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Orbiting Deep Space Relay Station Study Final Report

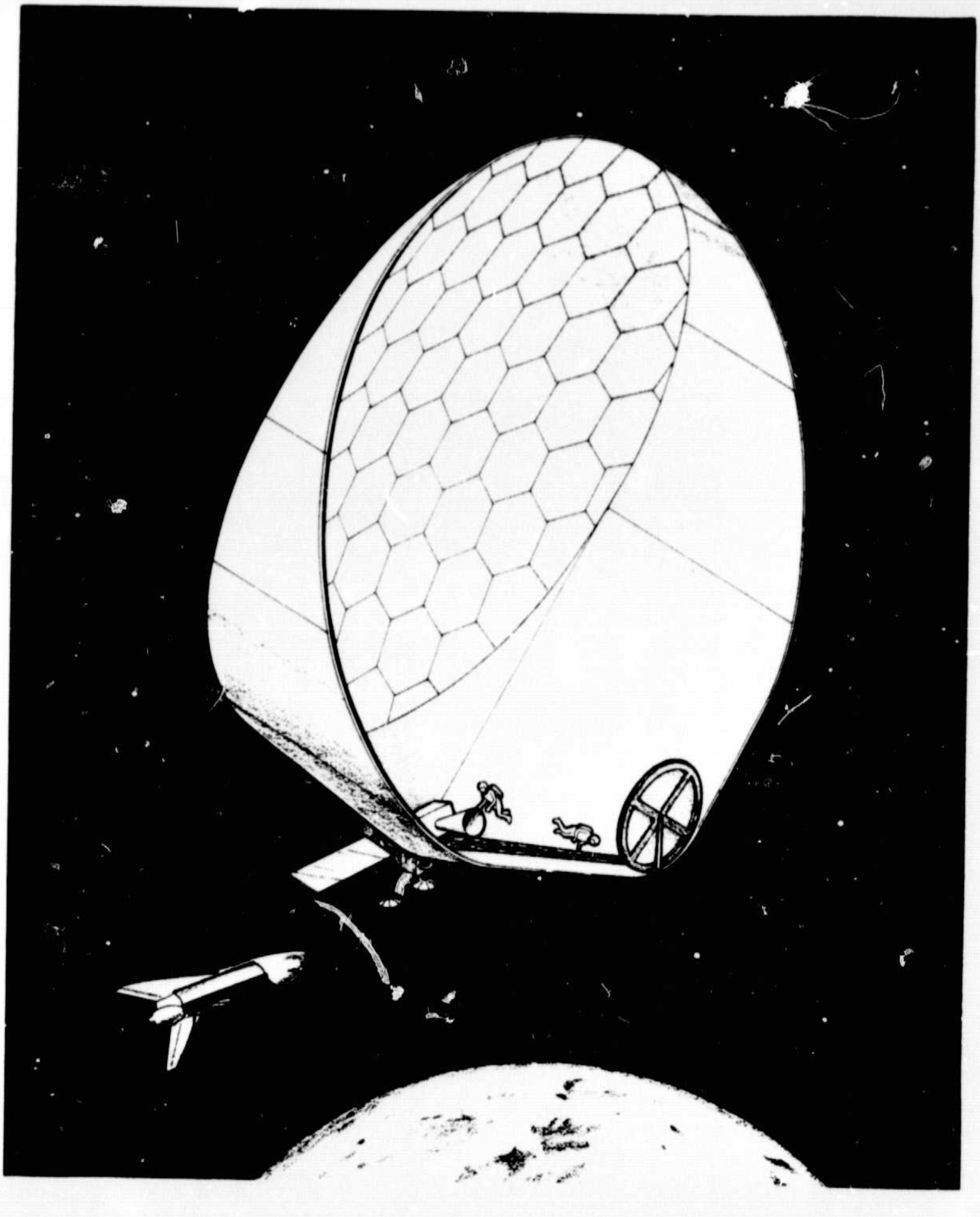
Volume III. Implementation Plan

John A. Hunter

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 to economically boost large payloads into orbit, it becomes practical to seriously consider such an orbiting station. The technical feasibility of an orbiting Deep Space Relay Station (ODSRS) was demonstrated in a 1977 study sponsored by NASA OSTDS. The present study (1978) had broader objectives, including an evaluation of the deep space communications requirements in the post-1985 time frame, a conceptual design of an ODSRS system, and an implementation plan with schedule and cost estimates and new technology requirements. 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.

Acknowledgement

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. Swedling, J. Wright, M. Koerner, G. Ragsdale, M. Katow, H. Price, C. Guernsey, A. Galbraith, B. Sharpe, and H. Partida. 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.

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Abstract

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

I. ODSRS Implementation

This volume defines the programmatic activity that would be required from the time the decision was made to implement an Orbiting Deep Space Relay Station (ODSRS) until it became an operational part of the Deep Space Network (DSN). Included is a discussion of the conditions that would exist before the ODSRS became an attractive candidate to meet future tracking and communications requirements; a cost and schedule plan; a description of the required interfaces between the ODSRS, the DSN, and the Mission Operations System (MOS), and an assessment of the new technology developments required to enable this ODSRS design.

A. Conditions for Considering an ODSRS

The ODSRS, as a means of achieving tracking and communications functions that can be performed by existing ground stations, is not currently a cost competitive option.

There is, however, the possibility of changes in existing conditions that would make the ODSRS an attractive option or even the only means of meeting a future space mission requirement. Some of the potential future developments that would argue for a reevaluation of the ODSRS are the following:

1. **Loss of ground stations in Australia, Spain, or both.** The United States deep space exploration program requires occasional 24 hour per day tracking of most of its missions for periods ranging from a day or so to many months. This is usually during planned high activity periods, such as orbit insertion and operations or during spacecraft emergencies. If one of the overseas sites were lost, the capability for 24 hour a day tracking would cease to exist. One possibility is to design missions such that 24 hour a day tracking would never be required. This would imply a highly autonomous spacecraft, with high activity operations requiring real time telemetry to be precisely planned and timed to occur over Goldstone. This seems like a severe constraint, especially to telemetry, since the timing of valuable science data near a target planet can likely not be predicted with certainty. On-board recording could handle part of this problem, but the uncertainty in timing of critical data would mean that a large quantity of non-critical data would also have to be recorded. This could drive data storage capacity beyond reasonable limits. Some missions may require real time or stored telemetry data transmission periods that exceed the length of a Goldstone pass. The ODSRS could solve this problem, since it would provide 24 hour a day tracking of the target spacecraft for critical operations.

The ODSRS would not provide 24 hour command capability for emergencies if one of the overseas sites was lost, since there is no ODSRS-to-S/C transmitter. It would allow 24 hour telemetry coverage for failure analyses, but would require commanding to occur over an existing ground station.

Another problem that would exist if one or more of the overseas sites were lost is the inability to acquire 2- or 3-way navigation data from a spacecraft whose round trip light time was more than the length of a Goldstone Station pass. With the ODSRS, the ground station at Goldstone could transmit to the S/C, and the ODSRS could relay the returned signal from the S/C to the Goldstone ground station after the ground station had lost direct visibility of the S/C.

2. **Loss of S- or X-band deep space communications frequencies.** The S- and X-Band portion of the spectrum is becoming more crowded, and there is increasing competition for frequency allocations. It is possible that future events could cause the loss of S- or X-Band for deep space communications use. This could occur due to new international agreements, or due to violation of existing agreements by non-complying nations. A contingency plan should exist for this possibility. The ODSRS provides the capability for the use of higher frequencies that would be subject to degradation by weather and the Earth's atmosphere and would thus be unacceptable for ground station use.

3. **Precision navigation of a S/C probing into or passing behind the sun.** As detailed analyses of solar probes and other solar missions proceed, it is possible that the effects of solar plasma on S- and X-Band radiometric data cannot be adequately removed to provide the required navigation precision. The use of higher frequencies that are less susceptible to solar perturbations is a potential solution. Again the higher frequency capability of the ODSRS would enable this solution.

