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Bravo Economic Study of Landsat Follow-on Final Report

Prepared by
Advanced Mission Analysis Directorate
Advanced Orbital Systems Division

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Goddard Space Flight Center, Greenbelt, Maryland

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Systems Engineering Operations

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1. INTRODUCTION

This study is a part of the process of developing a plan for the Landsat Follow-On Project during the period when the Shuttle will be supporting the Landsat Follow-On system. The Landsat Follow-On Project plans two Delta 3910 launches from WTR. The first is scheduled for 1981; the second Delta launch will occur as needed to keep one satellite operational on orbit. The second satellite will be ready six months after the first. It could be launched any time after that. Shuttle support of the system could begin in early 1983 but would be scheduled to start after the second Delta launch.

The Landsat Follow-On satellite consists of two major systems; the instrument module and the Multi-Mission Modular Spacecraft (MMS). The instrument module contains the thematic mapper and the five-band multispectral scanner instruments. The instrument module also includes the solar array, the tracking and data relay satellite (TDRS) antenna, and the wideband data module. The MMS contains the modularized and standardized power, propulsion, attitude control, and command and data handling subsystems. Figure 1-1 is a schematic representation of the Landsat Follow-On orbital configuration. The Landsat Follow-On launch configuration will be designed to be compatible with both the Delta 3910 and Shuttle launch vehicles.

The study objective is to furnish NASA's Goddard Space Flight Center with updated economic data on the best way to design and operate the Landsat Follow-On spacecraft and payload. In order to accomplish this objective, Aerospace uses the Business Risk and Value of Operations In Space (BRAVO) techniques (see Reference 1).

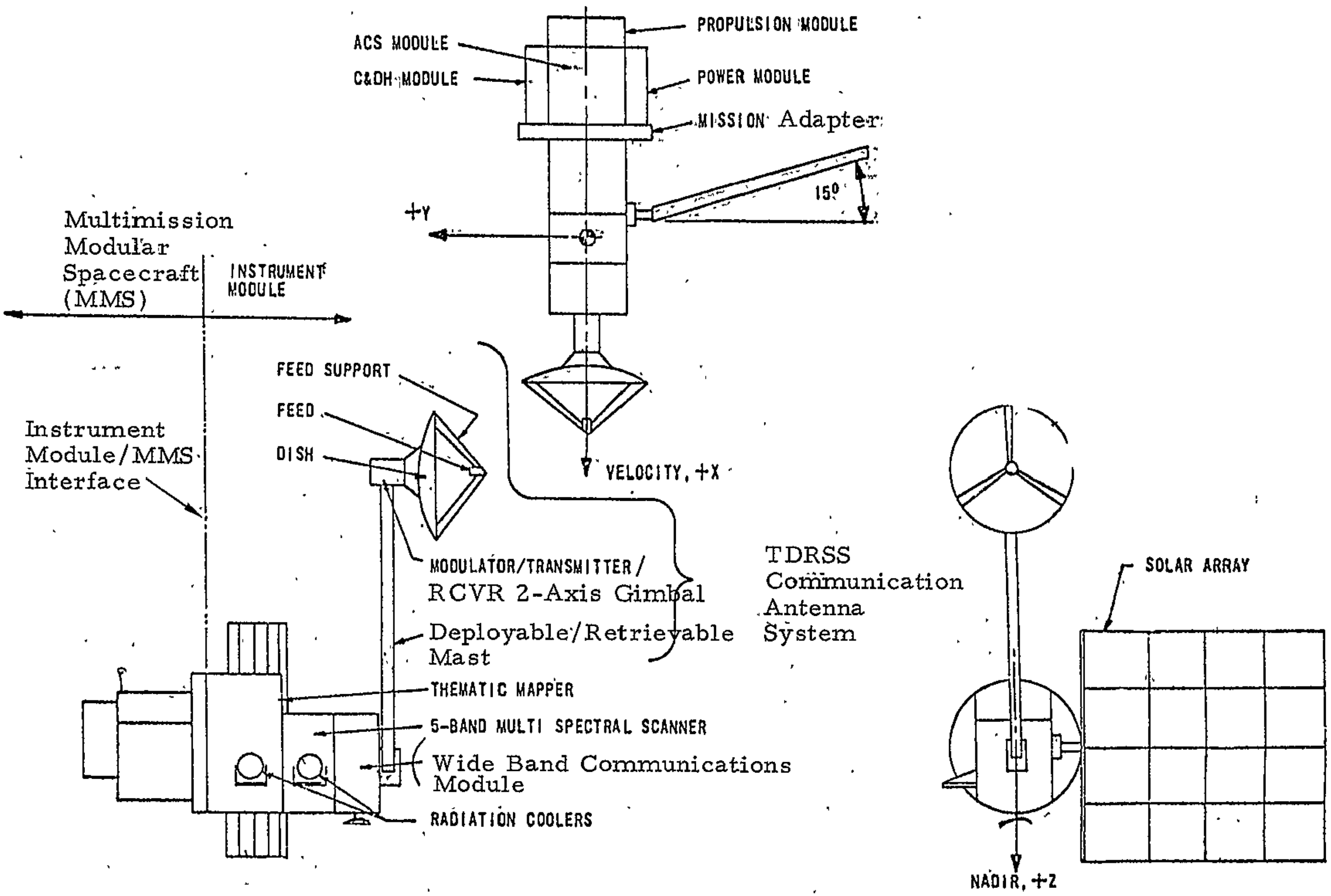

Figure 1-1. Landsat Follow-On Schematic

In order to accomplish this study, Aerospace performed the following tasks:

1. Defined the current spaceborne Landsat Follow-On in terms of BRAVO inputs
2. Performed satellite design synthesis to supplement design data furnished by NASA on the Landsat Follow-On
3. Described STS captures of the Landsat satellite and operating schedules for on-orbit service operation, ground-based refurbishment operation, and expendable operation of the Landsat Follow-On satellite
4. Estimated transportation costs for the Landsat Follow-On modes of operation
5. Estimated satellite traffic and system availabilities
6. Estimated system costs and made comparisons between alternative methods of operation and also compared alternative satellite designs
7. Optimized logistics for the Landsat Follow-On as a continuous earth observation payload with one satellite on orbit.

The Landsat Follow-On satellite orbits in a circular 705 km altitude, 98.2 deg inclination, 9:30 a.m. sun synchronous orbit. Various options were investigated for transporting the satellite to and from this destination by the orbiter. The low energy orbiter parking orbit is a 296 km altitude circular (160 nmi) orbit. The high energy Shuttle orbit is the 705 km orbit of the Landsat Follow-On satellite. An intermediate elliptical parking orbit was also considered with 185 km perigee and 705 km apogee.

Studies were made with the instrument module of the Landsat Follow-On satellite unmodularized, with it designed as one large module, with it designed in three modules, and with it designed in four modules. With the three module design, some of the satellite equipment was not modularized and remained attached to the satellite spaceframe. With the four module design, all electronic equipment is in modules.

The satellite design redundancy level was changed by varying the component redundancies associated with the MMS design. Satellite mean mission duration was varied from two to three to four years to test the economic value of these variations in design.

In all, 36 variations on the Landsat Follow-On design were provided in this study. Nine of the satellite designs were flown in all three modes of operation. The remaining 27 variations in satellite design were logistically flown and simulated for on-orbit service operation.

For those not familiar with the BRAVO analysis and study techniques, it is important to understand the basic approach. In order to compare systems, first the space system mission capabilities are made equal and then the space system risk (outage) is made as nearly equal between the two systems to be compared as is possible. The costs of two or more systems with equal mission capability and equal system risk are compared. The only criteria required is that the best system is the lowest cost system.

2. TERMINOLOGY

Spacecraft

The term spacecraft refers to the portion of the Landsat satellite on the Multimission Modular Spacecraft (MMS) side of the instrument module/MMS interface (see Figure 1-1).

Instrument Bay

The term instrument bay (or instrument module) refers to the portion of the Landsat forward of the interface (see Figure 1-1).

Satellite

The term satellite refers to the entire orbiting vehicle, spacecraft plus instrument bay.

On-Orbit Service Mode of Operation

In the on-orbit service mode of operation, the Landsat satellite and the Shuttle orbiter rendezvous and dock, and one or more of the following activities take place: failed instrument or spacecraft modules are replaced on the satellite; a worn out or wearing out instrument or spacecraft module is replaced; a failing module (that is, a module which has one or more redundant components failed) is replaced. The entire satellite is returned to the ground for refurbishing in the case where a failure is encountered in the non-modularized portion of the satellite. These on-orbit service flights are triggered either by a failure or by accumulating a full load of failing modules.

Ground Refurbishment Mode of Operation

In the ground refurbishment mode of operation, an orbiting satellite is replaced on orbit with a spare (usually a refurbished satellite). After a satellite is returned to the ground, six months are allowed for refurbishment.

Expendable Mode of Operation

In the expendable mode of operation, the satellite on orbit which suffers a failure is replaced by a new satellite from the ground. The simulation in this analysis procures the satellites in advance of the need for replacement so that there is no procurement delay.

Availability

Availability is the measure of the time the satellite is operating properly and equals the system up time divided by the system up time plus the system down time.

Landsat Follow-On Transitional Scenarios

When the Landsat D and D' are transitioning from Delta support to Shuttle support, either of two conditions are assumed to be the case. One Landsat D, D' satellite may be operating and the other recoverable for reuse; or one Landsat D, D' satellite may be operating and the other failed to an extent that the orbiter cannot recover it.

Landsat Follow-On Scenarios After Transitioning to the Space Shuttle

After transitioning to the Space Shuttle, the Landsat Follow-On satellite can be supported by the Shuttle assuming any of several different scenarios related to Shuttle user charges and flight scheduling practices.

1. Shuttle user charges assume flight sharing for all Landsat flights. This means that either an Office of Space Flight (OSF) or a satellite mission operations manager will arrange for shared flights and Shuttle user charges are on a flight-sharing basis.

2. The current OSF user charge system is assumed with the advance flight contracting and scheduling required and no flight sharing for Landsat Follow-On since the Landsat cannot use any of the standard orbits now proposed.

3. The current OSF user charge system is assumed with advance flight contracting and scheduling, but with the addition of the Landsat sun synchronous orbit as a flight-sharing destination. For this arrangement and scenario, the flight-sharing trip must be contracted for and scheduled at least 12 months in advance of the flight. If the user schedules the flight less than 12 months in advance, a full flight charge is made.

Shuttle Delay

Shuttle delay refers to the elapsed time between encountering a satellite failure and replacement of that satellite or its repair on orbit.

