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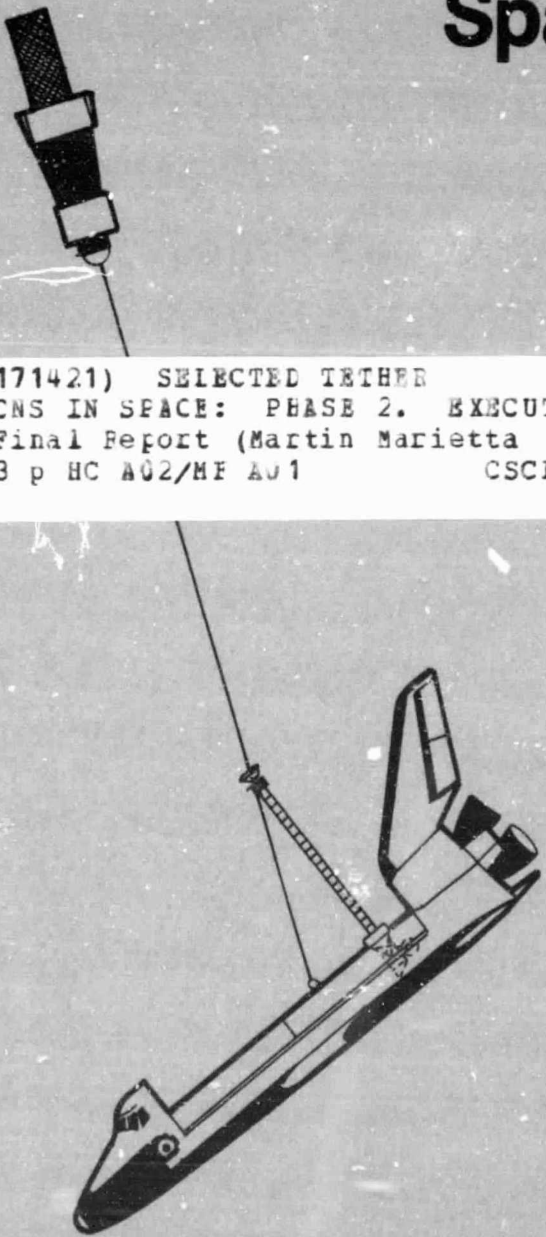
MCR-85-1309

Executive Summary
Phase II
Final Report

February 1985

Selected Tether Applications in Space



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EXECUTIVE SUMMARY

PHASE II STUDY OF SELECTED TETHER APPLICATIONS IN SPACE

CONTRACT NAS8-35499

FEBRUARY 1985

PERFORMED BY

MARTIN MARIETTA AEROSPACE
DENVER DIVISION

FOR

MARSHALL SPACE FLIGHT CENTER
HUNTSVILLE, ALABAMA

FOREWORD

This Executive Summary Report is submitted in accordance with the requirements of Contract NAS8-35499, Statement of Work paragraph 6.5, and Data Requirement DR-4. The study was performed under the technical direction of James K. Harrison, Contracting Officers Representative.

The study was performed by the Space Systems Division of Martin Marietta Aerospace, Denver Division under Mr. Morris H. Thorson, and in the Spacecraft Systems Product Area under Mr. Lester J. Lippy.

The Study Manager was Mr. William Nobles. Mr. Jack Van Pelt was responsible for the comparison analysis task.

Technical consultation was provided by Mr. Joseph Carroll, Research and Consulting Services, under subcontract to Martin Marietta.

Areas of the study dealing with tether transportation applications benefited from the studies performed by Professor Manual Martinez - Sanchez, Sarah Ann Gavit, and Dale Stuart of the Space Systems Laboratory of the Massachusetts Institute of Technology.

Insight into the behavior of tethered platforms was gained from the studies on tethered constellations performed by Dr. Enrico Lorenzini and his co-investigators, Mr. David Arnold, Mr. Jack Slowey and Dr. Mario Grossi. This work was performed at the Astrophysical Observatory of the Smithsonian Institute.

1.0 INTRODUCTION AND CONCEPTS OVERVIEW

This summary report covers the results from Phases I and II of a study of selected tether applications in space. During Phase I five concepts were selected for more detailed concept development and evaluation. Based on the information and understanding developed during this initial phase of the study, two of the concepts were significantly modified and one new concept was added to form the concepts baseline for the second phase of the study. These concepts and their designation are given below:

Concept A2 - Tether Deorbit of Shuttle from Space Station. (Major revision from Phase I)

Concept B - Tethered Orbit Insertion of a Spacecraft from Shuttle, (Same as Phase I)

Concept C - Tethered Platform Deployed from Space Station (Same as Phase I)

Concept D - Tether Effected Rendezvous of an OMV with a Returning OTV. (Same as Phase I)

Concept E2 - Electrodynamic Tether as an Auxiliary Power Source for Space Station. (Major revision from Phase I)

Concept F - Tether Assisted Launch of an OTV Mission from Space Station. (New Concept)

1.1 Angular Momentum Balance

Insight gained in the Phase I study identified the significant quantity of angular momentum transferred to the Space Station by the tether deorbit of Shuttle (Concept A). It was realized that complementary concepts were required to, in turn, use this angular momentum for some beneficial purpose. Lacking such angular momentum consumer concepts, the number of full scale tether deorbit operations would be limited to one or less per year.

This consideration led to the development of Concepts E2 and F to function in a complementary role as consumers of angular momentum.

- o Concept E2 converts the angular momentum into electrical power for use on the Space Station.
- o Concept F uses the angular momentum for a tether launch assist to an OTV mission.

Angular momentum balance concepts based on the combination of Concept A2 with each of the complementary Concepts E2 and F were considered. Unfortunately, due to conflicting operational requirements, it does not appear to be feasible for E2 and F to be used concurrently. They have been evaluated as alternatives.

1.2 Complementary Concepts A2 and F

The combination of Concepts A2 and F were used as the basis for the conceptual design of a dual mode tether deployer system for Space Station. This system is shown installed into the Space Station in Figure 1. The Shuttle in process of being deployed is shown in Figure 2 and the OTV mission stack in deployment process in Figure 3.

An additional significant consideration with respect to the tether deorbit of Shuttle is the resulting reduction in the amount of bipropellant required for the Shuttle Orbital Maneuvering System (OMS) to complete the deorbit operation. This reduction is 45.8 kg (101 lb) per each kilometer of tether deployment. Since the nominal full scale tether deorbit uses 64 km of tether the resulting reduction is 6500 lbs per deorbit. To enable this scavenging operation an appropriately sized set of propellant tanks were incorporated into the Shuttle Interface Deployment Module (SIDM) which is used to attach the tether system to the Shuttle (See Figure 2). Subsequent to release of the Shuttle the SIDM with the load of scavenged propellant is retrieved back to the Space Station by the tether. This scavenged bipropellant can be used to supply operations of the Orbital Maneuvering Vehicle (OMV) and other bipropellant systems. This scavenged propellant represents one of the significant potential benefits to be derived from the use of these tether application concepts.

1.3 Complementary Concepts A2 and E2

Concept E2 for the use of an electrodynamic tether as an auxiliary power system for Space Station was developed during Phase II of the study to function as a consumer of angular momentum transferred by the Shuttle deorbit.

The system is designed to provide up to 75 kw of electrical power to the Space Station bus. The source of this energy is the orbital mechanical energy imparted to the Space Station by the tether deorbit of Shuttle. The amount of mechanical energy transferred by each deorbit operation is 21,700 kWh. This is shown in relationship to the orbit altitude in Figure 4. The conversion of this mechanical energy into electrical energy at power levels of 25 kW and 75 kW is given in Table 1. Each full tether deorbit would provide the energy to operate the tether power system for 29 days at 25 kW or for 8.4 days at 75 kW.