4. **Significant increases in yearly operations costs of ground stations.** The major factor driving the life cycle cost of the ODSRS is its high implementation cost. Its yearly operations cost is expected to be significantly less than for an existing ground station. If ground station operations costs increase dramatically, the ODSRS may become a viable option. Note that at least one ground station would have to be maintained, probably at Goldstone, to have command and two-way navigation capability.

5. **Significant decrease in ODSRS implementation cost.** New technology developments may significantly reduce the cost of building and launching an ODSRS.

6. **Dramatic increase in the value of ODSRS peculiar radiometric data.** Future developments may place a premium on a type of radiometric data that is enabled or enhanced by an ODSRS, and cannot be obtained by using a ground based station. Some examples of radiometric data that may be enhanced by an ODSRS are:

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

b. Two-Station differenced doppler data. For some missions, such as VOIR, 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 longer 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.

c. Gravity wave detection. 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.

d. 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 could improve the quality of these experiments.

e. Far-field calibrations. Radio science requirements place extremely tight requirements on the entire communication system. 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.

f. 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.

g. Relativity experiments with S/C behind sun. The use of 32 GHz should significantly improve this experiment by minimizing the effect of the solar corona on the data.

h. Multilateration. Synchronized range and range rate data from several receiving stations can be used to estimate spacecraft position accurately. This technique is enhanced by long baselines, such as the ODSRS would provide.

B. ODSRS Schedule and Cost Plan

A major goal of the ODSRS study was to develop a cost estimate for the implementation and operation of an ODSRS so that it could be compared to other system options. A schedule was needed to develop the cost plan and to define the events and lead times necessary if a future decision was made to implement an ODSRS. This section describes the approach and assumptions used in developing the schedule and cost plans, presents the results along with an estimate of their uncertainty, and discusses the sensitivity of the total Project cost to a major error or change in one of its elements.

1. **Study approach.** The approach used in developing the ODSRS schedule and cost plans was to break the project down into clearly defineable systems, evaluate the schedule and cost for each system, then combine the results. This enabled the results to be presented in such a way that a future change in a significant assumption could be evaluated for its effect on the cost of the affected system, and this change could then be evaluated for its effect on the total ODSRS Project cost..Seven major systems are defined as follows:

(1) ODSRS-peculiar new technology developments.

(2) ODSRS subsystem hardware and software design, fabrication, and pre-launch test, and operations.

(3) ODSRS program management, mission design, system design, and pre-launch integration, test and operations,

(4) ODSRS ground support stations design, fabrication, test and integration,

(5) Shuttle and shuttle related orbital operations,

(6) Post-launch ODSRS ground operations to support orbital assembly, alignment, test and integration,

(7) ODSRS control center and ground station operations and maintenance.

Schedule and cost estimates were made for each of these seven systems as follows:

(1) When schedule and cost data was available, estimates for each subsystem element of the system were obtained from the subsystem engineers, and these were combined into a total system estimate

(2) When cost data was not available, estimates were made for each element of the system based on the judgment of the team members. The source and uncertainty of the data used to develop each estimate is defined in Section 3, Results;

(3) JPL cost model estimates were made for the elements of the ODSRS for which they were applicable. These were compared to the subsystem based estimates for validation. In some cases, the cost model output was used as the cost data baseline.

(4) These raw cost estimates were all made in FY 78 dollars. They can be inflated as required for a given launch date.

2. **Assumptions.** The following assumptions were made for developing the ODSRS Project cost and schedule estimates:

a. Contracting mode. An in-house contracting mode was assumed where JPL does the mission, system, and subsystem design and where subcontractors do the hardware detail design, fabrication, and testing. JPL then does the system integration and testing, and manages the ODSRS peculiar orbital assembly, test and alignment activities. This mode was deemed appropriate due to the new technology nature of the first ODSRS to be implemented. If required, the data is presented in a format such that a transformation to a system contract mode could be made.

b. Hardware quantity. For all ODSRS subsystem hardware, except the orbit transfer vehicle and the ground support stations, one flight unit and one PTM unit were assumed. The PTM unit led the flight unit by 9 months in delivery to JPL. It was expected that PTM integration and test at JPL would result in some changes being required to subsystems, and the 9-month lead time is required to allow implementation of these changes without disrupting the flight system schedule.

c. Environmental test philosophy. A large precision structure designed for an orbital environment cannot be completely tested in the limitations of an earthbound gravitational field. The bus portion, including electronics, will receive a standard vibration, shock, and STV test. The stowed configuration, including Shuttle packaging and mounting, will receive vibration and shock to Shuttle levels. Qualification of the entire ODSRS in the deployed and assembled configuration will be done by modeling, analysis and testing of partial assemblies of the structure, and antenna panels. An exhaustive system level EMI test will be required due to the extreme sensitivity of the ODSRS receivers.

d. AFETR operations. The ODSRS will be shipped to AFETR in the stowed configuration, installed in Shuttle mounting fixtures. No system testing of the ODSRS is planned at AFETR.

e. Launch and orbital test and assembly support. System and subsystem ground support for assembly, alignment and test operations from a Shuttle assembly base will be required from launch of the first ODSRS Shuttle payload for 60 days.

This allows time for launch and orbital operations on two Shuttle bays of ODSRS hardware and a third Shuttle containing the orbit transfer vehicle. Reduced support will also be required for an additional 60 days to "learn" how to operate the ODSRS with the DSN system. At 120 days after launch of the first Shuttle, the ODSRS will be turned over to DSN operations for normal S/C tracking support.

3. **Results.** Figure 1 shows a top level activity schedule for an ODSRS Project. It was assumed that ODSRS-peculiar new technology developments defined in Section II, New Technology Assessment, are completed at the start of the launch minus 5 year milestone "Technology Readiness Review." All other major activity milestones are shown on this schedule, and it can be used to determine the required Project start date for a given launch date.

Figure 2 shows the ODSRS subsystem activities leading to delivery of the subsystems for system integration in more detail. This subsystem schedule is a composite of all subsystem estimates and was used for defining Project level reviews and need dates. The orbit transfer vehicle and ground support stations did not fit this schedule outline and are shown separately as Figures 3 and 4.

Tables 1 through 7 list all subsystems and system data used to develop the ODSRS cost plan. Costs shown are in FY 78 dollars and can be inflated as appropriate to fit a given Project start or launch year. Tables 1 to 7 also show an evaluation of the uncertainty of each estimate and a description of the source or baseline from which the estimate was obtained. Table 8 is a summary of the major system cost totals showing ODSRS implementation costs and other project costs in FY 78 dollars.

4. **Total cost sensitivity to changes in data.** The major cost driver of the ODSRS system was the Orbiter subsystems required to maintain orbital operations. These subsystems are similar to those required to support a flight spacecraft, and the cost estimates for them reflect this similarity. Most of these subsystem estimates are comparable to current spacecraft subsystem costs, and the system total cost is not likely to decrease significantly unless new technology developments in more than one subsystem result in significant cost decreases. Experience with spacecraft system implementation also indicates that these costs are not likely to decrease significantly for the quantity of ODSRSs that would feasibly be built.

The biggest single element in the system implementation cost is for the antenna surface and associated backup structure. These items add up to $65 million which is 30% of the total system cost. This cost is highly sensitive to the cost of the precision surface panels and their assembly and test. The ODSRS system cost could probably be reduced significantly by a new technology development that would enable the use of a precision deployable 30-meter antenna at 32 GHz.

5. **Life cycle cost comparisons.** A comparison of the ODSRS to other existing or planned systems does not result in exactly comparable performance and operations capability. Two Scenarios have been developed as a basis for life cycle costing.

Scenario 1. The first scenario is a future requirement to increase telemetry reception capability by 6 dB for one station by 1987, which is the earliest possible operations date for an ODSRS. One option for meeting this requirement is to add an ODSRS; the other option is to add one Large Advanced Antenna System (LAAS). Both options meet the requirement, and in addition, the ODSRS provides 24 hours per day telemetry coverage at 6 dB increased performance. Assuming an inflation rate of 7% and an M&O lifetime of 10 years, the life cycle cost comparison is shown in Table 9.