3. SUMMARY OF RESULTS

As was discussed in Section 1 (Introduction), the results and conclusions of this BRAVO study of the Landsat Follow-On Project are obtained by comparing the cost results with other systems characteristics held constant. In this study, the results discussed in this section were obtained by making these cost comparisons on primary tradeoff areas for the Landsat Follow-On Project when supported by the Space Shuttle. Additional results and sensitivity studies are discussed in Section 7. The many details of this effort are recorded in the Landsat Follow-On BRAVO Study Workbook, which is on file at The Aerospace Corporation.

All study results consider the first ten-year period of an ongoing (endless) Shuttle-supported period of operation following the second Delta Landsat Follow-On launch. The reusable satellite cases also assume that the Delta-launched satellites are reused. The plan is to operate the same instruments on orbit as near to continually as possible, on one satellite. A minimum availability figure which could be considered as satisfactory for the Landsat Follow-On satellite was set by Aerospace at 0.9.

Table 3-1 shows the study results for the Landsat Follow-On scenario after transitioning to the Shuttle, where shared Shuttle flight user charges are made for all Shuttle-supported Landsat Follow-On flights. For these data, the satellite mean mission duration (MMD) is three years. The Shuttle delay has been reduced until the system availability reaches at least 0.9. Shuttle delay is another term for the advanced scheduling or contracting for the flight. The satellite availability with six months Shuttle delay time was too low. Two months, the next increment investigated, was selected to make this comparison. The terms used in labeling

Table 3-1. Study Results - Effect of Satellite Logistics Mode, Shuttle Parking Orbits for a Ten-Year Period of Shuttle-Supported Operation with a Three-Year MMD Satellite, Availability ≥ 0.9, Shared Shuttle Flight User Charges

Mode of Operation				Number of Satellite Flights		Costs ($M)							Total Relative Cost Decrease (%)	
							Non-Recurring		Recurring					
Satellite Logistics (Satellite Design Used)	Shuttle Parking Orbit Altitude (km)	Availability	Shuttle Delay (Mo)	Retrieve & Refurbish To Establish Shuttle Supported System	Logistic Operations	Total Relative Costs	DDT&E Increment	Cost To Establish Shuttle Supported System(1)	Investment	Transportation	Satellite Refurb	Operations	Over Expend Mode	Over Ground Refurb. Mode
On-Orbit Service (3 Module Instrument Bay)	296	0.96	2	1.0	2.71	72	13	21	---	12	18	8	64	38
	705 x 185	0.96	2	1.0	2.71	67	11	19	---	11	18	8	66	40
	705	0.96	2	1.0	2.71	72	6	17	---	24	17	8	65	37
Ground Refurbish (Instrument Bay Not Modularized)	296	0.95	2	1.0	3.21	116	11	21	---	27	47	10	42	--
	705 x 185	0.95	2	1.0	3.21	112	10	19	---	27	46	10	43	--
	705	0.95	2	1.0	3.21	115	4	17	---	39	45	10	44	--
Expend (Instrument Bay Not Modularized)	296	0.96	2	---	3.23	201	8	37	119	27	--	10	--	--
	705 x 185	0.96	2	---	3.23	198	7	36	118	27	--	10	--	--
	705	0.96	2	---	3.23	205	4	36	116	39	--	10	--	--

(1). Assuming reuse of Delta-launched satellites this table are generally self-explanatory except for possibly the non-recurring cost and the total relative cost columns. These terms are defined in Section 6. The DDT&E cost increment is the development cost increase relative to the lowest cost satellite in this study. The cost to establish a Shuttle-supported system is essentially the cost to obtain the spare satellite on the ground, ready for launch. The total relative cost is the sum of all the non-recurring and recurring costs listed.

The purpose of Table 3-1 is to display the bottom-line numerical results of the BRAVO/Landsat Study assuming that the Landsat orbit can be a Shuttle standard mission orbit and that a way can be found to schedule shared flights on five months notice or less. The first two columns and the third column are inputs to the analysis. The information is included here to label the results of the design and analysis work which are shown in the remaining columns of the table.

The third column displays the satellite availability calculated for each case (row of data). Since the availability is primarily driven by the satellite mean mission duration (MMD) and the Shuttle delay in servicing or launching a replacement (see Figure 3-1), and these data are for satellite MMD = 3 years, the availability is primarily tied to the two month Shuttle delay.

The number of Shuttle flights for satellite logistics operations (see column six, Table 3-1) is that required to keep the satellite operating on orbit by countering: satellite random failures, satellite component wearout, depletion of expendables, or satellite infant mortality. The reduction of the number of flights to 2.7 from the on-orbit service case (from 3.2) is driven by a reduction in the number of flights required because of propellant depletion. Fewer flights are made solely for the purpose of renewing the propellant supply in the on-orbit service case. Truncated (with propellant below minimum) propulsion modules are renewed on flights triggered by random failures or accumulation of a full load of failing modules. That logistics action takes care of propellant limitations for on-orbit service; however, for expendable operations or ground-based refurbishment operations, propellant depletion (with propellant below minimum) triggers a flight.

The flight shown in the fifth column for the reusable satellite cases retrieves a satellite (previously launched on the Delta 3910 launch vehicle). The satellite is then refurbished on the ground and becomes the ground-based spare. The cost for obtaining this ground spare is shown in the ninth column under "non-recurring, cost to establish Shuttle supported system." It is much higher for the expendable satellite case since a new satellite is procurred and held for launch (as a spare).

The total relative costs for Landsat spacecraft, instruments, and transportation are reduced from $198M in an expendable mode to $68M for on-orbit service during the ten-year period (see Table 3-1). The reusable satellites save 43 to 66 percent of the total relative costs compared to expendable satellites. On-orbit service of the Landsat Follow-On satellite can save 29 percent of the total relative costs compared to the ground refurbishment mode of operation.

The lowest cost Shuttle parking orbit is the elliptical orbit with 185 km perigee and 705 km apogee. This is the result for any of the three modes of operation.

Table 3-2 displays similar data to that displayed in Table 3-1 (see discussion above). The Landsat Follow-On flight charges are for dedicated or full charge flights. For this scenario, the data show that the 705 km altitude parking orbit leads to the lowest total relative system costs, independent of the mode of operation of the satellite system. The cost of the additional satellite self-propulsion required to transfer from

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Table 3-2. Study Results - Effect of Satellite Logistics Mode, Shuttle Parking Orbits for a Ten-Year Period of Shuttle-Supported Operation with a Three-Year MMD Satellite, Availability ≥0.9, Dedicated Shuttle Flight User Charges

Mode of Operation				Number of Satellite Flights		Costs ($M)							Total Relative Cost Decrease (%)	
							Non-Recurring		Recurring					
Satellite Logistics (Satellite Design Used)	Shuttle Parking Orbit Altitude (km)	Availability	Shuttle Delay (Mo)	Retrieve & Refurbish To Establish Shuttle Supported System	Logistic Operations	Total Relative Costs	DDT&E Increment	Cost To Establish Shuttle Supported System(1)	Investment	Transportation	Satellite Refurb	Operations	Over Expend Mode	Over Ground Refurb. Mode
On-Orbit Service (3 Module Instrument Bay)	296	0.96	2	1.0	2.71	101	13	21	---	41	18	8	55	26
	705 x 185	0.96	2	1.0	2.71	97	11	19	---	41	18	8	56	27
	705	0.96	2	1.0	2.71	89	6	17	---	41	17	8	59	28
Ground Refurbish (Instrument Bay Not Modularized)	296	0.95	2	1.0	3.21	137	11	21	---	48	47	10	39	--
	705 x 185	0.95	2	1.0	3.21	133	10	19	---	48	46	10	40	--
	705	0.95	2	1.0	3.21	124	4	17	---	48	45	10	42	--
Expend (Instrument Bay Not Modularized)	296	0.96	2	---	3.23	223	8	37	119	49	--	10	--	--
	705 x 185	0.96	2	---	3.23	220	7	36	118	49	--	10	--	--
	705	0.96	2	---	3.23	215	4	36	116	49	--	10	--	--

(1) Assuming reuse of Delta-launched satellites

the lower parking orbits to the final 705 km altitude circular orbit (which is the satellite destination) cannot be offset by shared flight cost reductions available to the satellite project, as it was in the previous case (see Table 3-1). The cost of retrieving the Delta-launched satellite to be used for a ground spare is not treated as a dedicated flight. The cost savings for reusable modes of operation in this scenario are shown on the right in the table.

The data displayed in Table 3-2 also apply for the Landsat Follow-On scenario after transition to the Shuttle when flight-sharing user charges apply for only lower altitude parking orbits and only for a Shuttle delay time of greater than or equal to 12 months for Landsat Follow-On flights. These same full flight user charge data apply since the Shuttle delay required to obtain a reasonable system availability is less than 12 months.

Table 3-3 displays the cost increment (which turns out to be a cost increase) for reducing the satellite MMD from three years to two years for all three modes of operation. The table reflects dedicated Shuttle user charges in accordance with the last two scenarios discussed above. The 705 km Shuttle parking orbit was used for all data displayed in Table 3-3.

Figure 3-1 displays the effect of Shuttle delay on operational mode comparison. Again the ten-year period of Shuttle-supported operation is assumed. A flight-sharing user charge is assumed for flights scheduled 12 months or more in advance. This is the reason for the breaks in the cost curves shown at 12 months Shuttle delay in Figure 3-1. The availability plot in this figure shows that 0.9 availability can be obtained with Shuttle delays of five months or less.