1.4 Concept C

Concept C is for a tethered platform deployed from Space Station. This concept was developed during Phase I of the study. While the concept was intended to be of general applicability, a specific mission was selected as an example. The mission selected was an Infrared Astronomy Observatory platform. This mission was selected because it requires isolation from contaminating environments and periodic replenishment of the telescope cryogen. A schematic of the platform is shown in Figure 5 with the example payload installed.

1.5 Concept D

Concept D is for a tether mediated rendezvous with an aerobraked Orbital Transfer Vehicle (OTV) returning from a mission to geosynchronous orbit. The rendezvous is made with a tethered Orbital Maneuvering Vehicle deployed 7 nmi below the Space Station. This concept was developed during Phase I of the study.

The benefits comparison performed during Phase II showed that there is no significant performance advantage when this method of OTV retrieval is compared with the baseline non tethered approach. This has led to a recommendation that this concept not be pursued any further.

1.6 Concept B

Concept B is for a Shuttle based tether deployer system to insert payloads into higher orbit. Various typical payload/missions have been examined. The deployment of the Advanced X-ray Astrophysical Facility (AXAF) is shown in Figure 6.

Concept B provided the basis for the conceptual design of a tether deployer system for Shuttle which mounts directly into the payload bay without the use of the Spacelab pallet for structural support. This permits a lighter and shorter deployer design. This tether deployer system is shown in Figures 7a and 7b.

