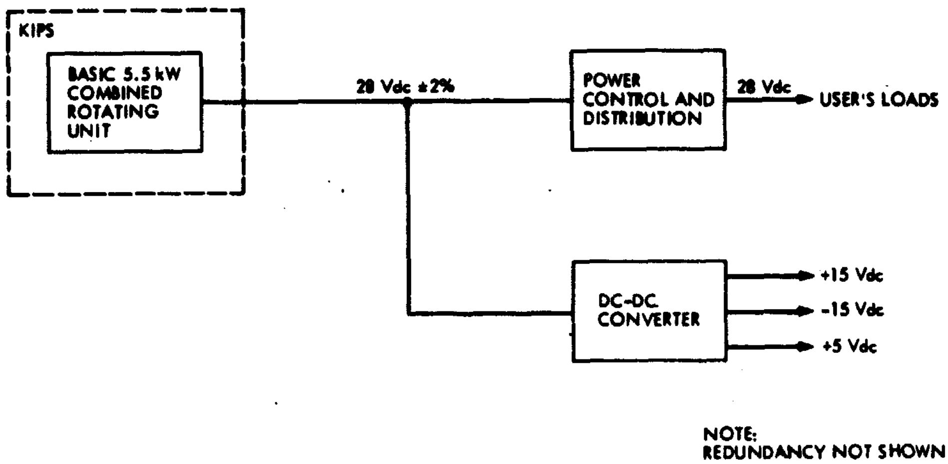


Figure 32. ODSRS power system basic block diagram

Table 28. ODSRS Power Subsystem Specification Sheet

KIPS (Isotope Dynamic Power System)		Remarks
Total power req'd (EOM)	5.5 kwe	End of mission
Total mass (less radiator)	431 kg	Including fuel
	579 kg	Including redundant elements
Specific power density	13.0 W/kg	
Radiator area req'd	21 m^2	
System efficiency (28 Vdc)	20.4%	

Table 28. ODSRS Power Subsystem Specification Sheet (contd)

KIPS (Isotope Dynamic Power System)		Remarks
System efficiency (110 Vdc)	22.0%	
Isotope thermal fuel required	24.5. kw_t	(Plutonium 238)
Turbine inlet temperature	700°F	
Turbine inlet pressure	87 psia	
Rotational speed	27.8 1 rpm	
Turbine flow rate	275 lb/hr	

For the 10-year ODSRS mission lifetime, a reliability of 0.95 has been determined by the developer (Sundstrand) for the basic isotope dynamic power conversion system, with an additional combined rotating unit (CRU) operating in standby. The additional CRU has a mass of 68 kg. An improvement in reliability to 0.957 can be obtained by adding on one power conversion unit (PCU) operating in parallel. The mass increase for the additional PCU would be about 89 kg. The overall 5.5-kW system mass with a reliability of 0.957 would be 579 kg.

I. Computer and Control Subsystem

1. Requirements

The following requirements are placed on the Computer and Control Subsystem:

(1) Receive real-time command data from the STS, decode the command and route an execute message to the appropriate subsystem.

(2) Receive non-real-time (stored) command data from the STS, decode the command and route the data to the appropriate storage registers.

(3) Provide onboard operations control of the ODSRS utilizing previously stored command sequences. Provide the basic ODSRS timing for clocking these stored sequences. Route execute and magnitude messages to appropriate subsystems as the stored sequence requires.

(4) The CCS will interact with the AACS for articulation and pointing commands. The detail of subsystem responsibilities for these functions between AACS and CCS has not been defined.

(5) The ODSRS stationkeeping data handling (SDH) subsystem may be combined with the CCS.

(6) No onboard data storage will be required.

The CCS interfaces with all subsystems on the ODSRS for control functions. This requires a control command from the CCS to the subsystem and a verification response from the subsystem to the CCS. Since the CCS will have return lines from all subsystems, it has been suggested that the telemetry data handling function could be efficiently combined with the CCS.

The CCS will have additional interfaces with the STS to receive command data from ground controllers. It will also have an interface with the AACS articulation and pointing function.