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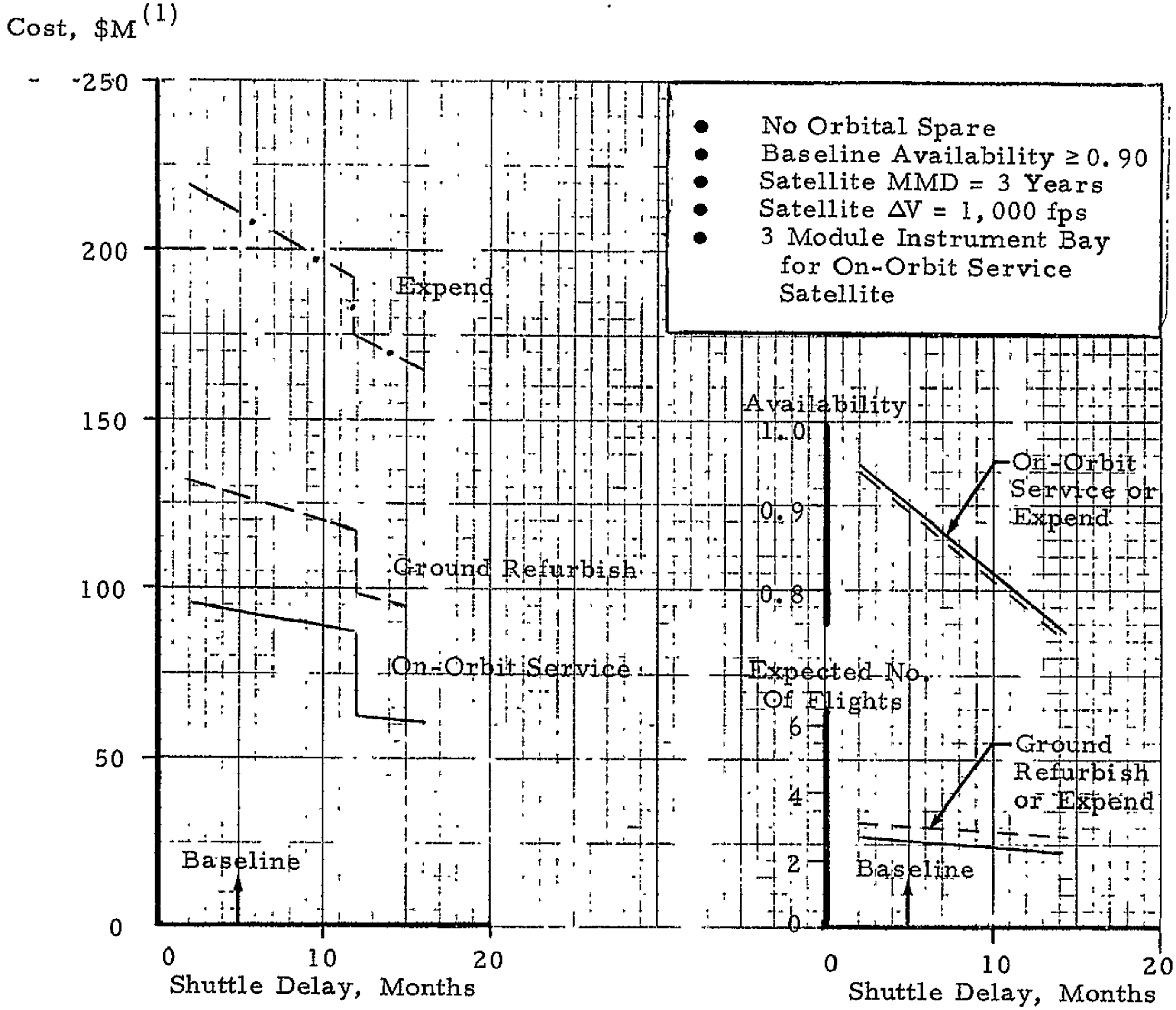
Table 3-3. Study Results - Comparison of Operating Modes
Ten-Year Period of Shuttle-Supported Operation
Availability ≥0.9, Dedicated Shuttle User Charges
705 x 185 km Shuttle Parking Orbit

Mode of Operation				Number of Satellite Flights		Costs ($M)							Total Relative Cost Decrease (%)	
							Non-Recurring		Recurring					
Satellite	Number Of Satellite Instrument Bay Modules	Availability	Shuttle Delay (Mo)	Retrieve & Refurbish To Establish Shuttle Supported System	Logistic Operations	Total Relative Costs	DDT&E Increment	Cost To Establish Shuttle Supported System(1)	Investment	Transportation	Satellite Refurb	Operations	Over Expend Mode	Over Ground Refurb. Mode
On-Orbit Service														
MMD = 2 Years	3	0.95	2	1.0	3.43	107	7	19	---	52	19	10	63	37
MMD = 3 Years	3	0.96	2	1.0	2.71	97	11	19	---	41	18	8	56	27
Ground Refurbish														
MMD = 2 Years	0	0.93	2	1.0	4.61	171	4	19	---	70	64	14	41	--
MMD = 3 Years	0	0.95	2	1.0	3.21	133	10	19	---	48	46	10	40	--
Expend														
MMD = 2 Years	0	0.94	2	---	4.65	288	3	37	164	70	--	14	--	--
MMD = 3 Years	0	0.96	2	---	3.23	220	7	36	118	49	--	10	--	--

(1) Assuming reuse of Delta-launched satellites



(1) Recurring Cost + DDT&E Increment

Figure 3-1. Effect of Shuttle Delay on Operational Mode Comparison Ten-Year Period of Shuttle-Supported Operation

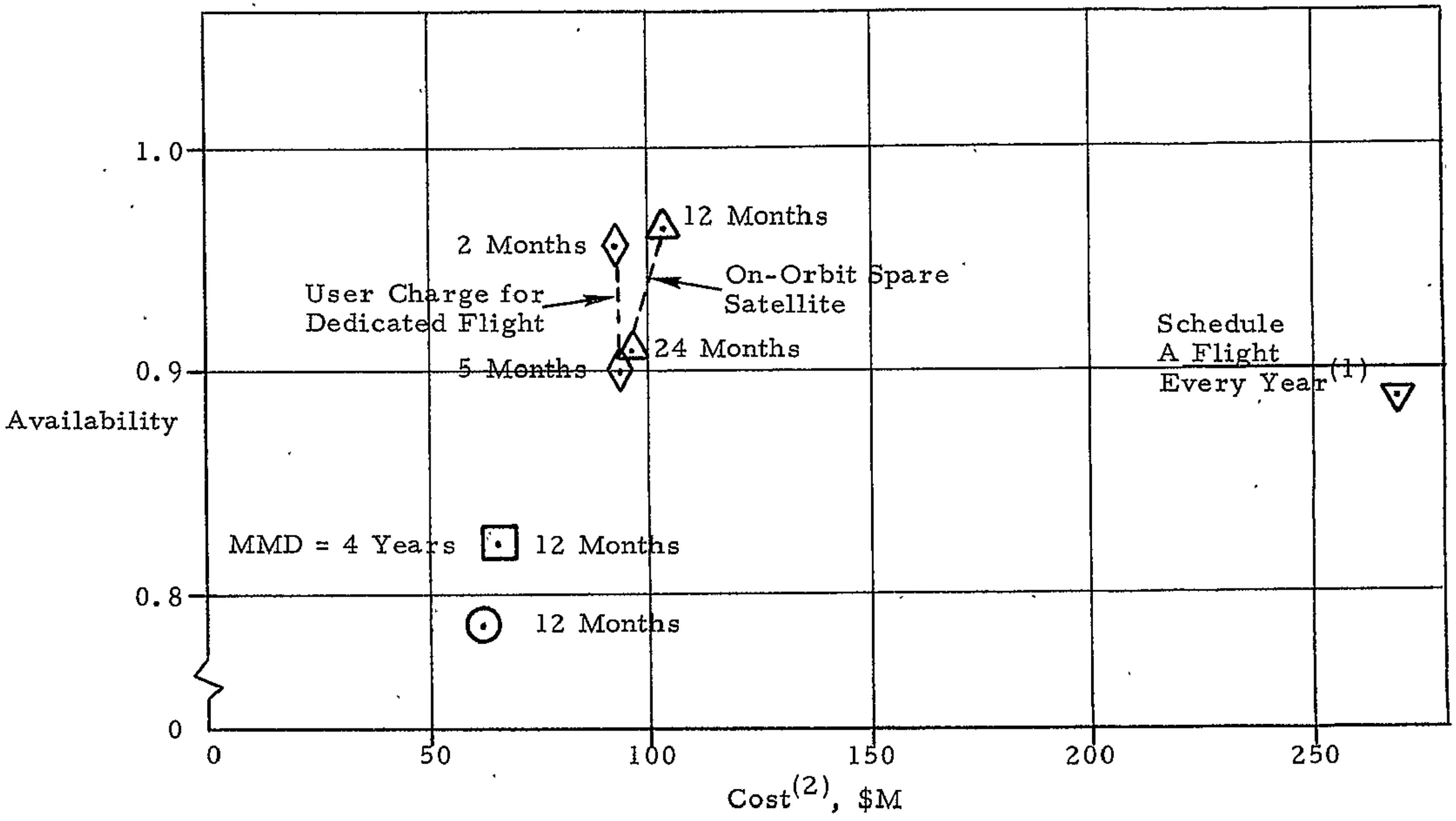
Figure 3-2 displays data which compares costs for the approaches available to the Landsat Follow-On satellite for increasing the satellite availability. The availability goal is 0.9 or greater. The data in Figure 3-2 show that a four-year MMD satellite has increased availability compared to the three-year MMD satellite, but the change does not result in satisfactory system availability. Another scheme for increasing availabilities would schedule flights on regular intervals, thus minimizing system down time without requiring call-up flights. Scheduling a flight every year will obtain close to 0.9 availability, but it is excessively expensive.

Another approach to increasing availability makes use of an on-orbit spare satellite. When the Landsat Follow-On satellite fails to perform, the spare takes over. However, this still increases the system cost for a ten-year operating period relative to paying for dedicated flights scheduled two to five months in advance. The additional funding for the on-orbit spare satellite case is "front end" money required for an additional satellite when the transition to Shuttle-supported operation takes place.

Table 3-4 displays data comparing the cost of the on-orbit service mode of operation as it is affected by the number of satellite bay instrument modules. The results show that completely modularizing the satellite instrument bay with four modules is the lowest cost approach. With four instrument bay modules, the lowest number of satellite flights result and the smallest amount of hardware is refurbished.

Figure 3-3 shows the effect of instrument life on the Landsat system cost and expected number of flights. The instruments being considered are the thematic mapper and the multispectral scanner. A dramatic increase in system cost is expected if the instrument life is limited to two or three years. It is recommended that components or operations which would limit the life of these instruments be avoided.