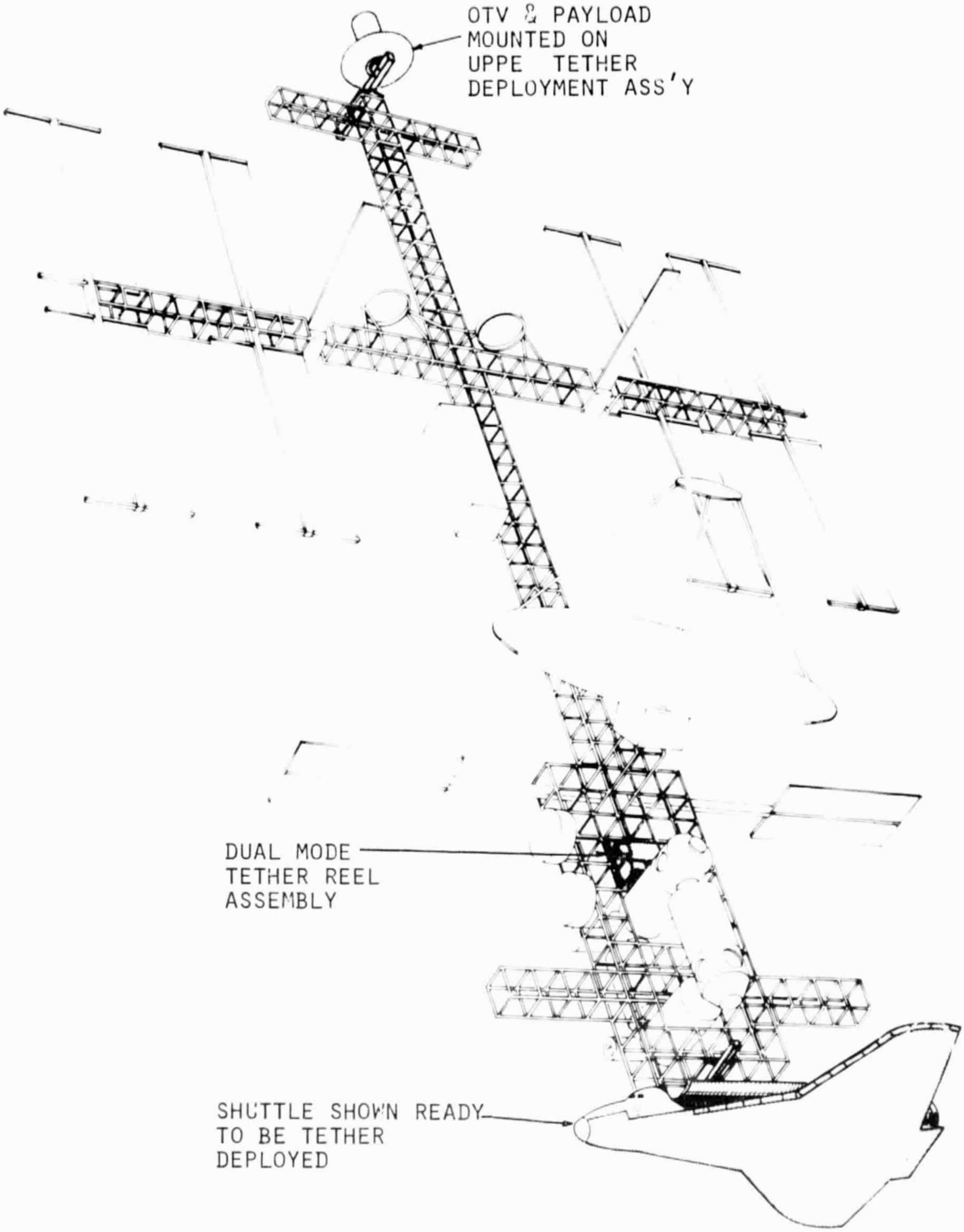

Figure 1 Dual Mode Tether Deployment System Installed on Space Station

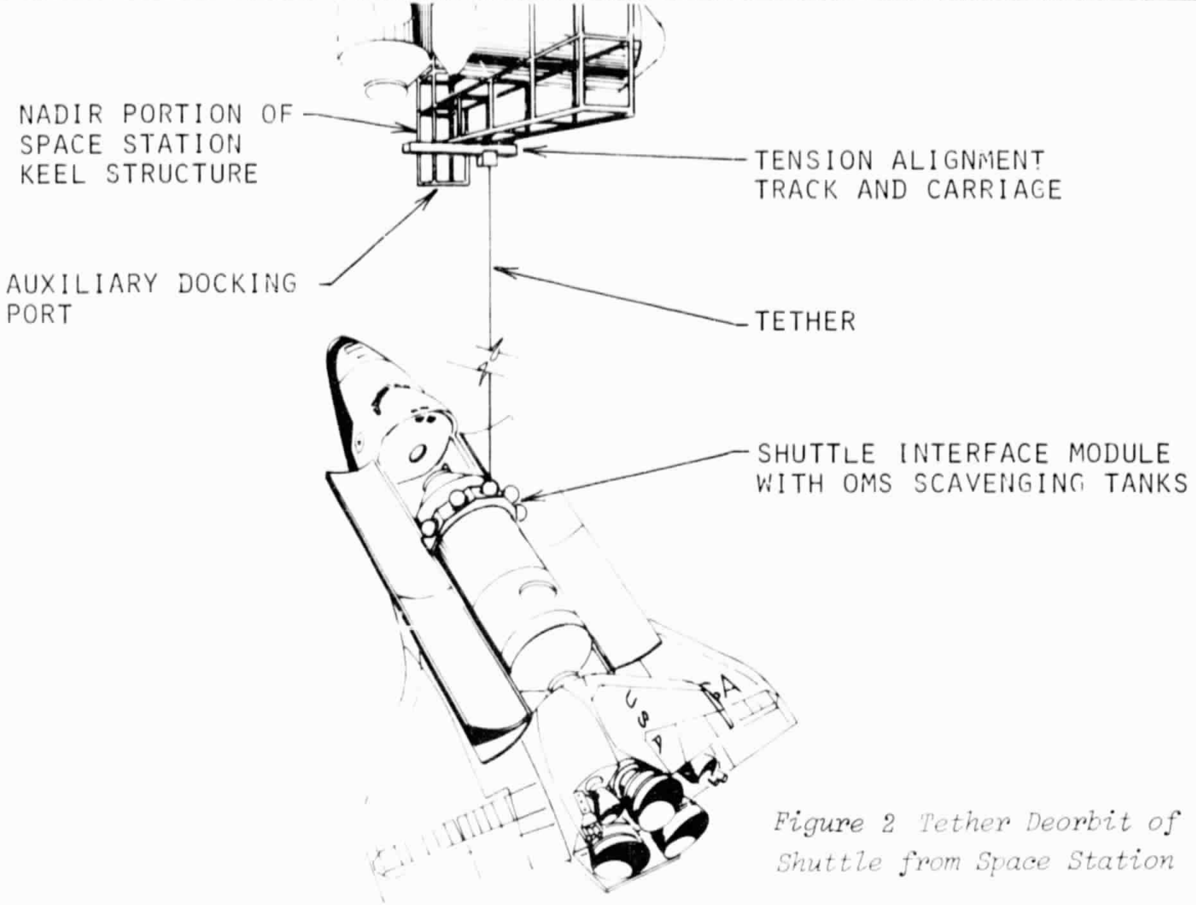

Figure 2 Tether Deorbit of Shuttle from Space Station

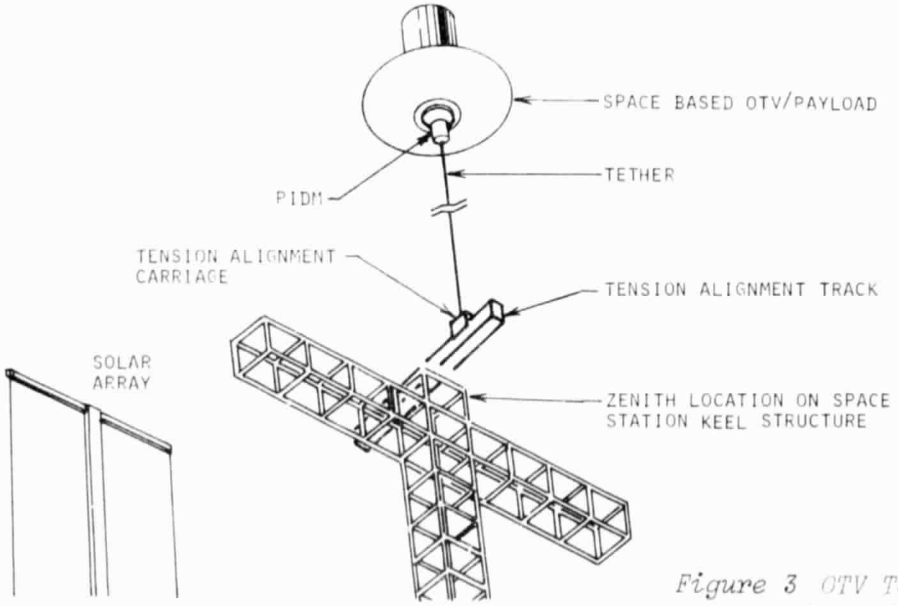

Figure 3 OTV Tether Launch Assist

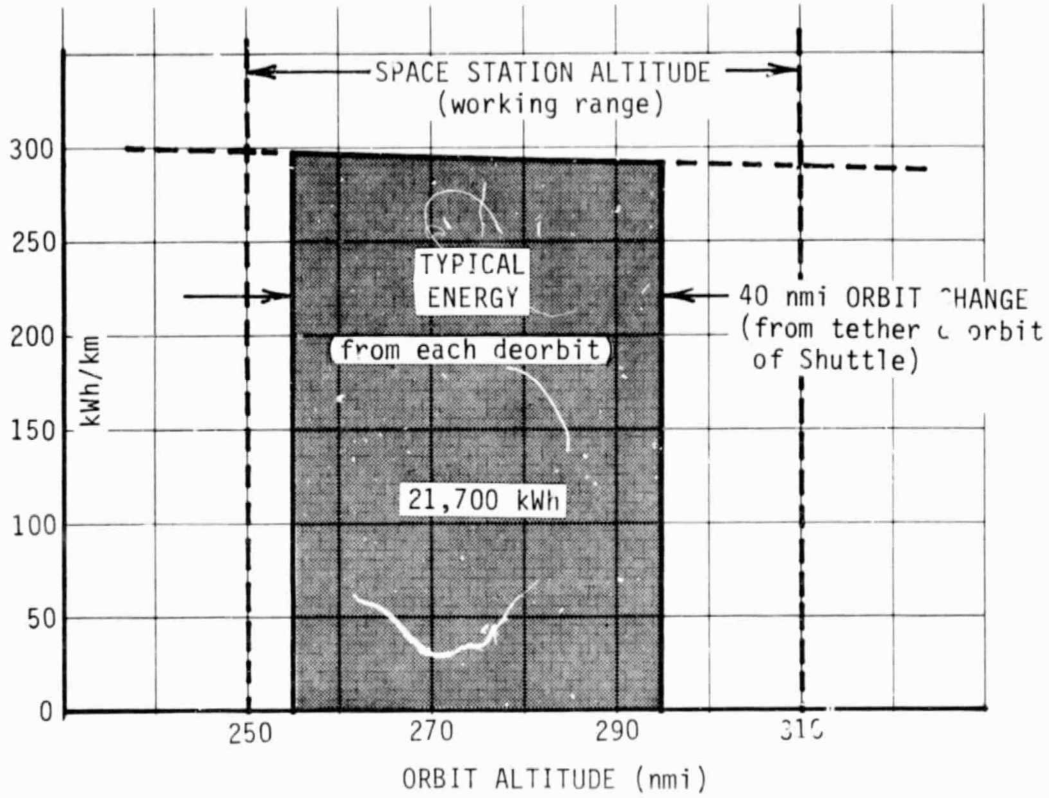

Figure 4 Shuttle Tether Deorbit Energy Considerations

Orbital Mechanical Energy (kWh)/Altitude (km)	293 ± 4.5 kWh/km	
E.D. Power Tether Operating Power Level (kW)	25	75
Conversion Efficiency (%)	80	70
Mechanical Energy Converted per Day (kWh)	750	2571
Altitude Loss per Day (km)	2.6	8.8
Power System Operation Days per Shuttle Deorbit	29	8.4