Scenario 2. The second scenario is a future requirement to receive telemetry 24 hours per day using stations located in the territorial United States only. One option for meeting this requirement is an ODSRS; the other option is a network of LAASs located in Florida, Goldstone, and Hawaii. The ODSRS option meets the 24 hour per day telemetry requirement, but the LAAS network does not. Note that this scenario did not assume a network of 64 m DSN stations since they are more costly to implement and operate than the LAAS stations. Again, assuming an inflation rate of 7% and a 10 year M&O lifetime, the life cycle cost comparison is shown in Table 9.

C. DSN-MOS-ODSRS Integration

The ODSRS alone could not provide all of the S/C tracking functions now done by the ground stations of the DSN. A major difference is that the ODSRS has no transmit capability to a spacecraft. The ODSRS design philosophy was not to replace the existing DSN, but to provide an option for augmenting the DSN to meet future requirements. Potential future requirements include providing more available station hours per day for S/C tracking, providing increased telemetry performance capability, and providing 24 hour per day telemetry coverage without overseas stations.

1. **Interfaces.** The ODSRS requires interfaces with the DSN and the MOS for telemetry, ranging, command, radiometrics, and station keeping operations as follows:

a. S/C telemetry. The output of the ODSRS ground station telemetry receiver would be compatible with the output of the existing DSN ground telemetry system. It would require similar interfaces to the MOS as the existing DSN, with one excep-