Note:
- All Data Points for Three-Year MMD Satellites Except as Noted
- Launch Delays Shown in Months
- Shared Launch Costs Except as Noted



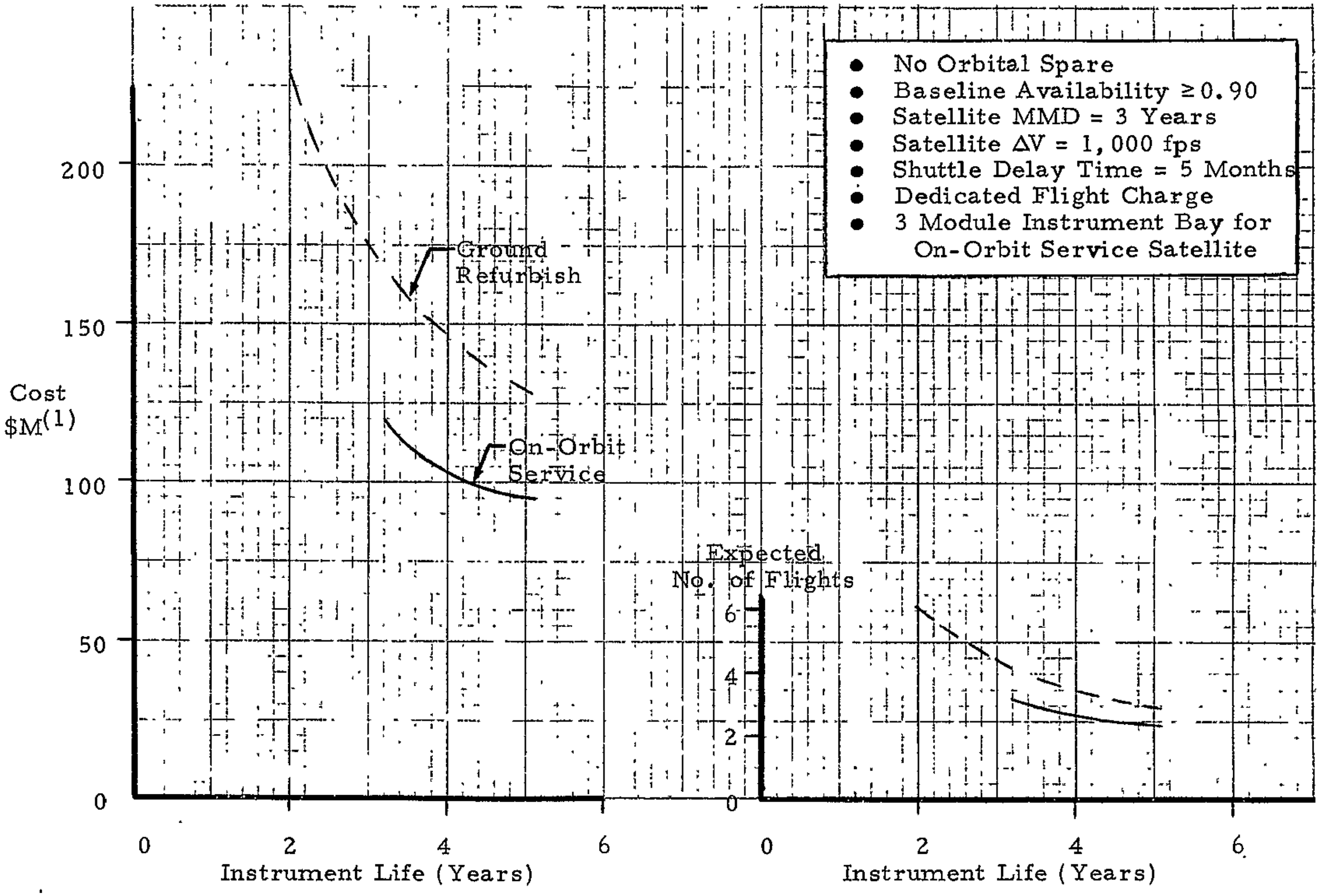
(1) Scheduled preventative maintenance mode.
(2) Total relative cost satellite + Shuttle user charge.

Figure 3-2. Cost Comparison of Alternative System Charges to Obtain Availability ≥ 0.9
Ten-Year Period of Shuttle-Supported Operation
Landsat Shuttle User Charges Shared Except When Launch Delay < 12 Months
On-Orbit Service Mode of Operation, 705 x 185 km Shuttle Parking Orbit

Table 3-4. Study Results - Effect of Instrument Bay Modular Configuration
Ten-Year Period of Shuttle-Supported Operation
Three-Year MMD Satellite, Availability ≤0.9
705 x 185 km Shuttle Parking Orbit
Shared Shuttle Flight User Charges

Mode of Operation				Number of Satellite Flights		Costs ($M)								
							Non-Recurring		Recurring					
Satellite	Number Of Satellite Instrument Bay Modules	Availability	Shuttle Delay (Mo)	Retrieve & Refurbish To Establish Shuttle Supported System	Logistic Operations	Total Relative Costs	DDT&E Increment	Cost To Establish Shuttle Supported System(1)	Investment	Transportation	Satellite Refurb.	Operations	Total Relative Cost Decrease(%) Over No Modules
On-Orbit Service	0	0.95	2	1.0	2.89	78	9	19	---	17	24	9	---
	1	0.96	2	1.0	2.62	84	10	19	---	9	38	8	---
	3	0.96	2	1.0	2.71	67	11	19	---	11	18	8	14
	4	0.96	2	1.0	2.41	62	11	19	---	9	15	8	20

(1) Assuming reuse of Delta-launch satellite.



(1) Recurring Cost + DDT&E Increment

Figure 3-3. Effect of Instrument Life on Landsat System Ten-Year Period of Shuttle-Supported Operation

4. SATELLITE DESIGNS

A number of Landsat Follow-On satellite designs were synthesized using the computerized satellite synthesis program described in Reference 1. The satellite synthesis computer program is modified for this application so that the satellite weights associated with the MMS could be estimated separately and tabulated separately from the satellite weights associated with the instrument bay. Techniques used broke down the spaceframe (structure, thermal protection, and wiring harness) weights between these two elements of the satellite. All satellites synthesized are Space Shuttle compatible. All satellites synthesized with no self-propulsion capability (i.e., $\Delta V = 0$ ft/sec) are Thor Delta 3910 compatible.

Figure 1-1 is from the May 1976 project plan draft for Landsat Follow-On and shows the profile for the Landsat Follow-On satellite. For this study, the baseline design achieved a three-year spacecraft mean mission duration using a 5.1-year design life for the satellite. A flexible solar array is incorporated. The satellite pointing accuracy equals 0.01 deg. The instrument bay for the baseline design has three modules, one for the thematic mapper, another for the multispectral scanner, and a third for the wideband data system.

Expendable satellites used in this study had a satellite self-transfer capability of 0, 500, and 750 ft/sec for the purpose of transferring from the optional Shuttle parking orbits to the final satellite destination. Ground refurbishment and on-orbit service satellites had self-propulsion capabilities twice those of the expendable satellites in order to make the round trip.

For the expendable and ground refurbishable satellites, the instrument bay is not modularized; only the multimission modular spacecraft (MMS) was modularized. However, for on-orbit service several modular instrument bay configurations were designed using the synthesis program. The weight statements resulting from these designs are shown in Table 4-1.

Variation in a satellite's mean mission duration (MMD) was accomplished by adding or deleting redundant components from the baseline three-year MMD design. The redundancy level for the instrument bay equipments remain constant for the two, three, and four-year MMD satellite designs. Table 4-2 displays the Landsat Follow-On spacecraft (MMS) design weights synthesized.

The Landsat Follow-On spacecraft (MMS) design weights shown in Table 4-2 are for no satellite self-propulsion capability ($\Delta V = 0$ ft/s These spacecraft designs were combined with instrument bay designs (those shown in Table 4-1), and the propulsion module replaced by a module design to have the appropriate propellant capacity and propulsion capability to achieve the desired ΔV. These combined spacecraft, instrument bay, and propulsion systems comprise the satellite designs used in this analysis. Representative synthesized designs are shown in Table 4-3.

Table 4-1. Landsat Follow-On Instrument Bay Design Weights, Effects of Modular Design of the Instrument Bay

Instrument Bay Weight Breakdown Item	Instrument Bay Weights (lbs.)			
	Non-Modular Bay	Bay Is One Large Module	Bay Has 3 Modules(1)	Bay Has 4 Modules(2)
Structure and Thermal	200	243	330	373
Electrical Distribution	221	241	280	300
Mission Equipment	898	898	898	898
Solar Array	120	120	120	120
Antenna	179	179	179	179
TOTAL	1618	1681	1807	1870

(1) The thematic mapper, multispectral scanner, and wideband data system are each designed as three modules. The TDRS transmitter, receiver front-end, and antenna, as well as the solar array, are not modular.

(2) All equipment is modularized.

Table 4-2. Landsat Follow-On Spacecraft (MMS) Design Weights, Effects of Increased Satellite Mean Mission Duration (MMD) through Redundancy Addition to Spacecraft, Satellite Self-Propulsion (ΔV) = 0 fps

Spacecraft Weight Breakdown Item	Spacecraft Weights (lbs.)		
	2 Year MMD	3 Year MMD	4 Year MMD
Structure and Thermal	388	415	443
Electrical Power	512	552	594
Communication and Data Handling	99	119	139
Attitude Control	243	278	312
Dry Propulsion	0	0	0
Main Propellant	0	0	0
Reaction Control System, Dry	29	38	47
RCS Propellant	69	78	86
TOTAL	1340	1480	1621

Table 4-3. Landsat Follow-On Satellite Design Weights (BRAVO Synthesized Designs Selected as Representative of Those Used in This Study)

Satellite Elements	Weight (lb)			
	Non-Modular Instrument Bay 2 Year MMD	Instrument Bay Has 3 Modules		
		2 Year MMD		4 Year MMD
	ΔV = 1000 fps	ΔV = 0 fps	ΔV = 1500 fps	ΔV = 1500 fps
Spacecraft (MMS)[1]	1340	1340	1340	1621
Instrument Bay	1618	1807	1807	1807
Propulsion[2]				
Propellant	(615)	0	(1160)	(1360)
Dry Weight	(360)	0	(679)	(799)
Subtotal	975	0	1839	2159
Total	3933	3147	4986	5587

[1] With no self-propulsion capability (ΔV = 0 fps)

[2] Satellite self-propulsion capability (ΔV > 0 fps)

5. SHUTTLE ACCOMMODATION AND USER CHARGES

The Shuttle user charges for the Landsat Follow-On satellite were calculated for this study for two different sets of conditions. The first set of conditions assumes that the Landsat Follow-On satellite is launched on dedicated Shuttle flights and serviced on dedicated Shuttle flights. The second set of conditions assumes that the Office of Space Flight proposed Shuttle user charge policy is applied but in a modified form. The user charge policy for shared flights assumed was that which existed in September 1976. The basic shared flight charge provision is shown in Figure 5-1.