Table 1 Conversion of Orbital Mechanical Energy into Electrical Power

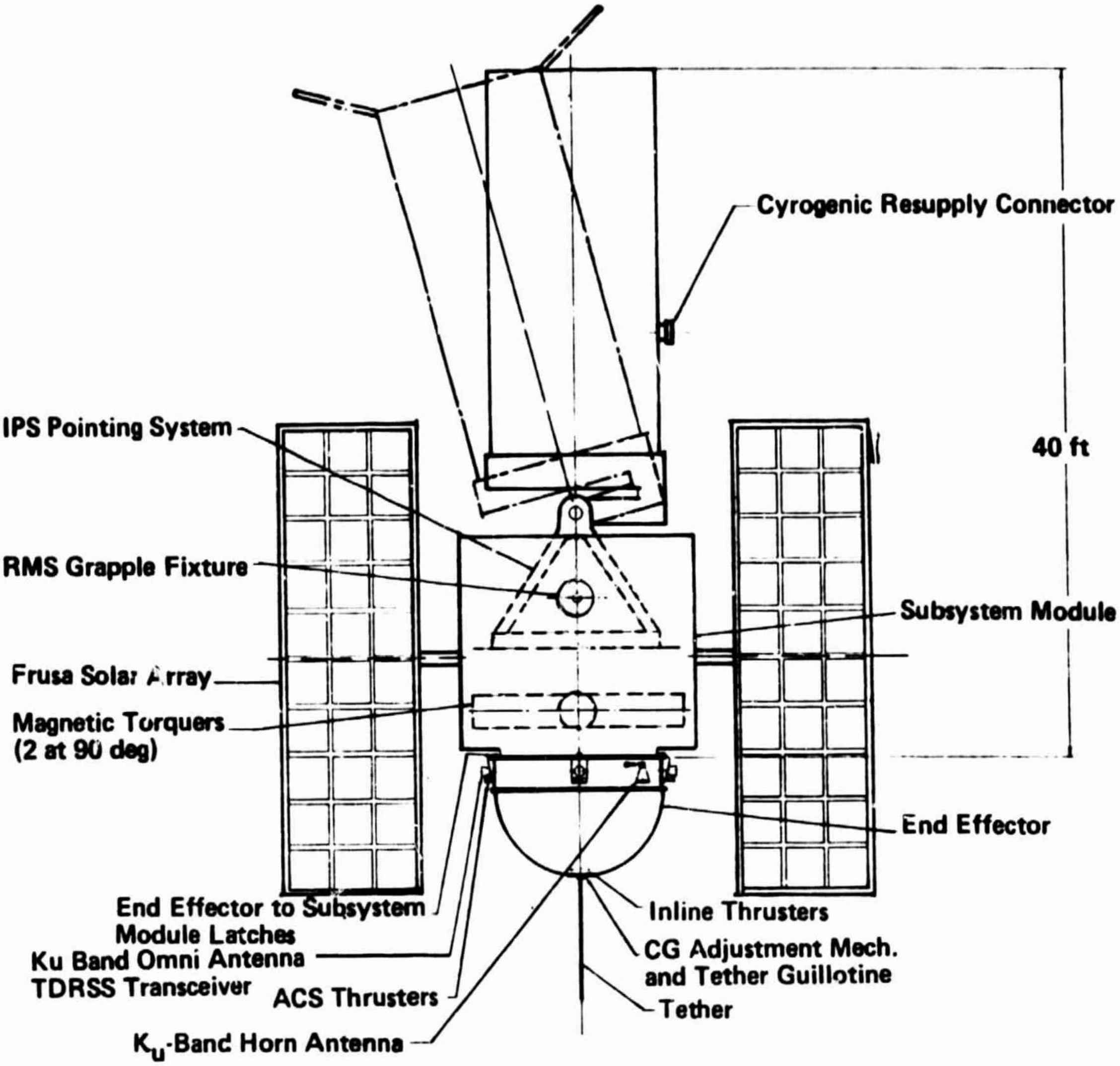

Figure 5 Tethered Platform with Mission Payload (IR Observatory - Typical)