2. Implementation Options

The NASA Standard CCS (STACC) has more than ample capability to handle ODSRS computing and control requirements. For example, ODSRS operations appear to be much less complex than a spacecraft and all its science instruments. The only question regarding use of the standard CCS is in design for 10-year lifetime. It would likely require two or three units, with appropriate modifications to detect anomalous behavior and select a new operating unit.

The current explosion in LSI, high density memory, and other technologies suggests that within a few years a CCS can be built that would be smaller, consume less power, be more reliable, and possibly be cheaper than existing designs.

3. Conceptual Design

The conceptual design of a CCS to provide ODSRS requirements has been done only to the depth necessary to determine they will not be difficult to meet. For this study, existing technology has been assumed to be adequate, and mass, power, and cost estimates are based on this assumption. This is considered a conservative assumption in view of likely future technology developments.

The conceptual ODSRS CCS will have a mass of 11 kg (25 lb), consume 20 W of power steady state, and have a volume of 0.03 m^3 (1 ft^3).

J. Orbital Transfer Vehicle

1. Requirements

The Orbital Transfer Vehicle (OTV) shall be capable of transfering the ODSRS from the nominal (maximum payload capacity) shuttle orbit of 370-km altitude and 28.5-deg inclination to a geostationary orbit of 36,000-km altitude and zero-degree inclination.

a. ΔV Requirements. In order to accomplish the orbit transfer the OTV shall be capable of imparting a velocity change of at least 4297 m/s to the ODSRS. Allowance shall be made for loss of cryogenic propellants due to boiloff prior to and during the orbit transfer maneuver. This ΔV requirement is based upon a five-burn transfer maneuver with an initial acceleration of 0.07 g. The ΔV requirement shall be adjusted to accommodate the actual burn strategy and acceleration levels chosen for the orbit transfer.

b. Maximum Acceleration. The OTV shall not impart an acceleration greater than 0.2 g to the ODSRS.

c. Duration of Orbit Transfer Maneuver. The ODSRS shall be delivered to geostationary orbit within 48 hours after the first engine firing.

d. Mechanical and Electrical Interface. The OTV shall provide mechanisms such that it may be mated to the assembled ODSRS in orbit without requiring EVA.

e. Dynamic Loads. The OTV shall be capable of withstanding all dynamic loads that may be encountered in the shuttle bay, including "crash" conditions.

f. Payload Capability. The OTV shall be capable of delivering a mass of 8448 kg to geostationary orbit, exclusive of the final stage mass and the mass of any interface components.

g. Launch Vehicle Requirements. The OTV, complete with all support cradles, propellants, and equipment necessary for integration to the ODSRS, shall be accommodated in one shuttle flight. Shuttle launch capability shall be assumed to remain near 29,400 kg per flight through the 1985 time frame.

h. On-Orbit Storage Time. The OTV shall be capable of storage in low Earth orbit for at least five days to allow time for integration and checkout of the OTV and ODSRS.

2. Implementation Options

Owing to the extremely high cost of developing an individual OTV to meet ODSRS requirements, the OTV design will be shaped by the OTV stages that will be in operation in the 1985 time frame. Slight modification of these existing stages or addition of smaller upper stages is the only viable option for ODSRS orbit transfer. It is quite possible that some ODSRS requirements (e.g., an equatorial orbit) will have to be compromised to keep OTV expenditures within reason.

Although no development efforts have begun on an OTV with capabilities approaching ODSRS requirements, numerous other projects now in the study phase have similar requirements. It appears likely that an OTV will be developed for operation in the 1985 to 1990 time frame that will be designed to occupy a dedicated shuttle flight.

It was assumed for this study that a single-stage cryogenic OTV will be available for use by ODSRS with a usable propellant load of 21,000 kg of liquid hydrogen and liquid oxygen. The initial mass of this stage was assumed to be 24,700 kg. This allows 4700 kg for support cradles, tools for integration of the OTV, etc. The specific impulse was assumed to be 4365 N-s/kg.

Such an OTV would be able to impart a ΔV of 4380 m/s to the ODSRS. This ΔV is sufficient to meet ODSRS requirements. Excess tank capacity may be sufficient to allow compensation for propellant boiloff during on-orbit storage and integration, depending upon the thermal characteristics of the propellant tanks. If boiloff is found to be a severe problem, or if the OTVs available in the 1980s are not capable of meeting the ODSRS requirements, it may be feasible to develop a smaller Earth- or space-storable upper stage for use with the existing OTV.