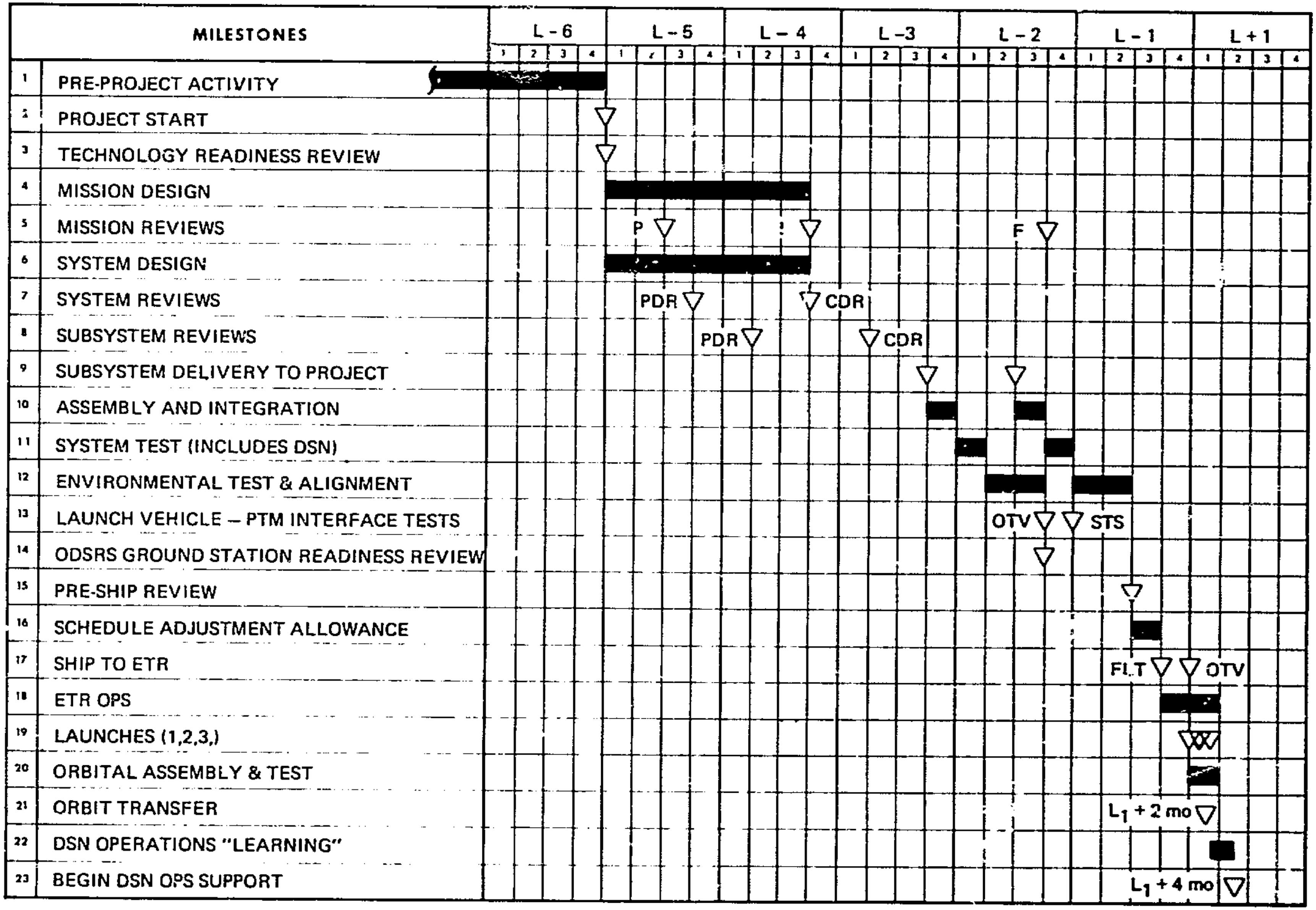


Fig. 1. ODSRS Project and System Master Activity Schedule

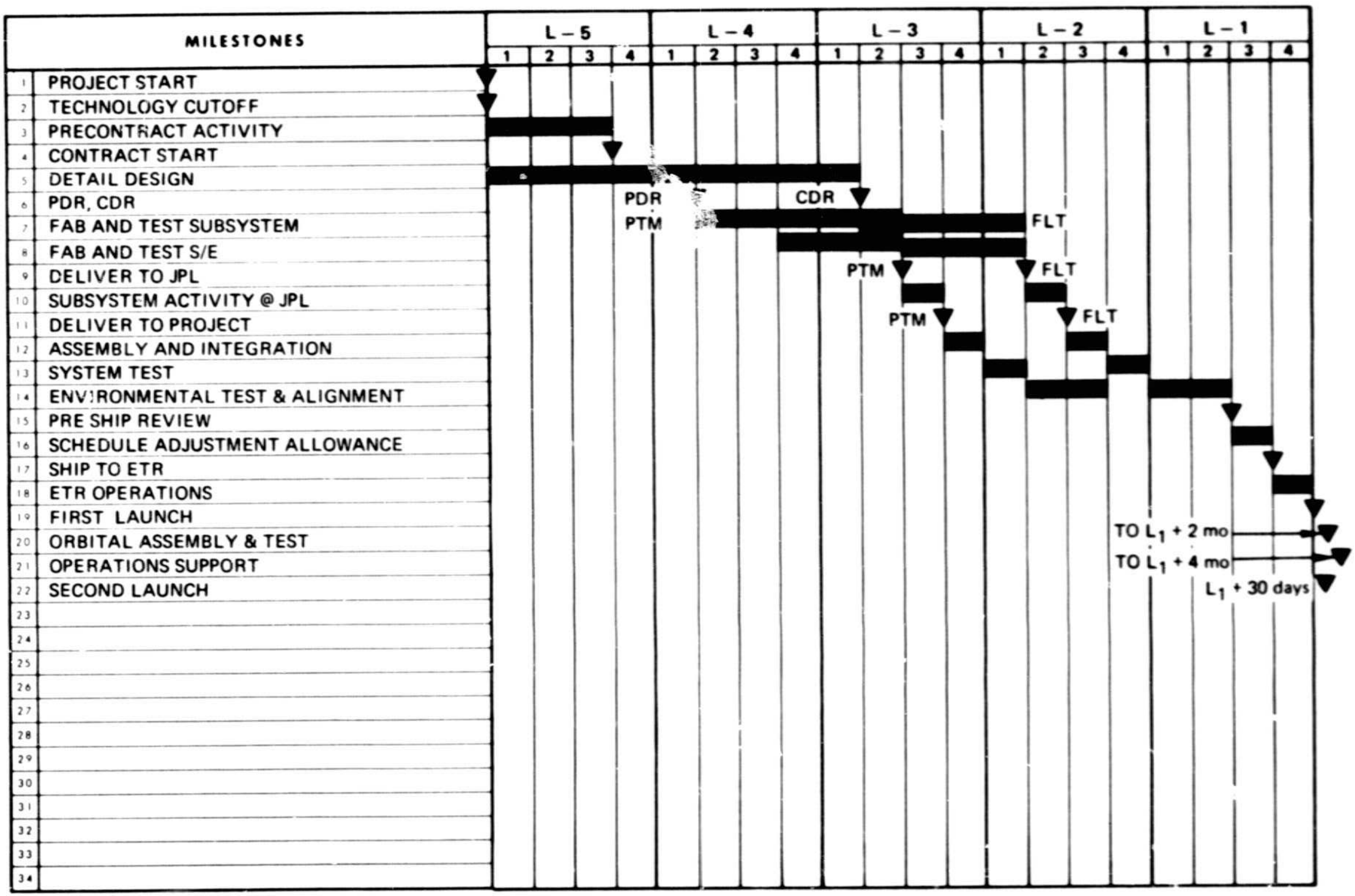


Fig. 2. ODSRS Subsystems Master Activity Schedule

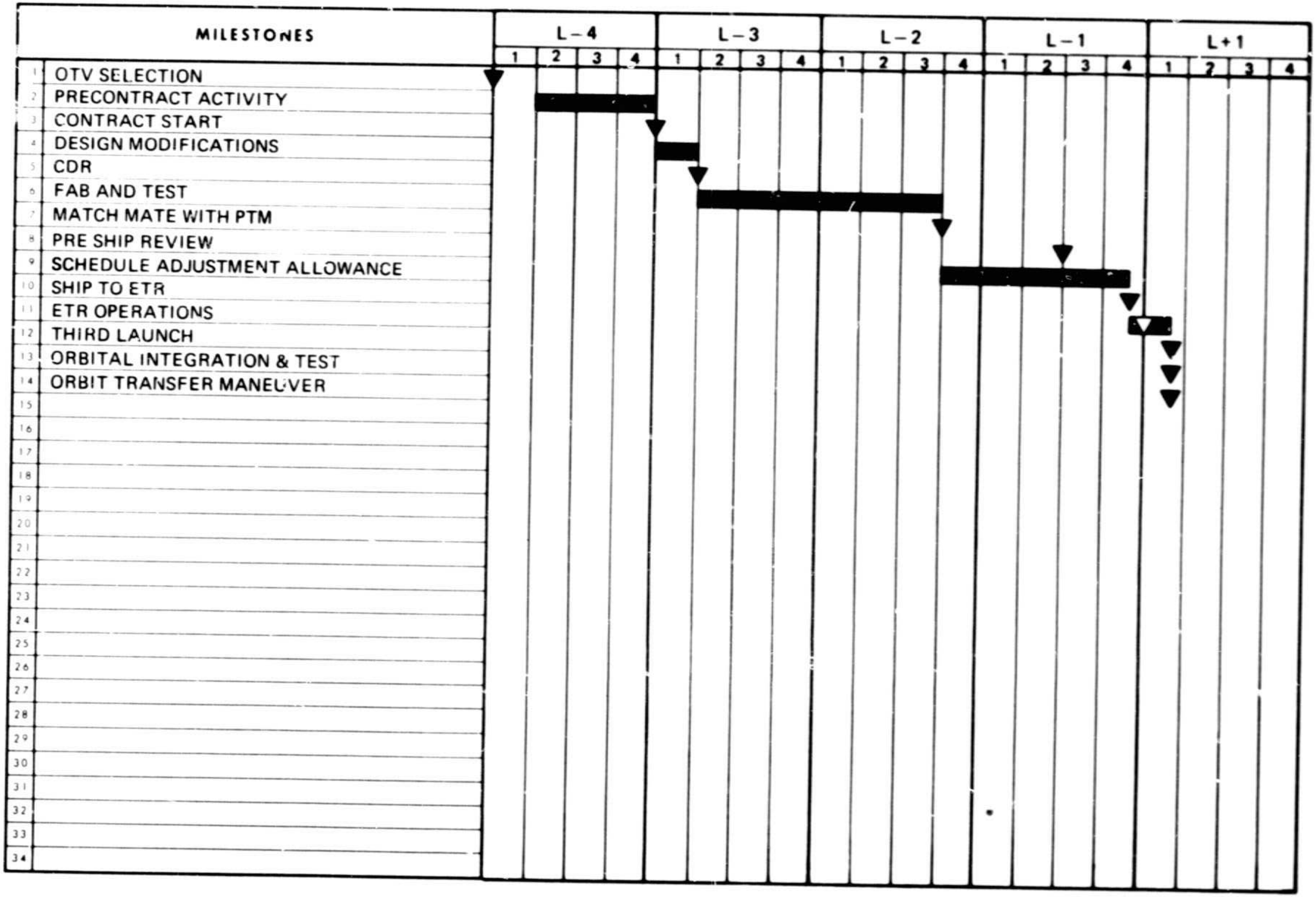


Fig. 3. ODSRS Subsystems IUS Transfer Vehicle Activity Schedule

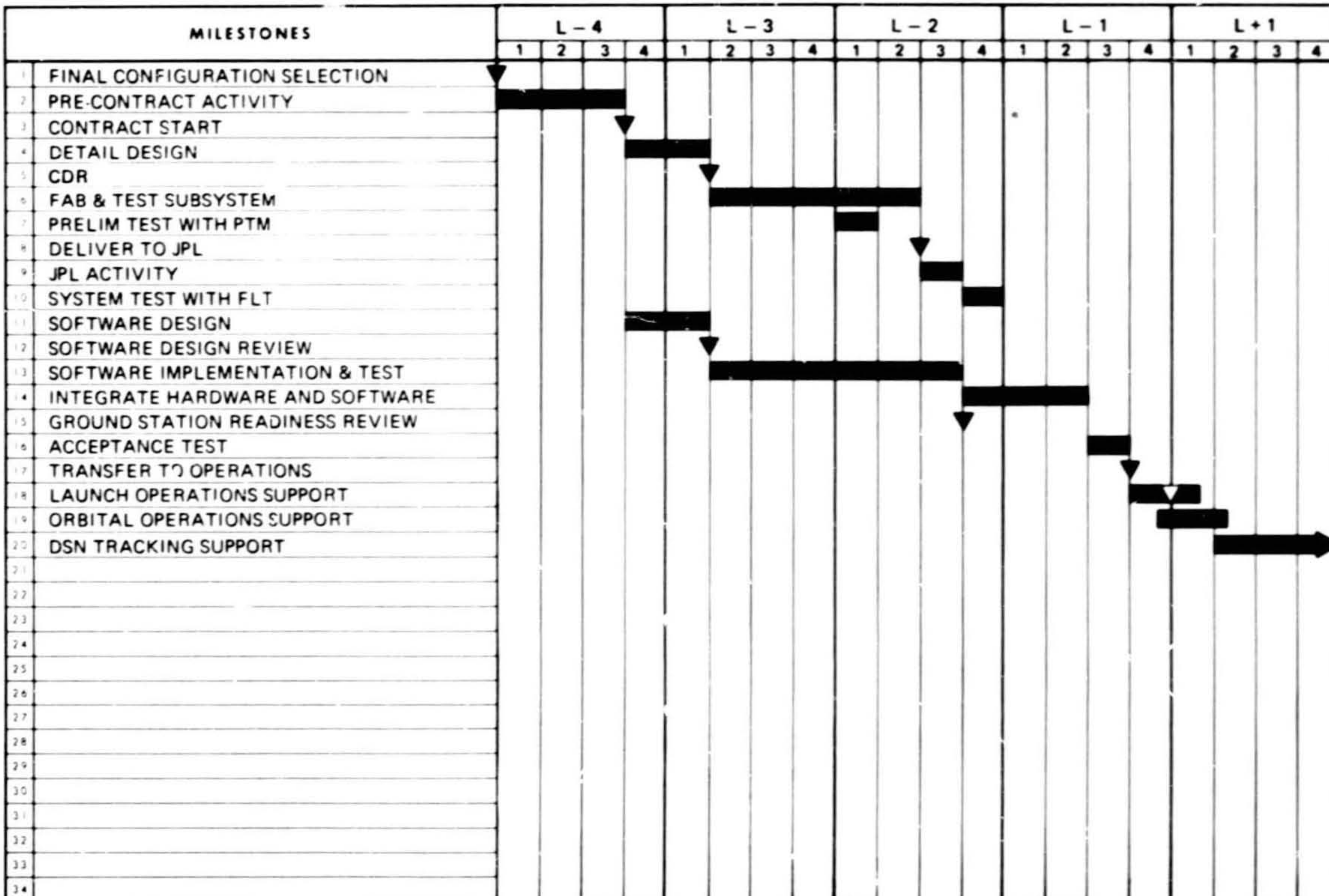


Fig. 4. ODSRS Ground Station Activity Schedule

Table 1. ODSRS Peculiar New Technology Development Cost Estimates

New Technology	Project Start* -3 yr	Project Start* -2 yr	Project Start* -1 yr	Total Cost*	Source of Estimate	Uncertainty Assessment
Antenna Design for RFI Rejection		120	770	890	Fig. 5	• New technology development for a Project start 10 or more years in the future has inherent high uncertainty.
Antenna Surface and Assembly	180	680	1750	2610	↓	• Total cost assumes that new technology developments planned by other programs and needed for ODSRS are completed as planned.
RFI Source Analysis		120	120	240	↓	
Automatic operations technique development		500	500	1000	↓	
TOTAL	180	1420	3140	4740		

*Costs are in thousands, FY 78 dollars.

tion. The ODSRS ground station would be colocated with the SFOF or any location where final data processing is done. This would eliminate the need for GCF interfaces.

b. ODSRS station location ranging. The ODSRS concept requires 3 simplified, widely spaced, ground stations to do 2-way ranging with the ODSRS for precise station location. One of the stations could be colocated with the telemetry receiving station, and the other two could be colocated with the two farthest stations of the navigation network, if implemented. ODSRS station location ranging will have to be used by the MOS to evaluate ODSRS effects on S/C radiometric data.

c. S/C command. At least one DSN ground station would be required to provide command capability to a flight spacecraft. This would not require an interface with the ODSRS per se, but it is a requirement for any tracking and communications system that contains an ODSRS.

d. S/C radiometrics. The output of the ODSRS ground station doppler and ranging systems will be compatible with the output of the existing DSN ground stations. It requires similar interfaces to the MOS as the existing DSN, with one addition. The prime interface is similar to the telemetry system; if the ODSRS ground station is colocated with the MOS data processing center, it requires no GCF interface. The additional new interface is required only if the ODSRS is being used to relay 2-way data to the Goldstone ground station after Goldstone has set from direct S/C view. This would require an additional ODSRS ground station located at Goldstone and an interface between its doppler and ranging output and the Goldstone radiometric data system.

e. ODSRS stationkeeping operations. Stationkeeping operations (command and telemetry) for the ODSRS will be conducted over the same ground antenna used for receiving S/C telemetry and radiometric data. The electronics for this stationkeeping are functionally separate from the existing DSN and MOS systems and do not require new interfaces. An operational interface to the MOS and DSN is required for planning and executing ODSRS tracking operations.