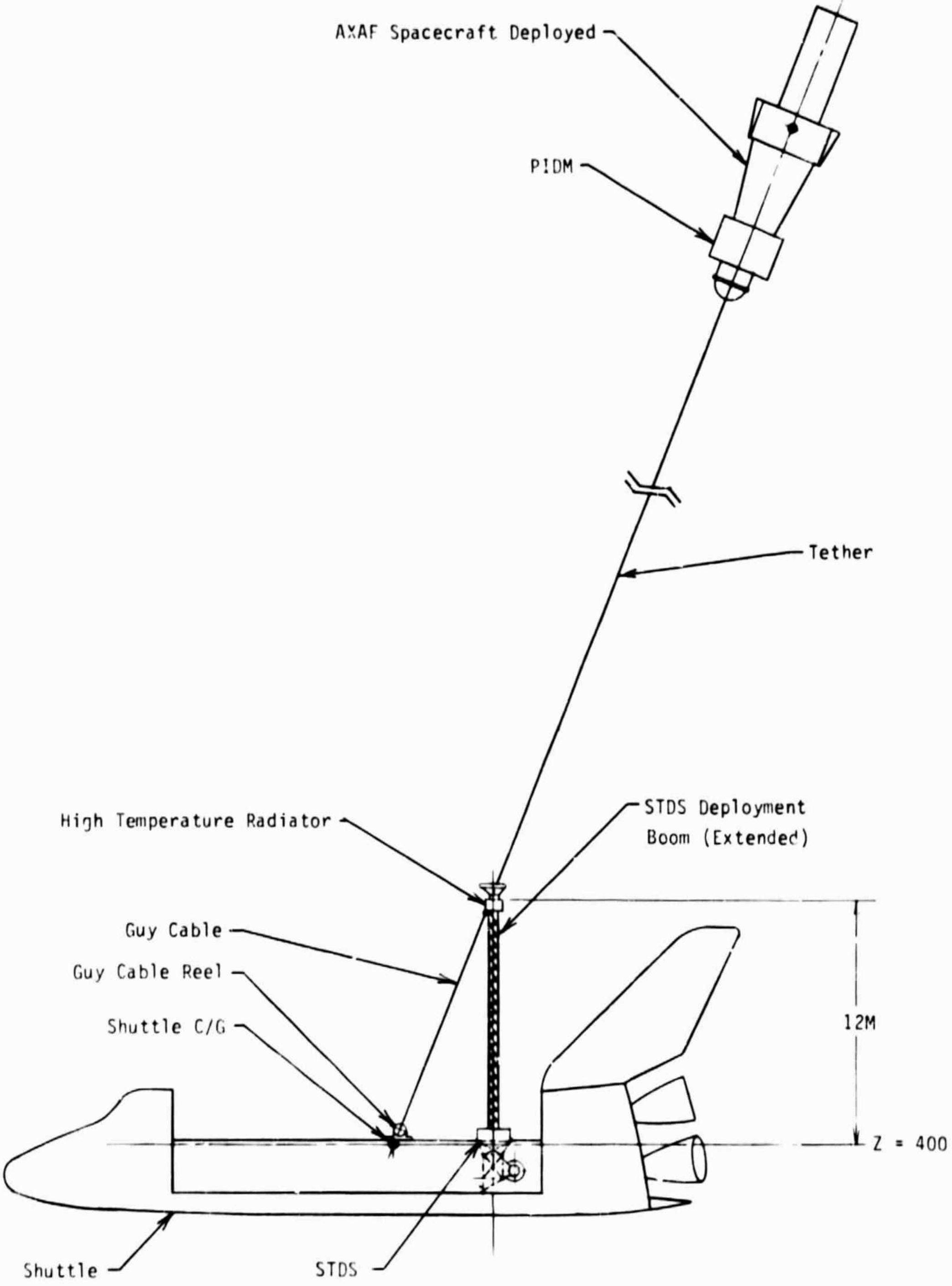

Figure 6 Tether Deployment of AXAF from Shuttle

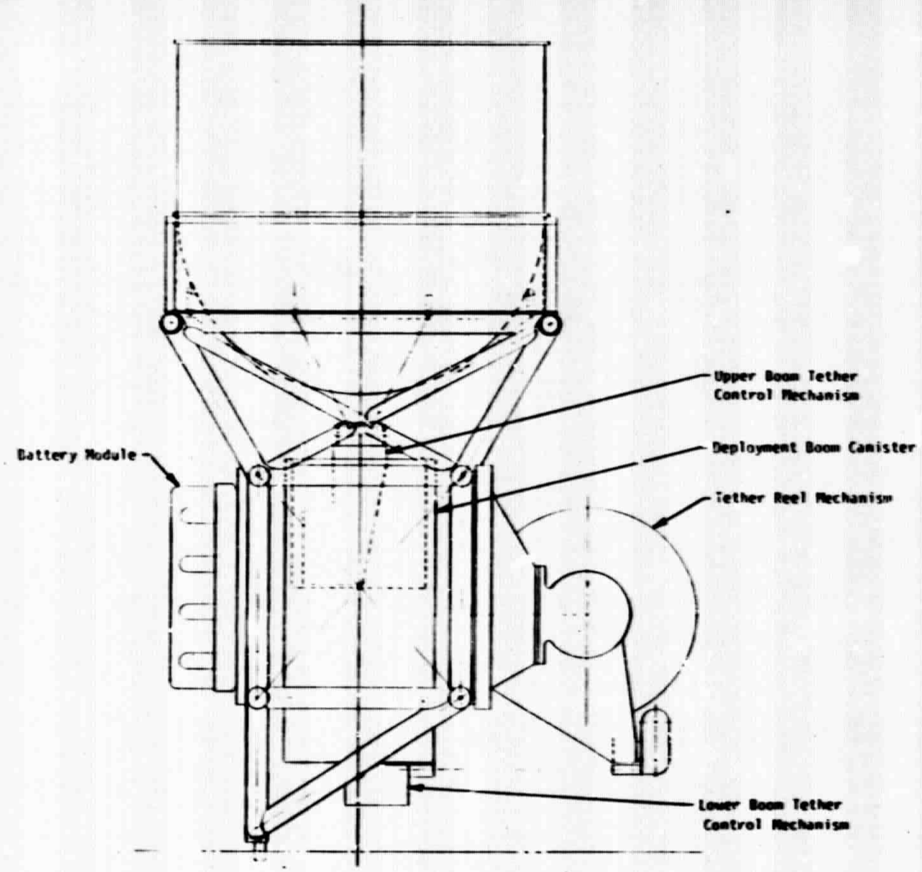

Figure 7a Tether Deployer System for Shuttle (side view)

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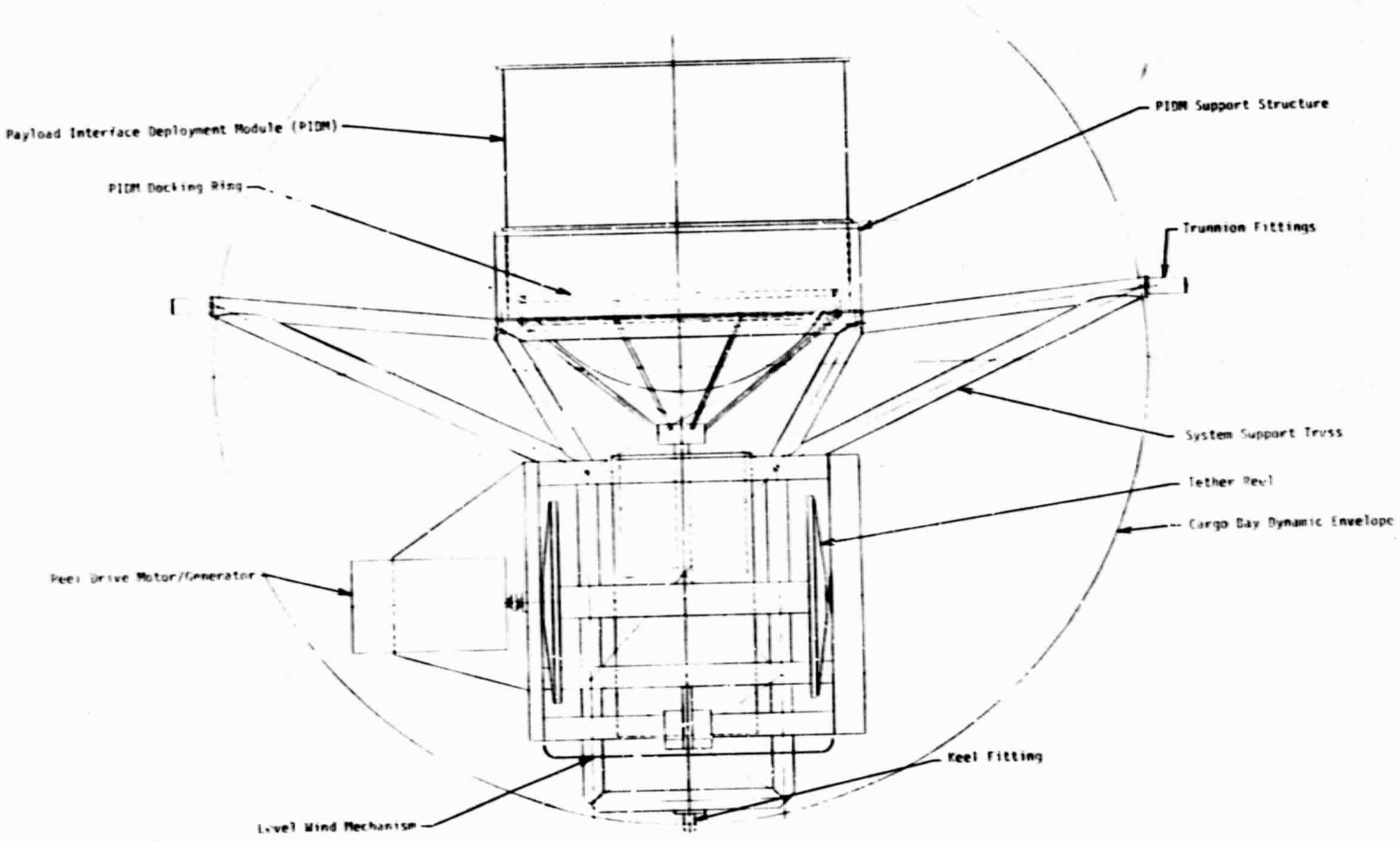


Figure 7b Tether Deployer System for Shuttle (front view)

2.0 COMPARISON WITH ALTERNATE CONCEPTS

This section summarizes the analysis approach used in the study, the results of the concept comparisons and the results of the benefits analysis associated with the Space Station angular momentum balance technique. The primary concepts discussed are those associated with the Space Station momentum balance and the main contributors to the benefits analysis (i.e. the tethered Shuttle deployment, A2 and the tethered OTV Launch, F).

The Space Station momentum balance approach considers the various tether applications affecting the station altitude including the Tethered Shuttle deployment, tethered OMV and OTV launches, and Space Station drag decay and keeps the Station within desired altitude limits to avoid compromising Shuttle payload delivery capability or other mission constraints. The tethered OTV Launch Mission (Concept F) was added to the previously selected concepts since it is the key transportation application concept for utilization of Space Station angular momentum.

2.1 Comparison Criteria

This sub-section summarizes the mission models and analytical approach and displays the results of parametrically examining Shuttle, OMV, and OTV performance at various tether lengths and payload weights to compare with untethered (baseline) approaches. It includes the effects of Space Station orbit decay and summarizes tether deployment and transportation principles. Throughout the comparison it was found that the common currency of tether transportation applications benefits is propellant savings. (i.e; Shuttle OMS propellant, OMV cold gas or propellant, OTV propellant, and Space Station drag makeup propellant.)

Various mission models were investigated including previous models used for OMV, OTV, and Space Station studies at Martin-Marietta Denver over the past 1-2 years. The recent mission models associated with the Space Station (mid-1984) were found to be the most useful in determining candidates for tether launches from the Space Station during the 1991 - 2000 time period. Although many OMV missions are planned for this period only about 18 (6%) were considered to be acceptable tether launch candidates. OTV missions do not begin until 1995, but 95% (69 missions) of the total number of missions planned through year 2000 are deemed to be good candidates for tether launch assist. These OTV missions all go to geosynchronous altitude, and are significant users of excess Space Station angular momentum.