A detailed study of the optimal orbit transfer propulsion scheme must be postponed until NASA initiates development of the basic OTV required. Development of a mission-oriented OTV would be prohibitively expensive.

3. Conceptual Design

In the absence of detailed information on OTVs that will become available in the 1985 time frame, it was assumed that an OTV such as that described above will be developed for general use. The OTV configuration for ODSRS would then consist of one cryogenic propulsion stage and an adapter assembly to provide electrical and mechanical interface between the stage and the ODSRS.

The adapter assembly will be the only OTV hardware developed solely for ODSRS. It must provide for on-orbit integration of the stage to the ODSRS with minimum EVA activities. Mechanical complexity of this component will be similar to that of docking modules developed in the past. It is possible that the OTV development will include a standardized interface for on-orbit assembly, which would minimize the development of ODSRS-specific hardware. The OTV and its interface adapter will be delivered to the assembled and tested ODSRS by a dedicated shuttle flight. Integration and checkout of the OTV must be performed as rapidly as possible to minimize boiloff of the cryogenic propellants.

The orbital transfer will be acccomplished by several (e.g., five) burns. Multiple burns are required to minimize gravitational losses during the orbit transfer. The ΔV requirement assumes that the inclination change will be distributed over all engine firings, so that the OTV will have to be continuously steered during firings. This will require the OTV to possess a very sophisticated control and guidance system. The minimum initial acceleration of 0.07 g required to keep the ΔV requirements within the capability of an OTV that may be carried in one shuttle launch implies that initial engine thrust must be at least 22,800 N (5130 lb_f), while the maximum acceleration of 0.2 g implies that the thrust at burnout must be less than 23,800 N (5350 lb_f).

It is highly unlikely that an OTV will be developed with nominal operating characteristics exactly corresponding to the requirements of the ODSRS project. Minor modifications, such as operating the engine slightly off of its nominal thrust or addition of a very small upper stage may be performed with reasonable cost penalties. However, major modifications, such as development of a new engine or an entirely new OTV could make development of an ODSRS unfeasible.

K. Stationkeeping Propulsion Subsystem

1. Requirements

a. Functional

1) Attitude Control Rotational Impulse. The Stationkeeping Propulsion System (SPS) on board the ODSRS must be capable of providing a total rotational momentum change of 730,000 N-m-s about each of three axes to provide for reaction wheel desaturation.

2) Attitude Control Torque. The attitude control thrusters must be fired at a duty cycle such that the average control moment during reaction wheel unloading is approximately 0.6 N-m. This is the maximum torque capability of the reaction wheels.

3) Stationkeeping Propulsion ΔV. The onboard propulsion systems must be capable of imparting a total ΔV of 60 m/s to the ODSRS to provide stationkeeping capability.

4) Operational Life. The stationkeeping and attitude control propulsion system must be capable of reliable operation over a 10-year period.

b. Interface

1) Attitude Control. Chemical thrusters for the ODSRS will be jointly shared by the attitude control and stationkeeping propulsion subsystems. Definition of specific control responsibility between these subsystems has not been determined.

2) CCS. The CCS will provide control functions to the SPS.

3) SDH. The SPS will provide operational telemetry data to the SDH.

4) PWR. The SPS will receive 28 Vdc from PWR.

2. Implementation Options

The options considered were electric pulsed plasma thrusters and a hydrazine monopropellant system. Both of these systems have been shown to be highly reliable utilizing existing technology. However, possible RFI problems and inherent low thrust rendered the pulsed plasma system impractical. The baseline system selected was monopropellant hydrazine.

3. Conceptual Design

Propulsion system sizing was based upon the assumption that 20-m moment arms are available in both pitch and yaw axes, while a 10-m moment arm is used for roll. The roll thrusters are to be mounted on 10-m booms and fired in couples, whereas the pitch and yaw thrusters are mounted on the spacecraft bus 20 m from the center of gravity. The total impulse required for attitude control under these assumptions is 146,000 N-s. The specific impulse of the thrusters was assumed to be 1750 N-s/kg at the duty cycle selected for reaction wheel unloading. The hydrazine required for attitude control is approximately 85 kg.