2. **ODSRS-DSN joint capability.** The difference that adding an ODSRS to the current or a future DSN makes is dependent on the DSN configuration that exists at the time. For planning purposes, adding one ODSRS would result in the following:

(1) It would add the capability for 24 station hours per day that could be available for receiving from one or more spacecraft, one at a time. The 24 hours would be reduced by the time required to slew between spacecraft and the ODSRS reprogramming time for a new spacecraft.

(2) It would provide 6 dB greater telemetry date rate capability, from a spacecraft equipped with a 32 GHz transmitter, relative to the existing 64M, X-Band DSN.

(3) It would add the capability for 2-way tracking (by Goldstone) of a S/C to which the 2-way round trip light time exceeded the length of the station pass.

(4) It would provide the data handling capability for VOIR class data rates (~8 Mbps) from the spacecraft through the ODSRS to the SFOF 24 hours per day without going through the GCF.

Table 2. ODSRS Subsystem Hardware and Software Design, Fabrication, and Pre-Launch Test and Operations Cost Estimates

Subsystem		Launch* -5 yr	Launch* -4 yr	Launch* -3 yr	Launch* -2 yr	Launch* -1 yr	Total Cost*	Source of Estimate	Uncertainty Assessment
Structure and Mechanical Support	JPL	1,360	7,835	6,535	3,110	1,210	20,050		
	CTR							Subsystem Engineer	Most subsystems assume new technology between 1979 and project start.
	Total	1,360	7,835	6,535	3,110	1,210	19,900		
Antenna, Mechanical	JPL	200	200	520	920	400	2,240		
	CTR	5,240	21,500	16,000	400	200	43,340		
	Total	5,440	21,700	16,520	1,320	600	45,580		
Antenna Electrical	JPL	280	280	280	280	280	1,400		
	CTR	300	7,300	3,750	250	0	11,600		
	Total	580	7,580	4,030	530	280	13,000	↓	↓
Cryogenics and low noise Receiver	JPL	260	260	310	310	210	1,350	Subsystem Engineer + study leader	Large uncertainty in contract cost for flight cryogenics
	CTR	1,000	2,000	4,000	3,000	0	10,000		
	Total	1,260	2,260	4,310	3,310	210	11,350		
Relay radio and stationkeeping telecommunications	JPL	530	930	1,015	1,260	1,025	4,760	Subsystem Engineer	Most subsystems assume new technology between 1979 and project start
	CTR	400	7,880	7,470	400	0	16,150		
	Total	930	8,810	8,485	1,660	1,025	20,910		
Attitude and articulation control	JPL	1,480	3,262	2,522	1,383	600	9,247		
	CTR	2,055	8,325	3,580	0	0	13,960		
	Total	3,535	11,587	6,102	1,383	600	23,207		
Power	JPL	918	2,436	2,047	1,329	409	7,139		
	CTR	0	10,000	3,000	6,000	0	19,000		
	Total	918	12,436	5,047	7,329	409	26,139		
Computer, control, & data handling	JPL	0	1,859	5,331	2,124	1,468	10,782		
	CTR	0	0	0	0	0			
	Total	0	1,859	5,331	2,124	1,468	10,782		
Orbit transfer propulsion	JPL	0	101	4,409	3,381	320	8,211		
	CTR	0	0	14,857	11,233	330	26,420		
	Totals	0	101	19,266	14,614	650	34,631		
Stationkeeping propulsion	JPL	569	569	569	569	569	2,845		
	CTR	410	1,638	1,638	1,638	1,638	6,962		
	Total	979	2,207	2,207	2,207	2,207	9,807	↓	↓
	JPL	5,597	17,732	23,538	14,666	6,491	68,024		Total compares to $234,000 estimate from JPL cost model
Totals	CTR	9,405	58,643	54,295	22,921	2,168	147,432		
	Total	15,002	76,375	77,833	37,587	8,659	215,456		

*Costs are in thousands, FY 78 dollars.