Figure 8 illustrates the basic transportation principles used in the transfer of angular momentum between tethered masses, as applied in this study. The left side of the chart shows the general relationship between the tethered masses for a static condition prior to tether release, with M_1 always defined as the lower mass. The distances that the upper mass rises and the lower mass descends from the original orbit mass center is a function of the two masses and tether length, a indicated. The right side of Figure 8 shows the original circular orbit and the post-release paths for the two

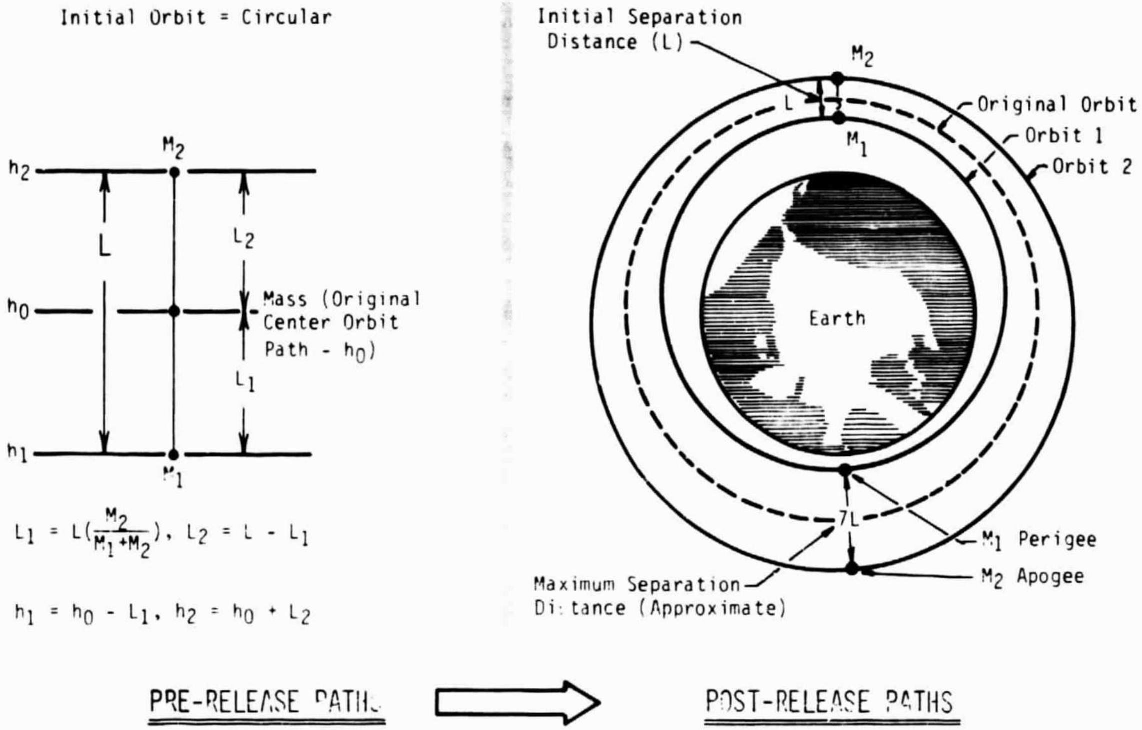
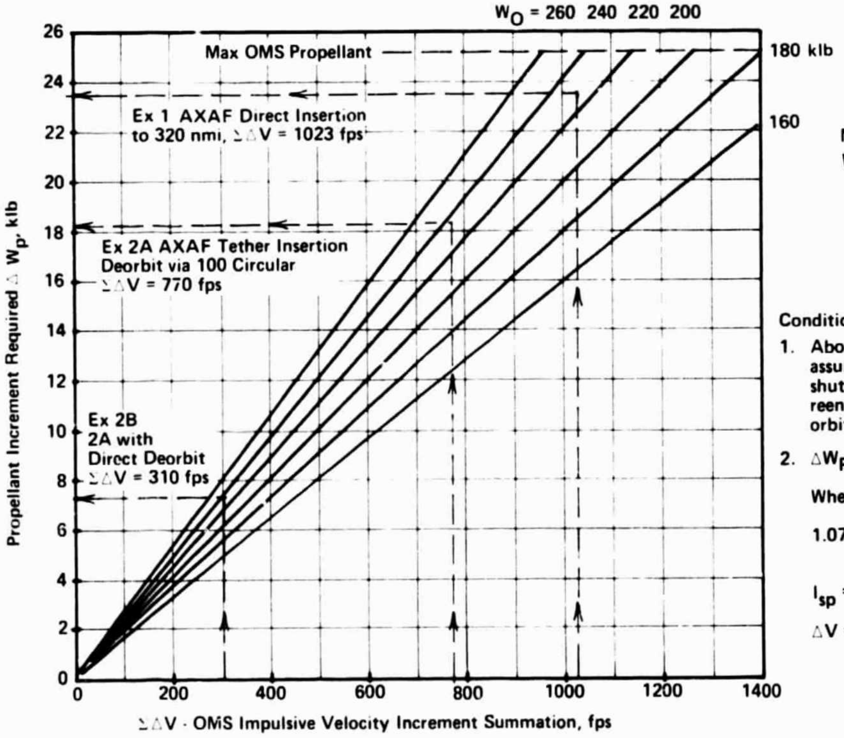


Figure 8 Tether Transportation Principles



Note:

W_o = Shuttle weight with cargo at start of initial OMS burn.

Conditions:

1. Abort situation assumed, where shuttle must reenter from orbit with cargo.
2. $\Delta W_P = 1.075\, W_o\, [1 - e^{(-\Delta V/gI_{sp})}]$

Where

1.075 = Factor for OMS propellant margin

I_{sp} = 313.2 sec

ΔV = ΣΔ from prior charts.

Figure 9 Shuttle OMS Propellant Requirements/Savings bodies. Notice that the lower body descends to a lower perigee and the upper body ascends to a higher apogee with a maximum separation of approximately 7 tether lengths after the release. These principles were applied to cases where Shuttle was used as the deployer and where the Space Station was used as a deployer, with detailed equations given in the study final report.

To determine OMS propellant requirements for missions involving the Shuttle, it was necessary to obtain delta velocity requirements for the OMS system for ascent and also for deorbit. This data was obtained and presented parametrically, using standard Shuttle performance estimation techniques. Direct insertion was always assumed for ascent (when applicable) with deorbit from a circular orbit or from the apogee of an elliptical orbit used as the recommended technique. The initial weight of the Orbiter at the start of the first OMS burn (W_0) was also estimated using standard Shuttle weight estimation techniques to determine first order propellant requirements.

Figure 9 presents the summary chart which shows the OMS propellant required as a function of the total delta velocity required and the initial Orbiter weight, with the equation and appropriate Shuttle parameters indicated. Examples of OMS propellant requirements are presented for the AXAF placement (Concept B) comparison between the baseline approach (23,500 lb) and two tethered approaches (18,500 lb and 7,500 lb), as indicated. For the examples shown, the direct deorbit from apogee (Ex. 2B) of the elliptical orbit was selected, with a potential maximum OMS propellant savings of 16,000 lb indicated. This same chart also gives the projected Shuttle OMS propellant savings of 6,500 lb for every full tether length deployment (64 Km) from the Space Station (Concept A2).