In order to calculate the cost of individual payloads transported on a flight shared with other payloads, the following steps are required:

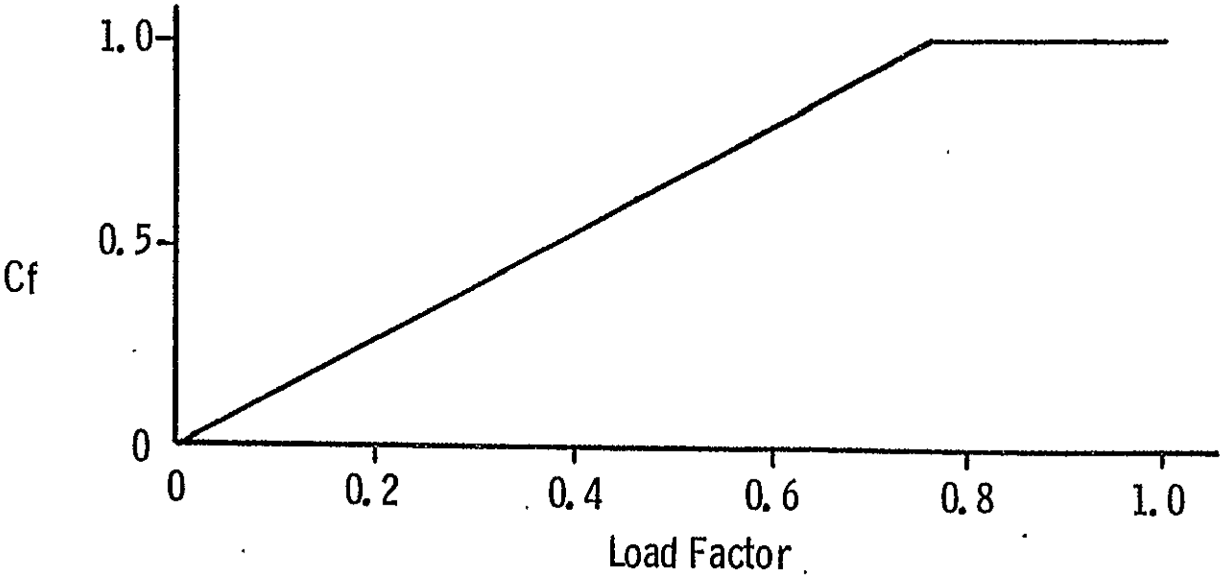
1. Find the load factor for the payload by dividing the payload weight by the Shuttle capability for the desired inclination (Table in chart)
2. Find the load factor for the payload by dividing the payload length by 60 ft
3. Enter the curve (chart) at the higher value obtained from Steps 1 and 2 and read the Cf from the curve
4. Multiply the Cf value times the quoted price per flight; this will result in the price for the payload flight.

The price for each payload flight (Step 4) entitles the user to be provided a prorated share of the facilities available on board the standard Shuttle flight, e.g., if the payload load factor is 0.5, then the payload is entitled to 50 percent of the power, cooling, and other services provided on the standard flight. Standard services required that exceed the prorated share will be an additional charge to the user based on the cost of the service provided.

$$\text{Price/Payload Flight} = \text{Cf} \times \text{Price/Flight}$$

$$\text{Load Factor} = \frac{\text{Payload Weight}}{\text{Shuttle Cap}} \quad \text{Or} \quad \frac{\text{Payload Length}}{60}$$

Whichever is Larger



Shuttle Cap	
Incl °	Wt. K #
28.5	65
56	57
90	40
104	32

Figure 5-1. Shared Flight Charge. 160 nmi

Billing Schedule

Contract Initiation	Payment due, percent		
	3 yr before scheduled launch date	2 yr before scheduled launch date	1 yr before scheduled launch date
3 to 5 yr before scheduled launch date	20	35	45
2 yr before scheduled launch date	--	58	45
1 yr before scheduled launch date	--	--	112

The modifications considered for the purposes of showing effects on the Landsat follow-on program for this study assume separately the following possible changes to the shared flight provisions in the user charge policy:

1. The 98.2 deg inclined Shuttle orbit is included as a flight-sharing orbit.
2. An elliptical parking orbit (100 nmi perigee and 385 nmi apogee) is considered in addition to the 160 nmi circular parking orbit.
3. Flights scheduled less than one year in advance of the launch date are considered including the 12 percent penalties shown in the billing schedule or one year scheduling before launch.

In this study the average cost or average price per Shuttle flight for the 10-year period 1983 through 1992 is estimated at $13.5 million for NASA payloads. If the 112 percent billing schedule is used, the average cost per flight is $15.1 million. The $13.5 million per Shuttle flight figure was arrived at using data from Reference 2. This reference shows that the average cost per Shuttle flight chargeable to non-NASA users is estimated to be $15M in 1975 dollars. If the estimates for facilities and equipment depreciation which are not applicable to NASA payloads are removed and the prices adjusted for the difference between 1975 and 1976 dollars, the $13.5M figure results.

For shared flights, typical charges per satellite flight used in this study are shown in Table 5-1. The charges shown are for three-year MMD satellites. The charges are slightly less for two-year MMD satellites when the charge is based on weight (W after user charge in Table 5-1). For four-year MMD satellites, these charges are slightly greater. When the charges are based on length (L after user charge quoted in Table 5-1), the charge does not vary with different MMDs. Satellite weights used in determining these user charges came from the satellite design synthesis described in Section 4. In addition to the satellite, the Landsat equipment in the Shuttle may include a satellite positioning platform, retention cradle, module exchange mechanism, and module magazine. The dimensions and weights of these equipments were supplied by Goddard Space Flight Center (Reference 3).

Table 5-1. Shuttle Shared Flight Charges, $M (1976)
3 Year MMD Satellites
$13.5M Per Shuttle Flight (1983-1992 Average)
112% Billing for 12 Months Notice In Advance of Flight Date

Satellite Transfer Cap (ΔV in fps)	Number of Satellite Modules	Shared Flight User Charge[1]		
		Deploy or Deploy/Retrieve[2]	On-Orbit Service One Orbiting Landsat[3]	On-Orbit Service Two Orbiting Landsats[3]
0	4	12.2 (W)	--	--
500	4	8.4 (L)	--	--
750	4	8.4 (L)	--	--
0	4	12.2 (W)	7.3 (W)	3.9 (W)
1000	4	8.4 (L)	3.0 (W)(4)	1.9 (W)
1500	4	8.4 (L)	3.1 (W)	2.2 (W)
0	7	--	8.2 (W)	4.4 (W)
1000	7	--	3.3 (W)	2.2 (W)
1500	7	--	3.6 (W)	2.5 (W)
0	5	--	9.3 (W)	4.6 (W)
1000	5	--	3.4 (W)	2.6 (W)
1500	5	--	4.3 (W)	2.9 (W)

Notes: (W) - User charge determined by cargo weight.
(L) - User charge determined by cargo length.

(1) User charge per satellite on orbit.

(2) Cargo includes positioning platform and retention cradle.

(3) Cargo includes positioning platform + module exchange mechanism + magazine. Length of equipment installed in the payload bay = 8.5 ft.

(4) If the length of the positioning platform + module exchange mechanism + module magazine increases from 8.5 ft to 10.5 ft, the user charge is determined by cargo length and increases to $3.5M per service.

6. COST ESTIMATING

6.1 DEFINITION OF COST TERMS

In discussing the cost estimates for the Landsat Follow-On project and presenting the results of this study, several terms are used as defined below:

1. DDT&E Cost Increment - The DDT&E cost increment equals the satellite DDT&E cost estimate minus the reference satellite DDT&E cost estimate. For this study the reference satellite is the two-year MMD expendable satellite design with no self-propulsion capability ($\Delta V = 0$ ft/sec) when considering DDT&E costs. This satellite was selected as the reference since it is the lowest cost satellite to develop used in this study, thus making all DDT&E cost increments positive.

2. Cost to Supported System - The cost to establish a Shuttle-supported system is sometimes termed "transition costs." It consists of the cost of acquiring the ground spare or spares, the cost of purchasing propulsive modules required for satellites already placed on orbit by the Thor Delta 3910 launch vehicle, and the cost of ancillary equipment peculiar to the Shuttle operation.

    a. The cost of acquiring ground spares mentioned above consists of the cost estimate for refurbishing or purchasing new ground spare satellites or modules acquired for the purpose of logistics support during Shuttle operations.

    b. The cost of MMS/Shuttle ancillary equipment is assumed to be negligible since it is scheduled for development and purchase by previous MMS projects.

3. Relative Non-Recurring Costs - The relative non-recurring costs are the sum of 1 and 2 above, i.e., the sum of the DDT&E cost increment and the cost to establish the Shuttle-supported system.

4. Recurring Costs - The recurring costs for this study include the satellite unit investment or procurement costs, the transportation costs (Shuttle user charges), cost estimates for satellite and/or module refurbishment, and satellite operations cost estimates covering the launch and initialization period for the satellite.

5. Total Relative Costs - The total relative costs equal the sum of the cost estimates for items 3 and 4 above, namely the sum of the recurring costs and the relative non-recurring costs.

6.2 COST ESTIMATES

The input data used in cost estimating were obtained from the satellite design synthesis data described in Section 4. As discussed in Section 4, the spacecraft weight information was separated from the instrument bay weight information; this enables cost estimating to be done on each of these elements of the satellite separately. The first step was to make cost estimates on the spacecraft and instrument bay portions of each of the satellites at the subsystem level and sum them for these elements. This was accomplished for the DDT&E costs and the average unit cost using the methodology and techniques described in Reference 1. The resulting cost estimates were reviewed and it was found that the spacecraft or MMS portion of the unit costs, although consistent in themselves, were a factor of 2 higher than the more detailed GSFC estimates made for the MMS satellite unit recurring cost considering the low-cost approaches being used in this design. Contributing to the low cost expected for the MMS units will be the cost benefits derived from modularization of the spacecraft subsystems and the use of standard NASA components and other space-qualified hardware in the satellite design. The basic spacecraft unit recurring costs were all reduced by a factor of 2 to complete the second step in the cost estimating procedure.

The third step in the cost estimating procedure was to estimate the cost differences associated with satellite self-propulsion (ΔV). The cost estimate made in a much more detailed manner at the component level in Reference 3 was compared to the estimates for similar units in this study and found to be in agreement.

As a fourth step, the spacecraft and instrument bay and propulsion system costs are combined to make up the satellite costs shown in Table 6-1. The spacecraft costs are listed in columns 3 through 6 and the instrument bay costs in columns 7 through 10. The last column lists the average total unit costs for the entire satellite. Similar costs were developed for satellites with two-year MMDs and four-year MMDs.