Table 3. Program Management, Mission Design, System Design, and Pre-Launch Integration, Test, and Operations

Item	Launch* -5 yr	Launch* -4 yr	Launch* -3 yr	Launch* -2 yr	Launch* -1 yr	Total Cost*	Source of Estimate	Uncertainty Assessment
Project Mgt & Mission Engr.	1,500	2,000	3,000	2,000	1,500	10,000	JPL cost model and ratios to hardware cost	Cost model designed for smaller spacecraft with scientific mission
System Engr.	1,000	2,000	2,000	2,000	1,700	8,700		
Assembly, integration, & system test	100	200	2,000	5,000	3,500	10,800		
System test support support equipment	400	7,000	10,000	5,000	500	22,900		
Environmental test & analysis program	500	500	2,000	3,000	2,400	8,400		
ETR operations & STS integration support					500	500	Assume ~$100,000 per mo for 5 mo	High uncertainty
Total	3,500	11,700	19,000	17,000	10,100	61,300		

*Costs are in thousands, FY 78 dollars.

Table 4. ODSRS Ground Support Stations Design, Fabrication, Test, and Integration Cost Estimates [1]

Item	Launch* -4 yr	Launch* -3 yr	Launch* -2 yr	Launch* -1 yr	Launch* + 1yr	Total Cost*	Source of Estimate	Uncertainty Assessment
System engineering, integration and documentation	120	120	120	180	60	600	Study team estimates	
Software	60	150	150	140	0	500		
S/X/Ku Band 5 m Antennas (3 each)		150	150			300		
Antenna pointing sys. (3 each)		150	150			300		
Antenna structure & electronics housing (3 each)		300	300			600		
Redundant S and X Band receivers (3 each)		600	600			1,200	Derived from ratios of current hardware cost	
Redundant telemetry channels (3 each)		960	960			1,920		
Redundant Ku Band receivers (1 each)		150	150			300		
Redundant doppler extractor (1 each)		75	75			150		
Redundant ranging channels (4 each)		400	400			800		
Redundant S/X Band exciter & xmtr		200	200			400		No close design to compare to – "Navigation Network" is closest, their estimate is ~$10,000,000 for 3 stations
Redundant command modulator		100	100			200		
μ-wave hardware		150	150			300		
Total	180	3,505	3,505	320	60	7,570		

*Costs are in thousands, FY 78 dollars.

[1] Includes 1 station to receive S/C telemetry, control ODSRS and range with ODSRS, plus 2 stations to range with ODSRS.

Table 5. Space Shuttle and Shuttle Related Orbital Operations Cost Estimates for ODSRS Launch, Assembly and Test

Item	Cost*	Source of Estimate	Uncertainty Assessment
3 Space Shuttle launches at 20M$ each.	60	Currently advertised Shuttle cost.	Very high uncertainty in orbital operations cost due to lack of data.
60 days of on-orbit assembly and test using the Shuttle as a work platform (assume 300,000/ day).	18	• Defined operations cost not available. • Current estimates run up to $350,000 per day for complex operations	
TOTAL	78		

*Costs are in millions of FY 78 dollars.

Table 6. Post-Launch ODSRS Ground Operations Cost Estimates to Support Orbital Assembly, Test, Alignment, and Integration

Item	Cost*	Source of Estimate	Uncertainty Assessment
120 days of operations support – 24 hours per day – assume average staff of 20 persons at earth based operations facility.	1680	28 MY at $60,000 per MY	Very high uncertainty in orbital operations cost due to lack of data.

*Costs are in thousands of FY 78 dollars.

Table 7. ODSRS Ground Stations and Control Center M&O Cost Estimate Starting at Launch Plus 120 days

Item	Cost* Per Year	Source of Estimate	Uncertainty Assessment
Annual maintenance and replacement cost for ground-stations, assumed at 5% of capital cost.	375	Study team estimate	
ODSRS control center staffing = 4 person-shifts per day	360	6 MY per year at $60,000	Assumes automatic station operations concept
TOTAL	735		Likely a minimum, assumes no surprises

*Costs are in thousands, FY 78 dollars.

Table 8. ODSRS Conceptual Design Cost Summary

Item	Launch* -5 yr	Launch* -4 yr	Launch* -3 yr	Launch* -2 yr	Launch* -1 yr	Launch* +10 yrs	Total*	% of Implementation Cost Total
Project Start ▽					Launch ▽			
Mission and system design, integration, test operations and project mgmt	3,500	11,700	19,000	17,000	10,100	1,680	62,980	24%
Orbiter hardware engineering, design, fabrication, test, and operations	15,002	76,274	58,567	22,973	8,009		180,825	70%
• Relay Link	7,745	35,945	29,102	5,990	1,603		80,385	31%
• Station Keeping	7,257	40,329	29,465	16,983	6,406		100,440	39%
ODSRS ground station engineering, design, fabrication, test and operations		180	3,505	3,505	320	[illegible]	14,920	6%
Implementation Sub-total Cost	18,502	88,154	81,072	43,478	18,429	9,090	258,725[2]	100%
				Other ODSRS Related Costs				
New technology development			(Begins 3 yr prior to project start)				4,740	N/A
Shuttle and orbital operations							78,000	N/A
Orbit transfer vehicle[1]							34,631	N/A
Other Subtotal Cost							117,371	N/A
NASA Total Cost							376,096	N/A

*Costs are in thousands FY 78 dollars.

(1) From table 2

(2) Does not include orbit transfer vehicle

Table 9. ODSRS Life Cycle Cost Comparison

Item	Implementation Cost* 1983	1984	1985	1986	1987	10 Yr M&O 1988-1997*	Total Cost*
Scenario 1							
ODSRS	25,950	132,295	130,184	74,703	33,881	20,095	417,108
LAAS[1]	4,186	15,740	17,596	20,094	3,072	25,630	86,318
Scenario 2							
ODSRS	25,950	132,245	130,184	74,703	33,881	20,095	417,108
LAAS[1]	12,558	47,220	52,788	60,282	9,216	76,890	258,954

*Costs are in thousands, real year dollars.

(1) From Large Aperture Antenna System Study Report, inflated at 7%

II. New Technology Assessment

A major goal of the ODSRS study was to determine what new technology developments would be required to support an ODSRS launch in the post-1985 time period. Since some developments are expected to require long lead times, it is important to identify them at this time. This section presents a description of the technology development requirements identified for the ODSRS and a plan for the implementation of these developments.

A. Approach

During the ODSRS study, each system and subsystem design concept was reviewed for technology requirements. New technology requirements were restricted to those which the study team determined were feasible for the 1985 time period. For each area that required new technology, a technology development requirement was written. These requirements included:

(1) The technology required by the ODSRS

(2) The current state of the technology

(3) Work currently planned or expected for this technology

(4) Additional development required to be ready for an ODSRS Project

(5) A ranking of the importance of that technology to an ODSRS

For each technology that required additional new technology development to enable an ODSRS, a technology development plan was written. These plans include a more detailed discussion of the technology development and an estimated schedule and cost plan. Note that the schedule and cost plans were developed with some judgement as to a likely level of effort that would be supported, and the assumption that the ODSRS would not be a new Project start until at least the 1985 time frame. If needed, the technology availability could be speeded up with the addition of more money earlier.

B. New Technology Requirements

Table 10 shows the new technology requirements that were determined for the ODSRS system. They are listed in rank order of importance to the enablement of an ODSRS and are also categorized. The three categories are more important to note than the numerical ranking. For example, everything in Category A requires new technology to enable the ODSRS, and no other program is expected to develop this technology, so whether they are ranked first or third is relatively unimportant.

Category A. New technology is required to enable an ODSRS. It is unlikely that other programs or applications will require or support this development.