As previously indicated, very few tether launch candidate missions were identified for the OMV based at the Space Station. These were analyzed using a recent configuration of the Martin-Marietta OMV configuration and were found to have an insignificantly small influence on the momentum balance of the Space Station. These effects are summarized in the benefits analysis (2.3).

A similar analytical approach was taken to analyze OTV performance, using the Martin-Marietta Aft Cargo Carrier (ACC) configuration. Tether lengths up to 150 km were considered using OTV propellant loads up to 51,000 lb and payloads up to 20,000 lb. resulting in a mission stack mass of 78,000 lb. Typical velocity requirements were used to determine propellant required for the transfer of the OTV to geosynchronous orbit both with and without the tether launch assist and for the return of the OTV stage (without payload) from geosynchronous orbit to the Space Station via the aerobraking maneuver. Figure 10 presents the projected OTV propellant savings and indicates a maximum potential savings of 4300 lb (8%) over the baseline cryogenic propellant requirements. Average propellant savings per OTV mission are approximately 2900 lb.

Space Station performance, in the context of the momentum balance analysis, can be thought of in terms of the propellant required to overcome aerodynamic drag effects and keep the Station at its nominal altitude of 270 nmi. This information was obtained from the Martin-Marietta Space Station study team and assumes a hydrazine propulsion system. Average orbit stationkeeping propellant requirements per quarter vary from a maximum of 2890 lb in 1991 to a minimum of 280 lb in 1996 and again increase to 2455 lb per quarter in the year 2000. This range reflects the drag variation for a typical Space Station configuration through the solar cycle occurring in this time period, with 1991 near the peak of the upper atmosphere density cycle. Corresponding decreases in Space Station altitude (without propulsive maneuvers) would vary from 12 nmi to 1 mi to 10 nmi per quarter year. Assuming a Space Station momentum balance approach using tether technology, all of the hydrazine requirements for orbit maintenance could be eliminated.

2.2 Comparison Results

The previous criteria were utilized to compare the various tethered concepts studied with their estimated or known baseline approach to obtain the benefits of the tethered approaches. A standard comparison format was developed to allow comparison of all concepts on a similar basis, and consisted of both quantitative and qualitative comparison data. Quantitative data included orbits used, propellant usage, tether system characteristics, Space Station angular momentum, and operation time. Qualitative data included mission complexity, risks, and cost factors. Results from the two most important applications are summarized here.

The primary source for increasing Space Station angular momentum is the tethered deployment of the Shuttle (Concept A2). This concept must be paired with the tethered launch of the OTV (Concept F) to keep the Space Station within average altitude limits (250-310 nmi). The increase in angular momentum raises the average altitude of the Space Station by 40 nmi and also eliminates the need for an average annual Space Station usage of 5500 lb of hydrazine propellant for orbit maintenance. The scavenging of 6500 lb of OMS propellant with every full length (64 Km) Shuttle tether deployment reduces transportation requirements for delivering OMV propellant (same as OMS propellant) to the Space Station and would also allow the Shuttle to refuel at the Space Station for extended missions or in an emergency situation.

The primary user of the Space Station angular momentum transferred by the Shuttle deorbit is the tethered launch assist of the OTV (Concept F). A maximum tether length deployment case (150 km) with the 20,000 lb payload causes a reduction of about 38 nmi in average Space Station altitude which nearly offsets the altitude gain of 40 nmi resulting from the tether deorbit of Shuttle (Concept A2). The tethered launch assist of the OTV provides a potential savings of 4300 lb of cryogenic propellant which can either reduce propellant delivery requirements to the Space Station or allow for an increase in OTV payload capability. The tethered approach also eliminates the OMV mission associated with OTV placement required for the baseline approach.