Table 6-1. Landsat Follow-on Satellite Typical Cost Estimate, $M (1976)
Three-Year Mean Mission Duration Satellites

Satellite Trans. Cap. (ΔV in fps)	Number Of Satellite Modules	Spacecraft (MMS)(1)				Instrument Bay				Average Unit Total
		DDT&E Increment(2)	Average Unit	Average Per Module	NRU	DDT&E Increment(2)	Average Unit	Average Per Module	NRU	
0	4	4.4	9.0	2.04	0.89	0	26.9	0	26.9	35.9
500	4	7.4	9.5	2.15	↓	↓	↓	↓	↓	36.4
750	4	8.4	9.8	2.23	↓	↓	↓	↓	↓	36.7
0	4	4.4	9.0	2.04	↓	0	26.9	0	26.9	35.9
1000	4	9.4	10.2	2.33	↓	↓	↓	↓	↓	37.1
1500	4	10.8	10.8	2.48	↓	↓	↓	↓	↓	37.7
0	7	4.4	9.0	2.04	↓	1.9	27.4	6.88	6.75	36.4
1000	7	9.4	10.2	2.33	↓	↓	↓	↓	↓	37.6
1500	7	11.5	11.0	2.53	↓	↓	↓	↓	↓	38.4
0	5	4.4	9.0	2.04	↓	0.5	27.1	27.1	0	36.1
1000	5	9.4	10.2	2.33	↓	↓	↓	↓	↓	37.3
1500	5	11.5	10.8	2.48	↓	↓	↓	↓	↓	37.9

(1) Including propulsion.
(2) Increment from two-year MMD design with $\Delta V = 0$ and 4 modules.

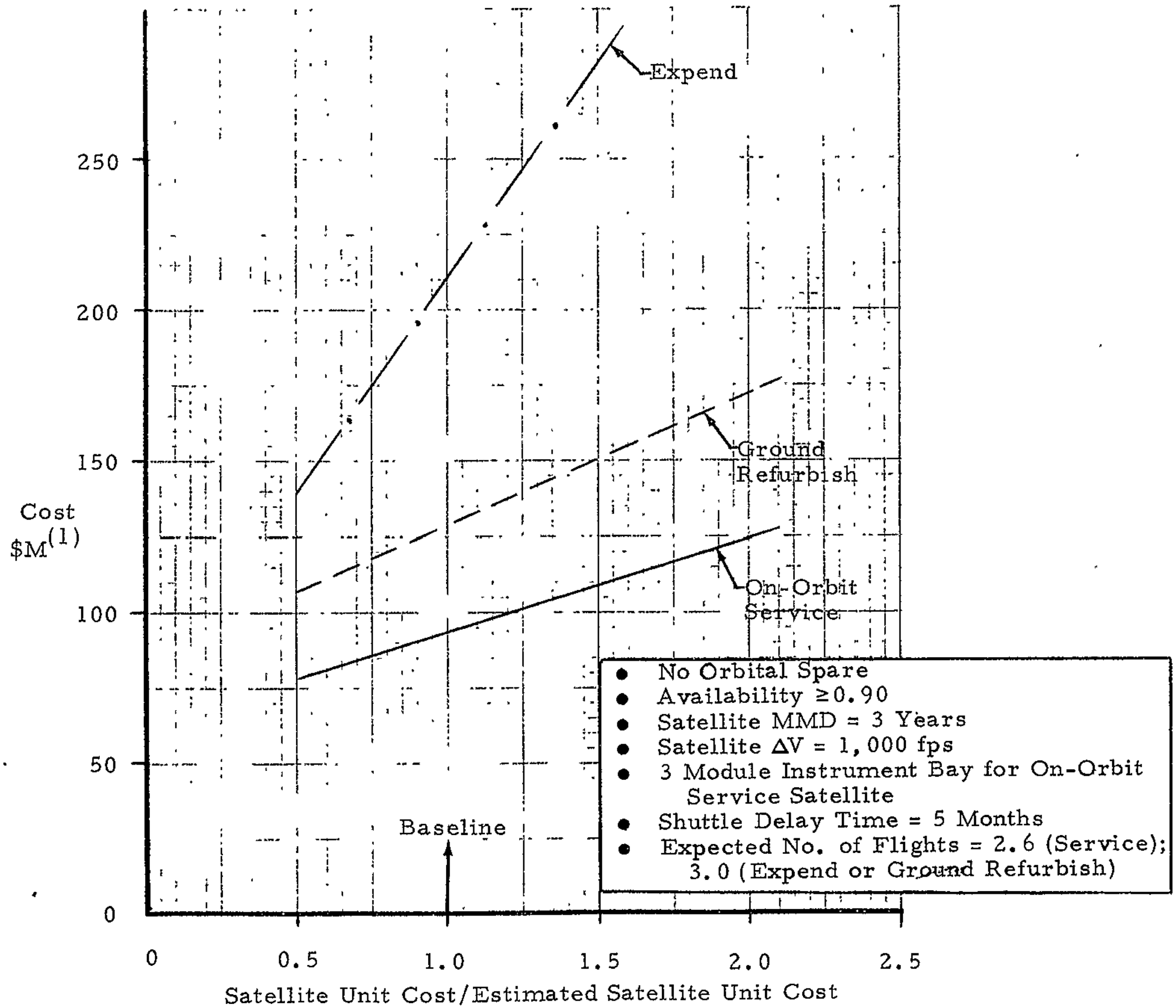
7. LOGISTICS, TRAFFIC, AND RISK ANALYSIS

Cost data used in the logistics analysis was furnished as a result of the cost estimating reported in Section 6 and the Shuttle accommodation and user charge analysis reported in Section 5. In the Logistics, Traffic, and Risk Analysis, a computer program implementing a set of techniques developed and reported in Reference 1 is used to calculate the traffic to and from orbit and sum the costs for the payloads and transportation. In order to simulate and track the MMS and instrument bay modules separately in the Landsat Follow-On satellite, the computer program for on-orbit service was rewritten for this study. The cost of procurring and refurbishing the instrument bay modules is much greater than that encountered in the case of the MMS modules. Thus, in order to keep the analysis accurate, the computer program was required to differentiate between the two modules. The traffic for each was estimated separately and the costs were separately accumulated. This is the first time in our experience that this type of calculation has been made with two distinct types of modules.

One spare satellite was maintained on the ground for all modes of operation studied. In addition, normal spare parts supplies are on hand. At the end of the first ten years of operation, a ground spare is available (and ready to fly) in support of the continuing Landsat Follow-On operation.

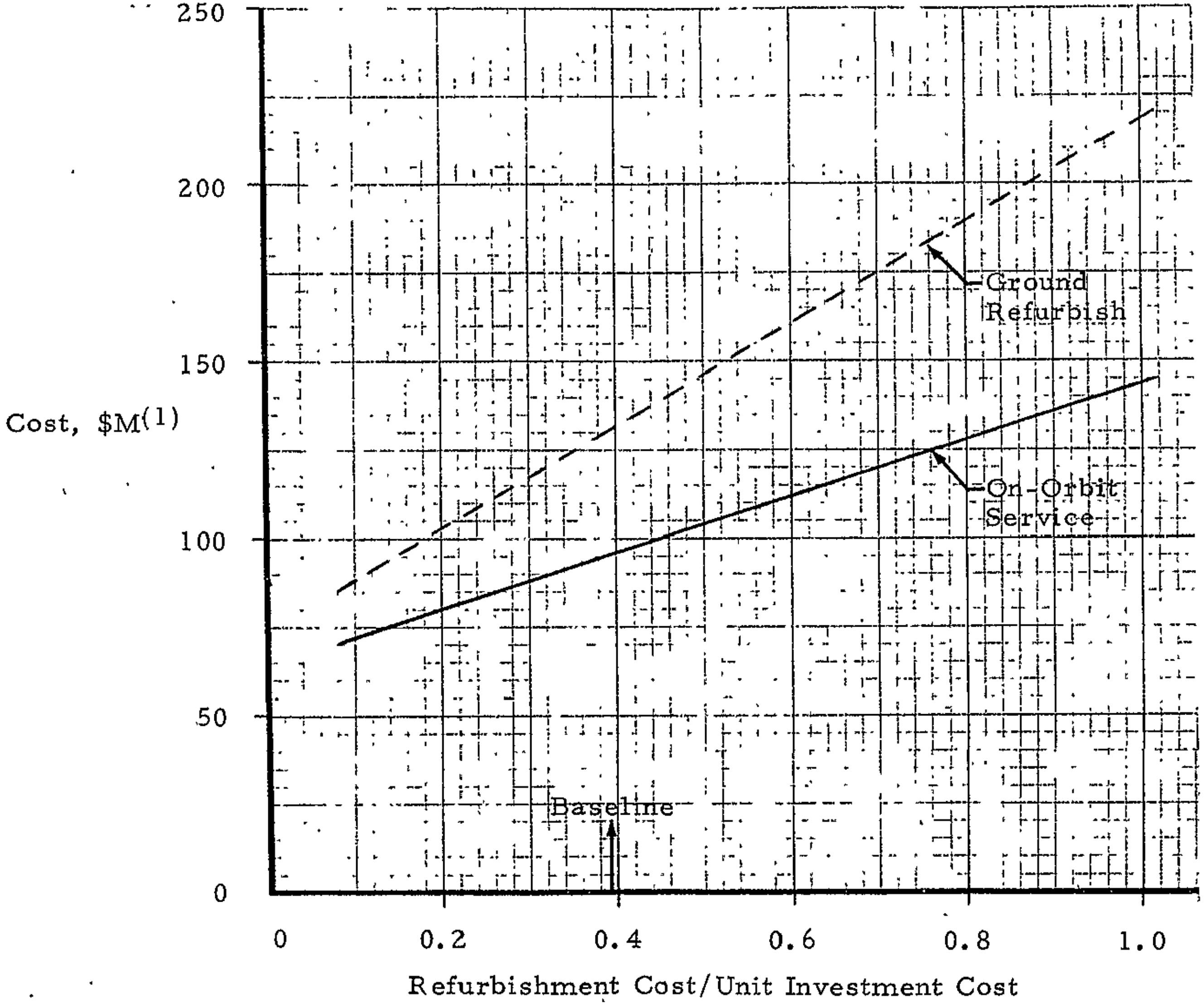
The Logistics, Traffic, and Risk Analysis is the final step in the BRAVO analysis for the Landsat Follow-On and results in the data and information shown and discussed in Section 2 of this report. In addition, sensitivities of the results of this study to certain input information were checked using these computerized techniques. The results are self-explanatory and are displayed in Figures 7-1 through 7-4. The effect on total relative cost (recurring cost plus the DDT&E increment) is shown for variations in user charge, satellite unit procurement costs, satellite refurbishment cost ratio, and transportation costs. Dedicated Shuttle flight user charges are assumed corresponding to current user charge policy for the maximum Shuttle delay which can be tolerated (five months) and still obtain a system availability greater than or equal to 0.9.