The propellant requirement for stationkeeping was determined from the initial spacecraft mass of 8448 kg, ΔV requirement of 60 m/s, and an assumed steady-state specific impulse of 2150 N-s/kg to be approximately 235 kg. The total propellant load is therefore 320 kg. The total propulsion system mass was scaled from Voyager to yield an estimated propulsion mass of 470 kg.

The maximum torque capability of the reaction wheels of 0.6 N-m implies that the pitch and yaw thrusters must deliver average thrusts no greater than 0.03 N. Since the smallest readily available thrusters have a thrust of 0.9 N, this implies that a duty cycle (electrical pulse length divided by the time between initiation of pulses) of approximately 0.033 must be used for the pitch and yaw thrusters. The roll thrusters, due to their lower moment arm, may be fired at a duty cycle of approximately 0.067. The minimum pulse length for which a specific impulse of 1750 N-s/kg can be maintained is approximately 100 ms. Therefore, the pitch and yaw thruster firing rate will be approximately one pulse every 3 s and the roll thrusters will fire one every 1.5 s during momentum dump. With this duty cycle each of the thrusters would be required to fire on the order of 500,000 times over the 10-year mission, which is achievable with present-day technology.

The stationkeeping propulsion can be accomplished by two thrusters in the 5 N thrust range. The total firing time over the 10-year mission will be approximately 14 hours. If stationkeeping maneuvers are performed once a day, steady-state firings of approximately 14 s will be required and less than 4000 firings will be required over the 10-year mission.

The system schematic will be based upon the requirement that no single point failure (with the exception of propellant tank and plumbing) should prove mission-catastrophic. Four thrusters (two primary, and two redundant) will be used for yaw axis reaction wheel unloading. Four primary and four redundant roll thrusters must be provided, as these thrusters are used in a couple. Pitch control may be provided by roll thrusters if necessary, so that only two primary pitch thrusters are needed. Two primary and two redundant stationkeeping thrusters will be provided. Four primary and four redundant roll thrusters must be provided, as these thrusters are used in a couple. Pitch control may be provided by roll thrusters if necessary, so that only two primary pitch thrusters are needed. Two primary and two redundant stationkeeping thrusters will be provided.

Of the total thruster complement of 18 thrusters, a maximum of six could be fired at one time (for simultaneous unloading of all axes and stationkeeping). Each thruster valve will draw 4.7 W, so that 28.2 W would be required to operate the thrusters. It is assumed that all latch valves are actuated prior to firings. A maximum of three propellant supply pressure transducers may simultaneously require 0.25 W each. If chamber pressure transducers are included on all primary thrusters, an additional 10 pressure transducers will bring the total transducer power requirement to 3.25 W. Assuming catalyst bed heaters are energized on each of the 10 primary thrusters, an additional 20 W would be required. The total peak power requirement is, therefore, 51.5 W. Power required to maintain propellant line and tank temperatures must be included in the spacecraft thermal control system power requirements.

The propellant supply is from a single tank with a 2:1 blowdown ratio. The tank diameter will be approximately 98.5 cm. The tank will require thermal control blankets and heaters to prevent propellant freezing.

L. Stationkeeping Data Handling Subsystem

1. Requirements

The Stationkeeping Data Handling Subsystem (SDH) is required to receive telemetry data from all ODSRS subsystems, encode and format the data as directed by the CCS, and modulate the data onto a telemetry subcarrier for transmission to Earth by the STS.

2. Interfaces

The SDH has interfaces to all ODSRS subsystems for operational telemetry data. It also has an interface to the CCS for control of SDH operations and to the PWR for 28 Vdc power.

3. Conceptual Design

For the ODSRS conceptual design, the SDH function is assumed to be handled by the CCS. Weight, power, and cost estimates have been made on this basis.

IV. ODSRS GROUND STATION DESIGN

A. Requirements

The ODSRS requires support from ground stations for the following functions:

(1) <u>Relay Telemetry</u>. Receive the K_u-band signal from the ODSRS and demodulate spacecraft telemetry data from this signal.