Category B. New technology is required to enable an ODSRS. Other programs and applications have closely related

Table 10. ODSRS New Technology Requirement Categories

Subsystem/ Technology Area	ODSRS Requirement	Current Capability	Development in Process or Expected	Additional Development for ODSRS	Category	Rank
Antenna - RFI control	• Antenna design to reject RFI from the earth and orbital sources.	• Offset feed antenna designs currently being developed have potential for reducing sidelobes over a hemisphere of the antenna. • Antenna shielding technology is being investigated. • An adequate capability for RFI rejection by antenna design does not exist.	• JPL has study effort on offset feeds. • An analytical approach to shielding to reduce antenna sidelobes exists for symmetrical feed antennas.	• A new technology program is needed to develop antenna design techniques for reduced and controlled sidelobes.	A	1
Antenna surface and assembly	• Antenna must be assembled, aligned, and tested in orbit using the shuttle as an assembly platform. • Assembly of antenna on earth and in orbit must be repeatable to 0.2 mm. • Antenna surface must be stable to 0.2 mm over all operating thermal gradients. • The materials used must have a 10 yr. unattended lifetime.	• No space qualified antenna design exists that meets ODSRS requirements for orbital assembly. • No technique exists for aligning and testing a 28 m 32-GHz antenna in orbit. Current techniques for large antennas on earth are too time consuming and complex to be used in orbit.	• Dr. Leighton (Cal Tech) has demonstrated a smaller antenna with surface tolerances and assembly repeatability (on earth) that meet ODSRS requirements. • Systems to make precision alignment measurements, such as laser rangefinders, are being developed. It is expected that this technology will meet ODSRS needs by 1985. • A deployable backup structure will likely be developed by ODSRS need date and can be adapted to ODSRS application.	• A new technology program is needed to develop a mechanical design that meets the requirements of the ODSRS for orbital assembly, alignment, testing, repeatability, thermal stability, and lifetime.	A	2
RFI source analysis	• Potential sources of RFI need to be analyzed to determine their effect on ODSRS bent pipe link performance.	• None significant.	• None significant.	• A new program is needed for obtaining and analyzing data on RFI sources that may affect low noise orbiting receivers.	A	3
Automatic operations for ODSRS.	• Techniques for automatic operation of the ODSRS while tracking a spacecraft need to be developed and demonstrated.	• Some for ground stations.	• None directly related to ODSRS.	• A new technology program is needed to develop automatic operations techniques for ODSRS.	A	4

Table 10 (contd)

Subsystem/ Technology Area	ODSRS Requirement	Current Capability	Development in Process or Expected	Additional Development for ODSRS	Category	Rank
Low noise cryogenic receiver	• Space qualified 32 GHz masers, S and X to 32 GHz upconverters, microwave components. • 10 yr. unattended operation.	• Design of microwave components and masers for operator maintained ground equipment is current state of art.	• S and X to 25 GHz upconverters are being developed for ground applications. • Current program plans should meet ODSRS requirements by ~1985.	• Program could be accelerated 2-3 yr with more dollars now. • An engineering development of space qualified receiver components in a cryogenically cooled package will be needed.	B	4
Cryogenic refrigerator	• Space qualified cryogenic refrigerator. • 10 yr unattended operation. • Capacity to cool two masers.	• Earth based cryogenic refrigerators are reliable with operator maintenance.	• An effort is in process for space qualified cryogenic refrigerators that are planned to meet ODSRS requirements by ~1985.	• An engineering development will be required to apply the 1985 expected design to ODSRS. • Program could be accelerated 2-3 yr with more dollars now.	B	5
Power	• Space qualified 5.5 kW, 100% duty cycle. • 10 yr unattended operation.	• Prototype 1 kW completed 1000 hr test. (KIPS)	• 1-2 kW KIPS for ground demonstration – 7 yr lifetime. • KIPS shuttle flight test planned before ODSRS need date.	• An engineering development program is required to resize the KIPS to 5.5 kW.	B	6
Attitude control	• Closed loop (monopulse) pointing to 0.002 deg for continuous tracking. • Open loop pointing to 0.02 deg for acquisition. • Space qualified, 10 yr lifetime.	• Attitude control electronics is current state-of-art.	• "AMFL" reaction wheels will meet ODSRS performance requirements in near future. • "DRIRU II" gyro will meet ODSRS performance requirements in 1979. • "Stellar" star tracker will meet ODSRS performance requirements by 1983.	• An engineering development program required to qualify these components for 10 yr lifetime.	B	7
Low noise monopulse feed system	• Low loss to minimize noise temperature degradation. • Able to point ODSRS to 0.002 deg. • Space qualified, 10 yr unattended operations.	• Design of individual elements is current technology, integration into system to meet ODSRS requirements is needed.	• S/X band low noise feedhorn for earth stations being tested at Goldstone. Will be expanded to K_U band.	• An engineering development program is required to develop a low loss, high performance, space qualified, feed system and multifrequency feedhorn with a 10 yr lifetime.	B	8

Table 10 (contd)

Subsystem/ Technology Area	ODSRS Requirement	Current Capability	Development in Process or Expected	Additional Development for ODSRS	Category	Rank
Prelaunch system test and verification	• Adequate demonstration of antenna and structure response to orbital environment prior to launch. • Analysis and test to verify attitude control interaction with large, nonrigid structure.	• Environmental test for smaller structures exists. • Analysis techniques for attitude control interaction exist but are not demonstrated on large structures.	• Environmental test for large structures is part of LSST program. • Analysis techniques for large structures is part of LSST program.	• An engineering development will be required to apply large structure analysis and test techniques to the ODSRS.	B	9
Precision ranging system	• ODSRS range known to 1 m from earth center in 3 axes (requires system accuracy of ∼10 cm to resolve ODSRS position to 1 m).	• ∼5 m.	• Work in process expected to yield 1 m in near future. • Proposed plan for 10 cm ranging development program is being worked now.	• None, if proposed program is implemented.	B	10
Orbit transfer vehicle for LEO to GEO boost.	• Transfer 8448 kg structure from 370 km orbit to 36,000 km orbit with plane change from 28.5 deg to 0 deg. Acceleration not to exceed 0.2 g.	• None.	• It is expected that an OTV meeting ODSRS requirements will be needed by many large space structures and that a general class OTV will be developed for this application.	• None, an existing OTV in the 1985 time frame will be adapted to ODSRS.	B	11
Precision deployable antenna	• A precision deployable antenna at 32 GHz and 28 m would simplify the ODSRS in orbit assembly and test.	• K-band deployable antennas are demonstrated at smaller sizes and lower frequencies.	• Several vendors are working on high frequency deployable technology.	• If orbital assembly and test of erectable ODSRS becomes a major problem, development of a deployable may be required.	C	12

requirements and are planning to complete the new technology development in time for an ODSRS Project. The ODSRS Project will have to provide the engineering development necessary to use this new technology for their application.

Category C. No new technology is required to enable an ODSRS, but new technology could enhance the ODSRS Project.

Table 11 shows the new technology that is required by systems that interface with the ODSRS to enable them to use the maximum ODSRS performance capabilities.

C. New Technology Development Plans

This section describes the schedule and cost plans for development of ODSRS new technology. Only new technologies that require additional work beyond currently planned programs in order to enable an ODSRS will be discussed. It was assumed that engineering developments for the ODSRS to use new technology that is expected to be developed by other programs in time for ODSRS would be a part of an ODSRS Project subsystem design activity. Note that if these new technology developments are not completed by other programs, the ODSRS will need to plan to support them.