The results of the sensitivity analysis do not alter the basic finding of the study; that the best way to operate the Shuttle/Landsat Follow-On system in the Shuttle era is with on-orbit service.



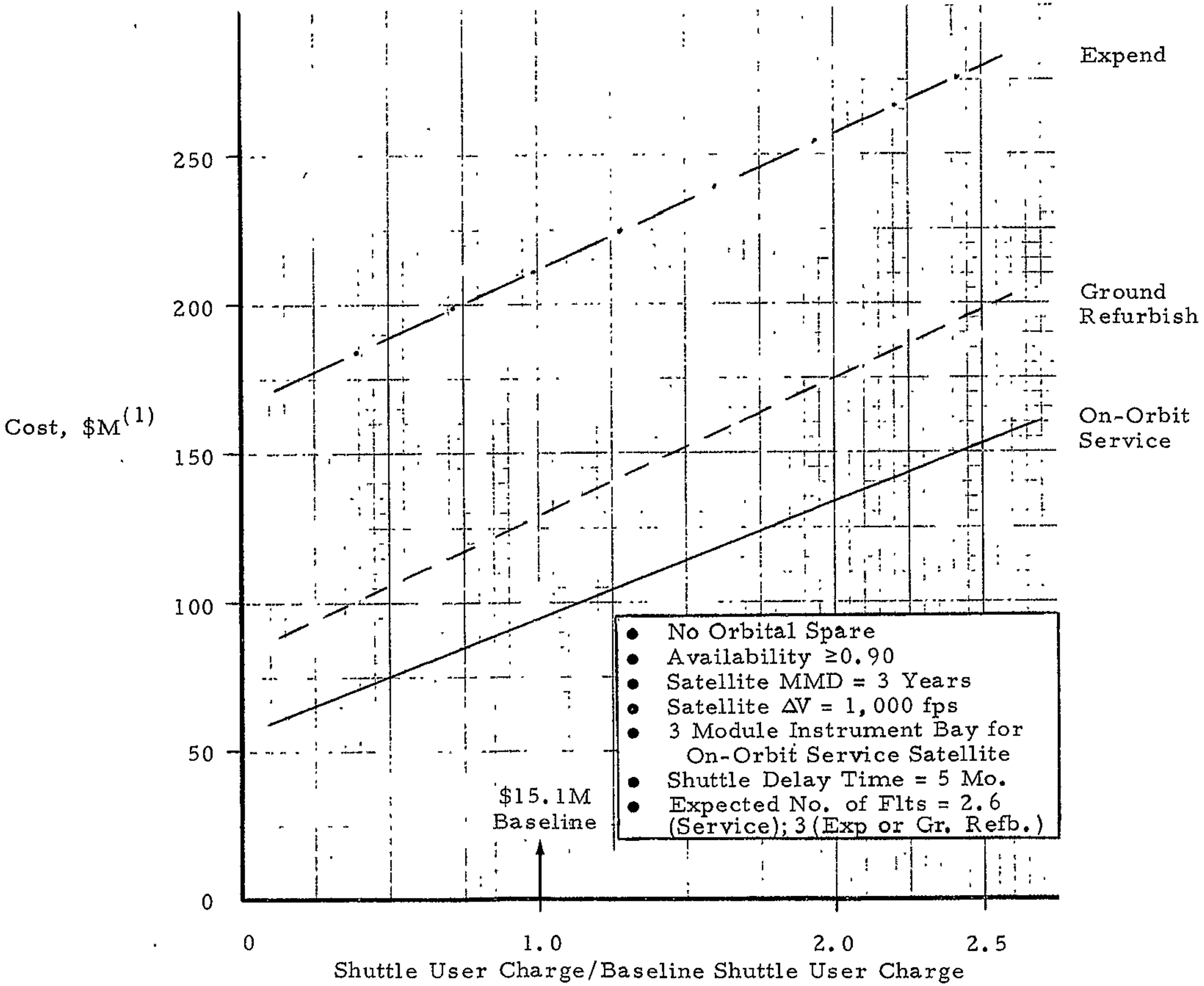
(1) Recurring Cost + DDT&E Increment

Figure 7-1. Effect of Satellite Unit Investment Cost on Operational Mode Comparison Ten-Year Period of Shuttle-Supported Operation



(1) Recurring Cost + DDT&E Increment

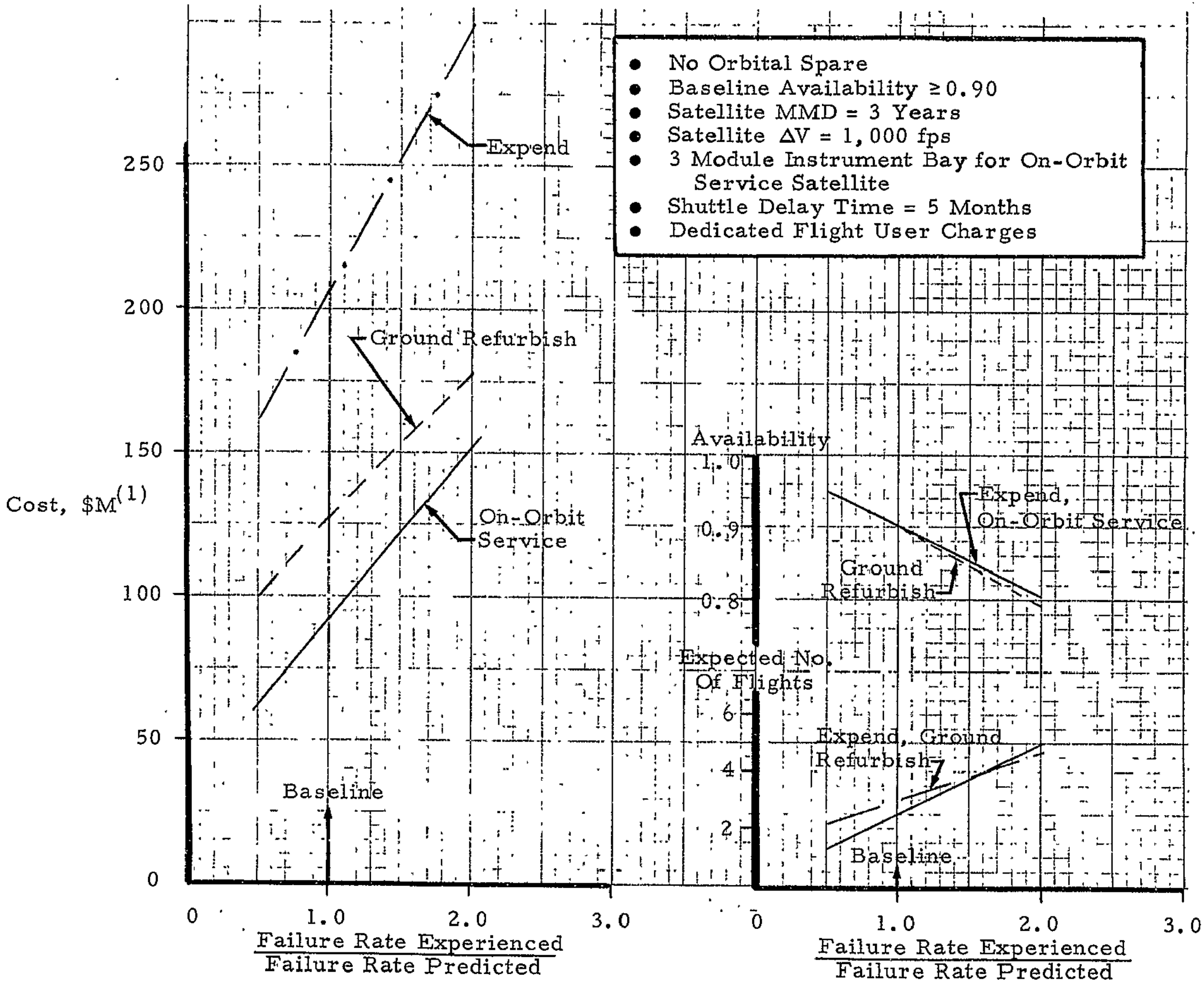
Figure 7-2. Effect of Refurbishment Cost on Operational Mode Comparison Ten-Year Period of Shuttle-Supported Operation



- No Orbital Spare
- Availability ≥0.90
- Satellite MMD = 3 Years
- Satellite ΔV = 1,000 fps
- 3 Module Instrument Bay for On-Orbit Service Satellite
- Shuttle Delay Time = 5 Mo.
- Expected No. of Flts = 2.6 (Service); 3 (Exp or Gr. Refb.)

(1) Recurring Cost + DDT&E Increment

Figure 7-3. Effect of Shuttle User Charge on Operational Mode Comparison Ten-Year Period of Shuttle-Supported Operation



(1) Recurring Cost + DDT&E Increment

Figure 7-4. Effect of Satellite Failure Rate Ratio on Operational Mode Comparison Ten-Year Period of Shuttle-Supported Operation

8. RECOMMENDATIONS FOR ADDITIONAL EFFORT

A plan should be developed for operating a sun synchronous orbit spaceline featuring repeated use of the same sun synchronous orbits for many sun synchronous payloads (i.e., Landsats, weather satellites, test satellites, Explorer satellites). The plan should consider the transportation cost savings available and the instrument compromises and operating compromises required for the satellite projects.

Consideration should be given to finding the best approach to providing for Landsat (and possibly other Shuttle users) to fly when satellite failure is encountered. These flights are contingent upon encountering a satellite failure requiring repair and will be needed within two to five months of the failures occurrance. How these contingency flights are to be handled is the problem. For instance, should STS operations reserve a few contingency flights per year for use by several projects, or should Landsat schedule flights and cancel, advance, or delay launch dates according to their needs?

Further study is needed in the area of refurbishment of satellites and satellite modules. This study should be made for the purpose of developing an optimum plan for MMS satellites in this regard. Make or buy refurbishment services should be considered. Common refurbishment requirements between satellite projects and unique refurbishment requirements need to be considered.