(2) <u>Relay Radiometrics</u>. Receive the K_u-band signal from the ODSRS and extract the spacecraft doppler data contained in this signal. Demodulate spacecraft ranging data from this signal.

(3) <u>Stationkeeping Telemetry</u>. Receive the S-band telemetry carrier from the ODSRS and demodulate the ODSRS engineering data from it.

(4) <u>Stationkeeping Command</u>. Receive stationkeeping command data from the ODSRS control facility and modulate the S-band carrier with it and transmit it to the ODSRS.

(5) <u>Stationkeeping Ranging</u>. Modulate a ranging subcarrier onto the S-band carrier for transmission to the ODSRS. Receive the S- and X-band[2] signals from the ODSRS, demodulate turnaround ranging data from them.

(6) <u>Data Processing</u>. ODSRS ground stations are assumed to do only modulation and demodulation of telemetry, command, and radiometric data streams. This will minimize station implementation and operations cost. All other data processing is assumed to take place at a central location such as the SFOF in Pasadena.

B. Conceptual Design

Figure 33 shows a functional diagram of the ODSRS ground station network configuration. This configuration supports the ODSRS requirements as follows.

1. Relay Telemetry and Ranging Receiving Station (RTRR)

The RTRR station is assumed to be colocated with the Space Flight Operations Facility (SFOF) in Pasadena. It shares a 5-meter antenna with the ODSRS stationkeeping command, telemetry, and ranging station. This antenna will have feeds for simultaneously receiving at S-, X-, and K_u-bands. The K_u-band receiver for the relay link will be a noncryogenic paramp.

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[2]The stationkeeping ranging system is assumed to be implemented by an S- and X-band system. Final design of the 10-cm ranging system may use higher frequencies.