Table 11. ODSRS Related Technology Requirements

Subsystem/ Technology Area	Requirement	Current Capability	Development Planned or Expected	Additional Development Required	Notes
32 GHz transmitter for spacecraft using ODSRS	• K_A band, 20 W transmitter on spacecraft	• No space qualified TWTA (or other) at 32 GHz and 20 W	• Two vendors (at least) have TWTAs for ground based applications that are close to ODSRS frequency and power requirements and are generically the same as flight hardware	• A major program will be required to design and space qualify K_A band TWTs and power supplies	Required by a spacecraft to use ODSRS maximum performance
• Attitude control for spacecraft using ODSRS (assumes ~ 5 m S/C antenna at 32 GHz)	• Open loop pointing of spacecraft antenna to ~ 0.07 deg	• ~ 0.3° to 0.4° (Galileo)	• Development planned should provide technology readiness by 1983 for 3 axis stabilized spacecraft	• None, if planned developments are completed	• Further development will be required to spinning spacecraft

1. **RFI control.** RFI has been identified as the most serious potential problem of the ODSRS. The ODSRS will have an extremely sensitive receiver, designed to receive weak signals from deep space probes at ranges of hundreds of millions of kilometers. Even extremely low level RFI that would not affect a typical orbiting receiver could cause serious interference with an ODSRS. It is necessary to design the ODSRS to reject all electrical signals except those from the target spacecraft. A major factor in this rejection will be reduction of the sidelobe structure of the ODSRS antenna. In particular, support strut scattering present in symmetrically fed antennas must be eliminated. The technology of offset feed, unblocked, quasicassegrain antennas is rapidly developing (Refs. 1, 2) and appears adaptable to the ODSRS application. Further, the technology of using shielding to reduce sidelobe levels is being developed (Ref. 3) and appears promising. A major deficiency is an analytical approach to determining fundamental limitations as sidelobe suppression and the design of antennas for RFI rejection in general. A new technology program for antenna design for RFI rejection would include:

- Investigation of fundamental limitations on sidelobe control.
- Developing design techniques for sidelobe reduction.
- Fabrication and test of a model "reduced sidelobe" antenna to demonstrate analytical techniques.

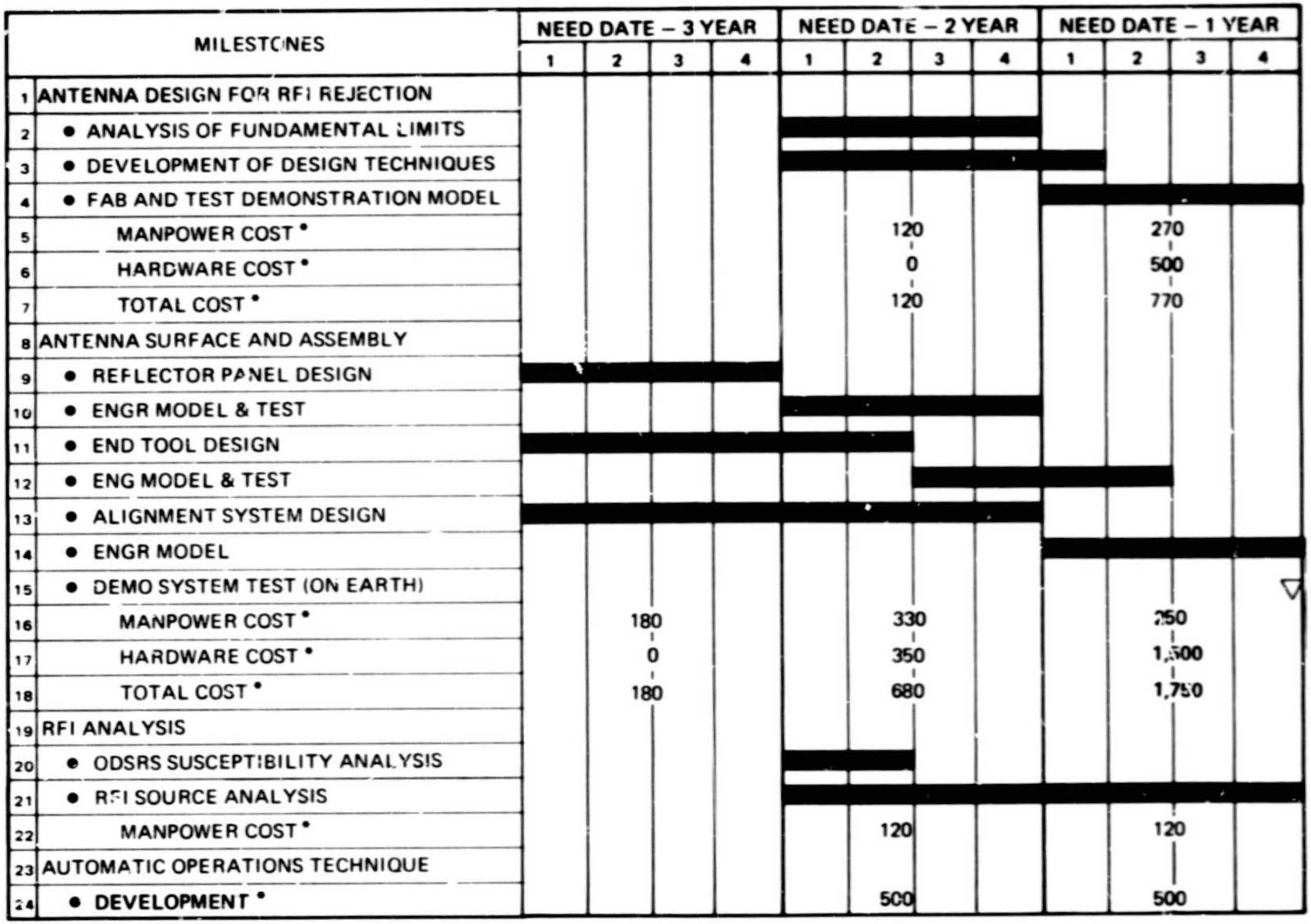
The schedule and cost estimate for this effort is shown in Figure 5.

2. **Antenna surface and structure.** Another potential major problem for the ODSRS is the orbital assembly, alignment, and checkout of a precision antenna surface. This process takes weeks for a DSN antenna on earth and uses mechanical alignment tools and techniques that would probably be impractical in orbit. The ODSRS assembly in orbit must be repeatable to within 0.2 mm of its final assembly on earth, and the surface must be stable to 0.2 mm over all thermal gradients and orbital operating conditions. It is expected that some mechanical alignment will be necessary during assembly in orbit to obtain the required surface accuracy, although the design goal is to achieve adequate orbital assembly repeatability without alignment. The ODSRS surface and structure materials must last for 10 years in geosynchronous orbit.

It is assumed that a deployable backup structure that meets ODSRS requirements will be developed by the ODSRS need date, and that it can be adapted to the ODSRS applications. It is also assumed that a mechanical alignment technique, such as laser rangefinders, will be developed and can be applied to the ODSRS alignment process.

The surface panel concept chosen for the ODSRS is similar to the design demonstrated on a smaller antenna for earth applications by Dr. Leighton of Caltech. For the ODSRS, the reflective panels are a thin graphite composite sheet supported by multiple flextures to a backup structure. A new technology program for the ODSRS would include:

- Thermal design of reflective surface panels to maintain 0.2 mm stability over all operating conditions.



* COSTS ARE IN THOUSANDS, FY 78 DOLLARS

Fig. 5. New Technology Development Plans for ODSRS

- Mechanical design of reflective surface panels for 0.13 mm manufacturing tolerances.
- Mechanical design of reflective surface panels for repeatability of 0.2 mm assembly tolerance using the Shuttle RMS with an appropriate end tool. This includes design of the end tool.
- Development of an automatic, mechanical alignment checking and realignment technique using a laser rangefinder (or other available device) driving a computer that drives the RMS end tool.
- Fabrication and test of engineering model structure and surface panels, RMS end tool, and mechanical alignment system.

The schedule and cost estimate for this new technology is shown in Figure 5.

3. RFI source analysis. A major unknown in the ODSRS conceptual design is what the orbital RFI environment will really be. Some simplified examples show that a problem could be caused by many RFI sources. A study of the effects of an RFI source on the ODSRS requires a definition of the characteristics of that RFI source. The problem is that no comprehensive study of RFI sources and definition of the RFI environment around the ODSRS exists. The development of this and its use for the ODSRS would include the following:

- Analysis of the ODSRS system to define the characteristics of RFI that could affect its operation.
- Comprehensive analysis of RFI sources (including earthbound, orbital, classified and foreign) and definition of their characteristics.

The estimated cost and schedule for this RFI study program is shown in Figure 5. These costs and schedules are for new technology developments that are not expected to be completed by other users in time for an ODSRS program. It is assumed that an ODSRS Project would not be a new start before 1985.

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