9. SUMMARY OF RELATED STUDIES

Other studies have been made by Aerospace on NASA observatory satellites supported by the Shuttle. These studies included other satellite projects in addition to Landsat and considered project cost changes due to satellite standardization. The study results are summarized below for the reader's convenience.

9.1 ECONOMIC ANALYSIS OF GSFC EARTH OBSERVATION SATELLITE (EOS)/SHUTTLE MISSIONS

A recent study was made on the best way to operate earth observatory-type satellites with the Space Shuttle (Reference 4). The study considered the relative costs of multiple mission (standardized) spacecraft and custom-built spacecraft. The study also considered the costs of maintaining the observatories when satellite failure or end of life is encountered.

On-orbit service (by visiting the satellite on orbit with the Shuttle), retrieval and ground refurbishment of the entire satellite, and replacing a failed satellite with a new one were the three logistics modes considered. The study showed that the Multimission Modular (standard) Spacecraft saves significant non-recurring (i.e., DDT&E or development) cost. The study also showed that the best (lowest cost) way to keep each observatory going on a continuous basis is on-orbit service.

Reference 4 reported on the economics of the low altitude observatory missions shown in Table 9-1 when supported by the Space Shuttle. The instruments and orbits for each mission were specified. The instruments were updated approximately every four years. The satellite outage was made approximately the same, thereby leaving the cost as the only open quantity or variable for making comparisons. Thus the criteria is that the lowest cost system (which also turned out to be the system with the lowest net present value) is the best.

Table 9-1. Low Altitude Missions Used in Economic Study of Multimission Modular (Standardized) Spacecraft

Mission	Number of Satellites In Orbit In Shuttle Era
Earth Resources (Landsat)	2
Water Resources, Pollution, and Commodity Predictions	1
Ocean Dynamics (Seasat)	2
Weather and Climate	2

The non-recurring (DDT&E) cost shows a significant reduction, due to the use of already-qualified modules on the additional projects (see Table 9-2). The original development cost of the standard modules is split equally between the missions. The cost estimates for new developments and modifications are added on for each mission. There is little difference between the average recurring (unit procurement) costs of standard and non-standard spacecraft. The reduction in cost for quantity production on standard spacecraft offsets the higher first article cost (which is due to overdesign or overkill) for the particular mission.

The search for the best way to operate these missions on a continuing basis is also reported in Reference 4. Comparisons are displayed in the last column of Table 9-3 as the ratio of mission costs. The ratio of the cost to establish and operate the mission identified in the first column and operated as described in the second column, to the cost to establish and operate the same mission in an expendable mode is shown. The cost to establish and operate includes the recurring costs for a period of nine years for transportation, satellite unit procurement, satellite refurbishment, launch support, and initial operation. For the average mission, the costs for on-orbit service are 62 percent of those for expendable satellite operation, a savings of 38 percent, or over 400 million dollars for these four missions alone. The savings for ground refurbishment came largely from reuse of the satellites. The savings for on-orbit service came from optimized reuse of the satellites. The reuse is optimized by returning the failed, failing, or worn-out modules for refurbishment and reuse. The entire satellite is replaced only in the infrequent case where a failure is encountered in the non-modular or non-replaceable part of the satellite.

9.2 ECONOMIC ANALYSIS OF 1960-1979 U. S. OBSERVATORY-TYPE SATELLITES (WHAT IF THESE PROJECTS HAD USED THE SPACE SHUTTLE)

The cost reduction power of the two concepts discussed in this section: (1) standardization of spacecraft modules to achieve reduction of

Table 9-2. The Effects of Standardization on Satellite Non-Recurring (DDT&E) Costs

Mission	% Savings in DDT&E Cost Due to Standardization
Earth Resources (Landsat)	50
Water Resources, Pollution, and Commodity Prediction	54
Ocean Dynamics (Seasat)	36
Weather and Climate	36

Table 9-3. Comparison of Satellite System Logistics Modes

Mission	Satellite Logistics Mode of Operation	Satellite Availability	Number of Satellite Launches	Cost to Establish And Operate Relative to Expendable Mode
Earth Resources (Landsat)	Expend	0.90	9.4	1.00
	Ground Refurbish	0.86	9.3	0.76
	On-Orbit Service	0.92	6.6	0.57
Water Resources, Pollution, and Commodity Prediction	Expend	0.92	5.7	1.00
	Ground Refurbish	0.90	5.6	0.74
	On-Orbit Service	0.90	6.5	0.65
Ocean Dynamics (Seasat)	Expend	0.86	10.7	1.00
	Ground Refurbish	0.79	10.4	0.71
	On-Orbit Service	0.83	10.8	0.63
Weather and Climate	Expend	0.88	10.0	1.00
	Ground Refurbish	0.85	9.9	0.83
	On-Orbit Service	0.84	11.0	0.63
Average:	Expend	0.89	9.0	1.00
	Ground Refurbish	0.85	8.8	0.76
	On-Orbit Service	0.87	8.7	0.62

non-recurring (satellite development) costs, and (2) on-orbit service (remove and replace modules on orbit) to optimize satellite logistics, is phenomenal. It is illustrated by estimating (based on Reference 4) the savings which could have been made in U.S. observatory-type satellites of the 1960s and 1970s had these concepts and the Space Shuttle been used. Costs could have been reduced by 1.8 billion dollars (see Table 9-4), considering the following NASA projects and postulating ten years of operation for each project:

1. Earth Resources Technology Satellite (ERTS)/Landsat
2. High Energy Astronomical Observatory (HEAO)
3. Weather Satellites (TIROS/TOS/ESSA/ITOS/NOAA)
4. Orbiting Geophysical Observatory (OGO)
5. Orbiting Solar Observatory (OSO)
6. Orbiting Astronomical Observatory (OAO)
7. Nimbus
8. Seasat
9. Advanced Technology Satellite (ATS)
10. Explorer

The first nine projects are postulated to have used the Multimission Modular Spacecraft (MMS), as well as four Explorer series missions. As shown in Figure 9-1, this spacecraft is designed such that all its electronic subsystems are packaged in removable drawers or modules which can individually be removed and replaced in orbit for purposes of repair and/or life extension of the mission.

Table 9-4. Estimate of Automated Satellite Cost Reductions with Shuttle Operation, On-Orbit Service Operations, and Multimission Modular Spacecraft (MMS or SMMS)

Cost Category	Satellite Cost Estimates (Billions of 1976 Dollars)		Cost Reduction Driver
	Cost	Reduction	
DDT&E	1.9	0.8	Satellite Standardization
Unit Procurement, Refurbishment, and Operations	2.8	1.0	Fewer Satellite Modules Flown, Many Modules Reused
Total	4.7	1.8	———

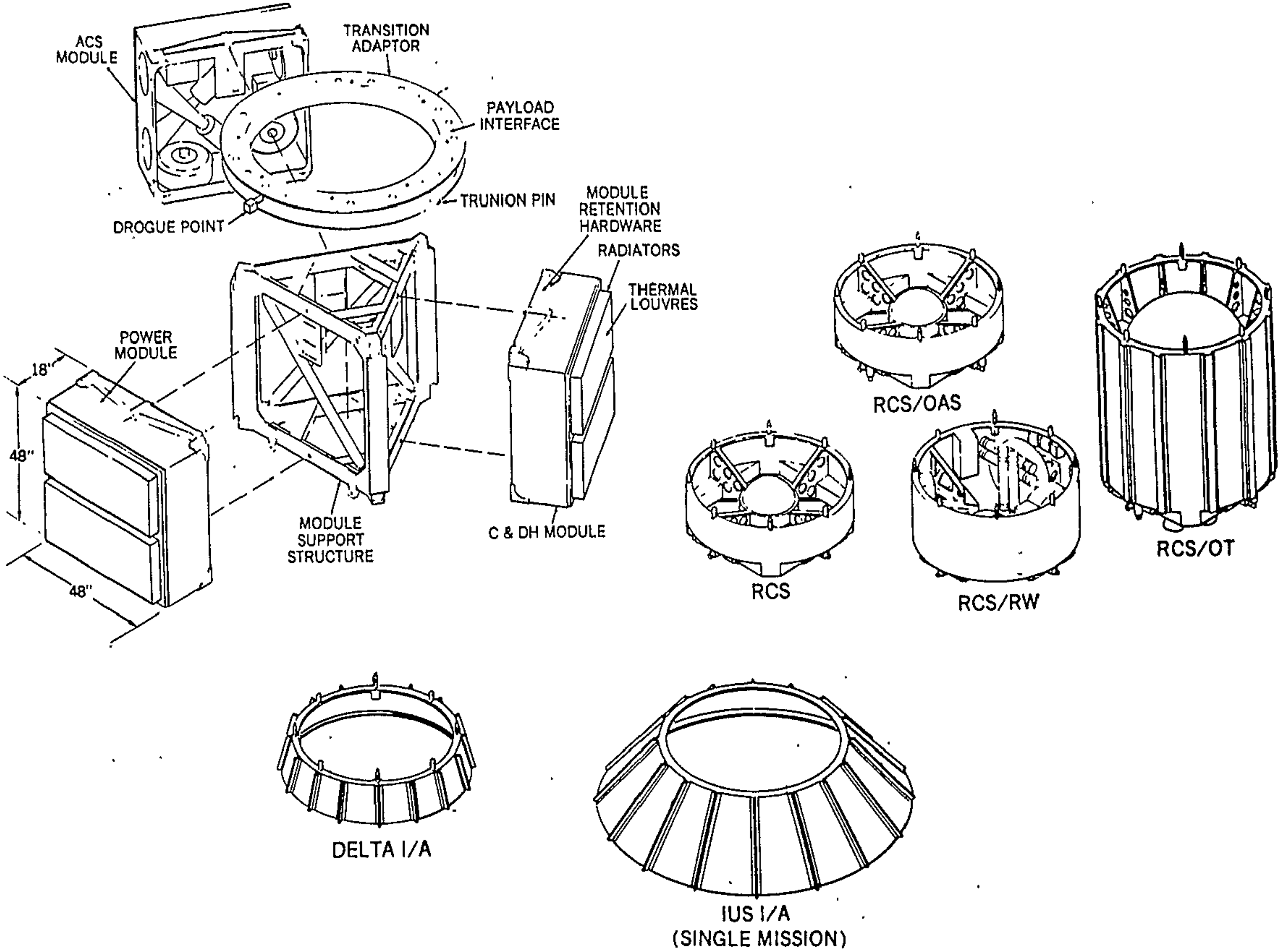


Figure 9-1. Multimission Modular Spacecraft

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