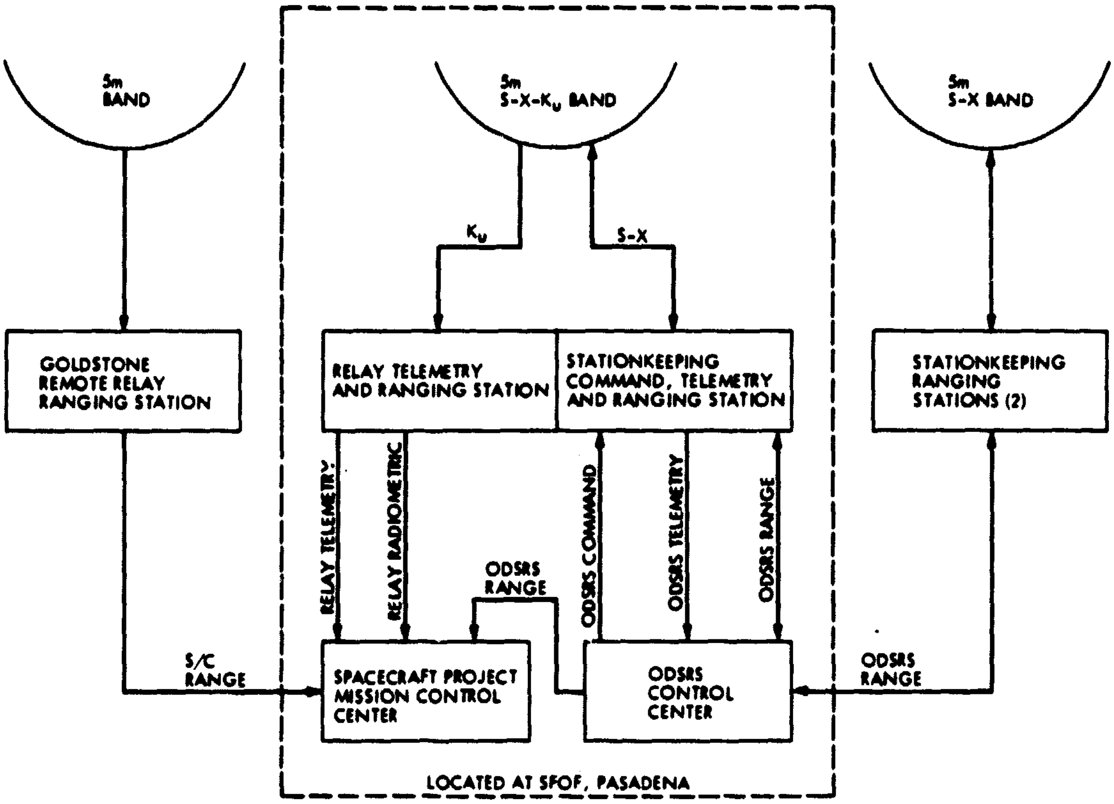

Figure 33. ODSRS ground station network

a. Relay Telemetry. Relay telemetry data will be demodulated from the K_u-band carrier and sent directly to the Mission Control Center for the project whose spacecraft is being tracked.

b. Ranging Information. The K_u-band carrier and ranging modulation on this carrier contain the radiometric data from the spacecraft being tracked. The relay telemetry and ranging receiving station will extract the doppler information and demodulate the ranging code from the carrier. This data will be sent directly to the mission control center for the project whose spacecraft is being tracked.

2. Stationkeeping Command, Telemetry, and Ranging Station (SCTR)

The ODSRS stationkeeping operations will be conducted from a control center located in the SFOF. The SCTR station will be colocated with the SFOF and will share a 5-meter antenna with the RTRR. It will have a 100-W transmitter at S-band and an uncooled paramp receiver at S- and X-band.

a. Stationkeeping Telemetry. Stationkeeping telemetry data will be demodulated from the S-band carrier and sent directly to the ODSRS control center for processing. This will be a 1200-bps telemetry stream.

b. Stationkeeping Command. Stationkeeping command data will be generated in the ODSRS control center and modulated onto a subcarrier with clock and sync data to form a composite command subcarrier. This subcarrier will be sent to the SCTR station and modulated onto the S-band transmitted carrier.

c. Stationkeeping Ranging. Station ranging data will be generated in the ODSRS control center and used to create a composite ranging subcarrier. This subcarrier will be sent to the SCTR station and modulated onto the S-band transmitted carrier. The turnaround ranging signal from the ODSRS will be demodulated from the S- and X-band carriers at the SCTR station and returned to the ODSRS control center for processing. The processed ranging data will be used by the ODSRS operations team to plan stationkeeping propulsion maneuvers and will be sent to the Mission Control Center for the project whose spacecraft is being tracked to use for navigation and radio science.

3. Stationkeeping Ranging Stations

To obtain the ODSRS orbit position accuracy required it will be necessary to range to the ODSRS from three widely spaced stations and combine the data for a 3-axis range solution. One station will be the SCTR station at the SFOF. The other two will be simplified stations with ranging hardware only and will be located at extremes of territorial United States boundaries. These stations will have 5-meter antennas with transmit capability at S-band and receive capability at S- and X-band. They will be designed for totally remote operation.

Stationkeeping ranging operations from these stations will be exactly the same as from the SCTR station. A possible exception is that the ranging subcarrier may be generated at the stationkeeping ranging station to avoid the problems of sending a precise wideband ranging subcarrier from the SFOF to the ends of the territorial U.S. and back.

4. Remote Relay Ranging Receiving Station

It is desirable to have the capability to receive the K_u-band relay carrier from the ODSRS and demodulate the ranging subcarriers at a DSIF station. This is for support of flight projects with long round trip light times where the station may set prior to the return of the 2-way ranging signal. In this case, the ODSRS could point one of its relay link antennas at the DSIF station and relay the carrier and ranging data even though the station could not see the spacecraft. For this function, we have assumed a 5-m k_u-band antenna with an uncooled paramp receiver that is colocated with station 14 at Goldstone.

C. Technology

1. Station Implementation

ODSRS ground stations will be designed for minimum maintenance, with a design goal of a "once a year" maintenance cycle. This is not expected to be a major driver on ground station technology. No significant developments are expected to be required for ODSRS ground station implementation.

2. Ranging Accuracy

The ODSRS navigatic requirement to determine its position to 10 cm in three axes cannot be met with current ranging systems or planned capabilities through 1985. This is a significant technology development that will be needed to make the total ODSRS concept viable.

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