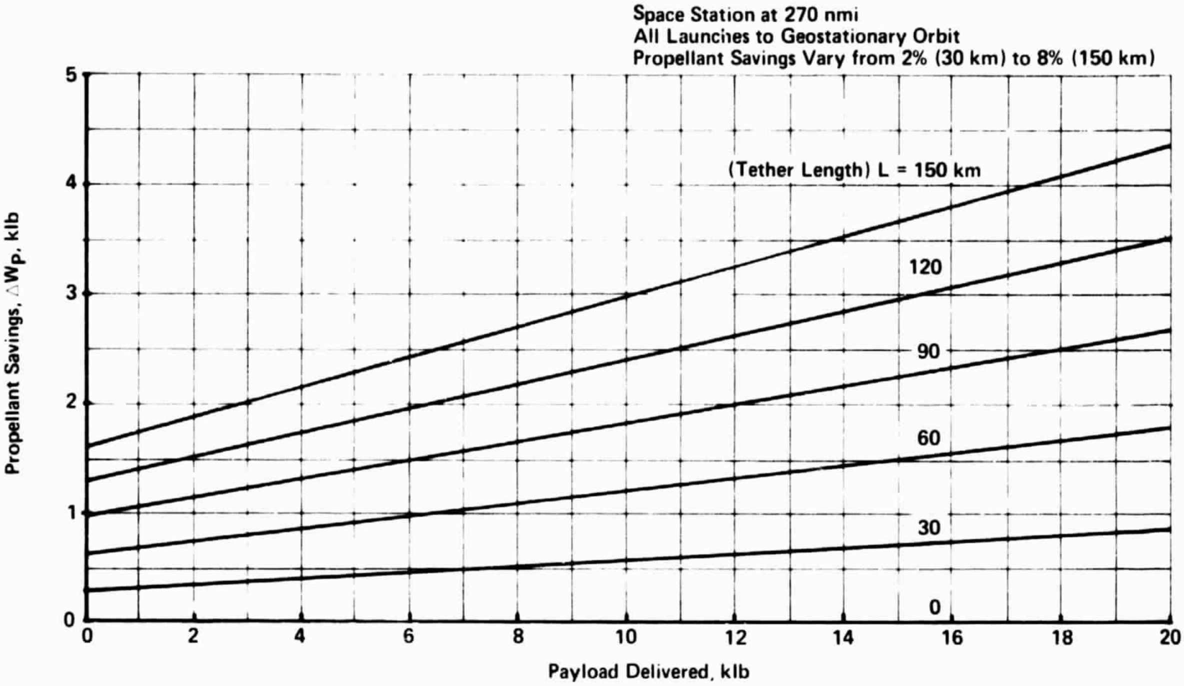


Figure 10 OTV Propellant Savings from Tether Launches

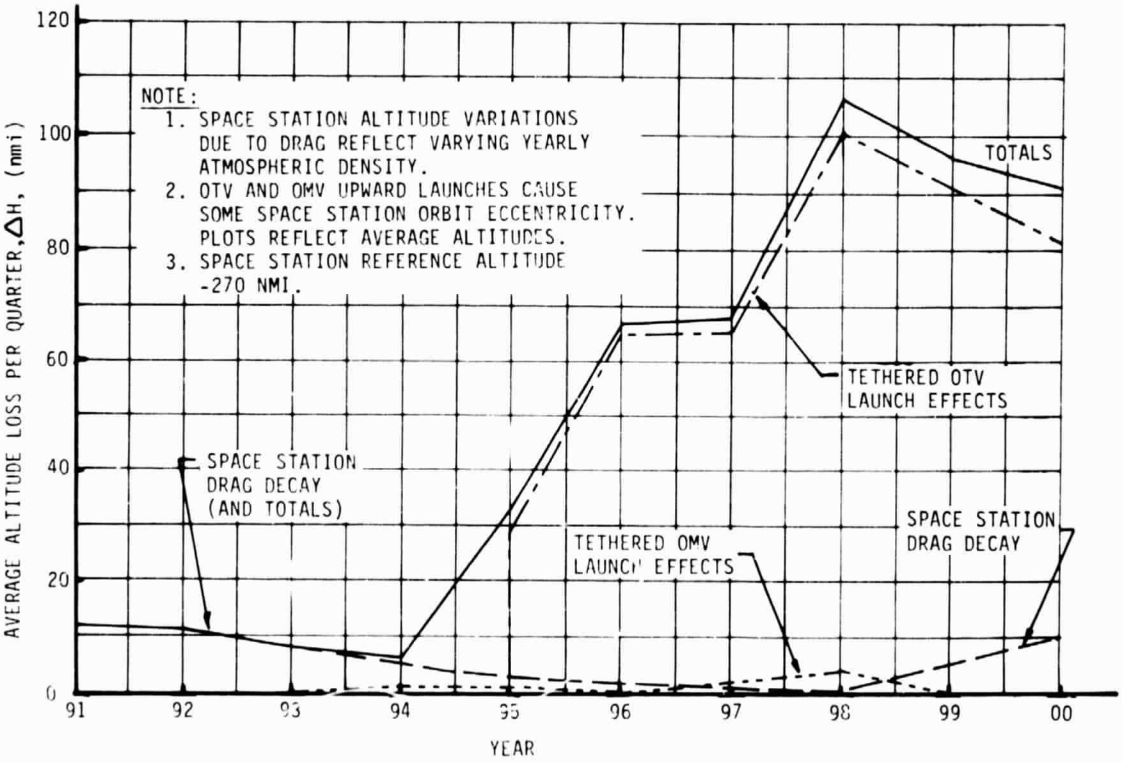

NOTE:
1. SPACE STATION ALTITUDE VARIATIONS DUE TO DRAG REFLECT VARYING YEARLY ATMOSPHERIC DENSITY.
2. OTV AND OMV UPWARD LAUNCHES CAUSE SOME SPACE STATION ORBIT ECCENTRICITY. PLOTS REFLECT AVERAGE ALTITUDES.
3. SPACE STATION REFERENCE ALTITUDE -270 NMI.

Figure 11 Potential Space Station Quarterly Altitude Losses

A dual mode deployer system with an estimated system mass of 25,000 lb is used for all tether operations on the Space Station and is designed to hold 150 km of tether (plus a 5% margin). Design requirements are determined by the tether assisted launch of the OTV with a maximum tether tension approaching 4,000 lb. Tether tension is slightly less for the Shuttle deployment case. Energy management considerations are 366 kWh generated during deployment and 29 kWh required for retrieval of the Payload Interface Module (PIDM). These deployment and retrieval energies are a maximum for Concept F. This dual mode deployer system is expected to be cost-effective for the Space Station since it will be used many times over the 10+ year mission time period.

2.3 Benefits Analysis

Since crew rotation is expected to be at quarter year intervals and drag makeup for the Space Station would occur at least quarterly, momentum balance was treated on a quarterly basis. For the benefits analyses, equivalent average station altitude changes were used to determine the effect of tether operations.

In Figure 11 the average quarterly Space Station altitude losses due to the tether operations identified from the mission models and including orbit maintenance for the Space Station are summarized for the 1991-2000 time period. For the first 4 years altitude loss varies from 12 nmi to 6 nmi per quarter and is primarily due to atmospheric drag. The tethered OMV launches have a minimal effect on Space Station altitude loss, as previously indicated . The primary altitude loss occurs with the first OTV launches in 1995 and varies from about 30 nmi to a peak of over 100 nmi per quarter in 1998. Some drop-off occurs after 1998, but total altitudes loss remains about 90 nmi per quarter year. These altitude losses are balanced by tether deorbits of Shuttle.

Figure 12 shows the tethered Shuttle deployments required per quarter to balance the altitude losses discussed previously. Only partial length tether deployments of 10 km to 20 km for the Shuttle deorbits are required during the 1991-1994 time period. As the number of OTV launches increase, more and longer tether deployments for the Shuttle are required to balance the altitude losses. Also shown are the annual equivalent number of full length tethered Shuttle deorbit operations required (e.g. in 1998 two full length and one partial length deployments per quarter would correspond to a year total of 11 tether deorbits with full length deployments). For comparison purposes, Shuttle traffic to the Space Station is expected to reach 14 flights per year in 1999, and in general more Shuttle flights are available than the number required for angular momentum balance.

The potential yearly benefits in propellant savings from Space Station tethered operations are summarized in Figure 13. Notice that the propellant and cold gas savings associated with OMV launches are almost negligible and do not justify tethered OMV launch operations from the Space Station. In the years 1991-1994 the lower dark bar corresponds to orbit decay propellant savings while the upper shaded bar corresponds to the OMS propellant scavenged by balancing the

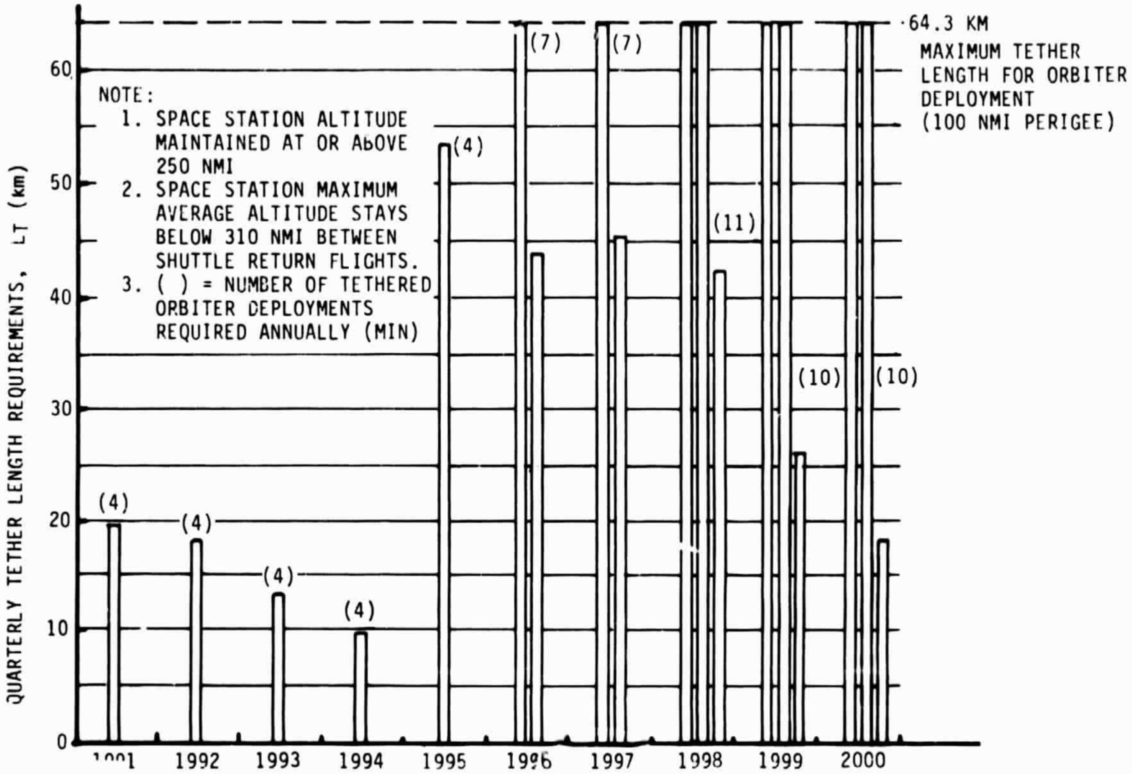


Figure 12 Shuttle Quarterly Tether Deployment Requirements to Maintain Space Station Altitude

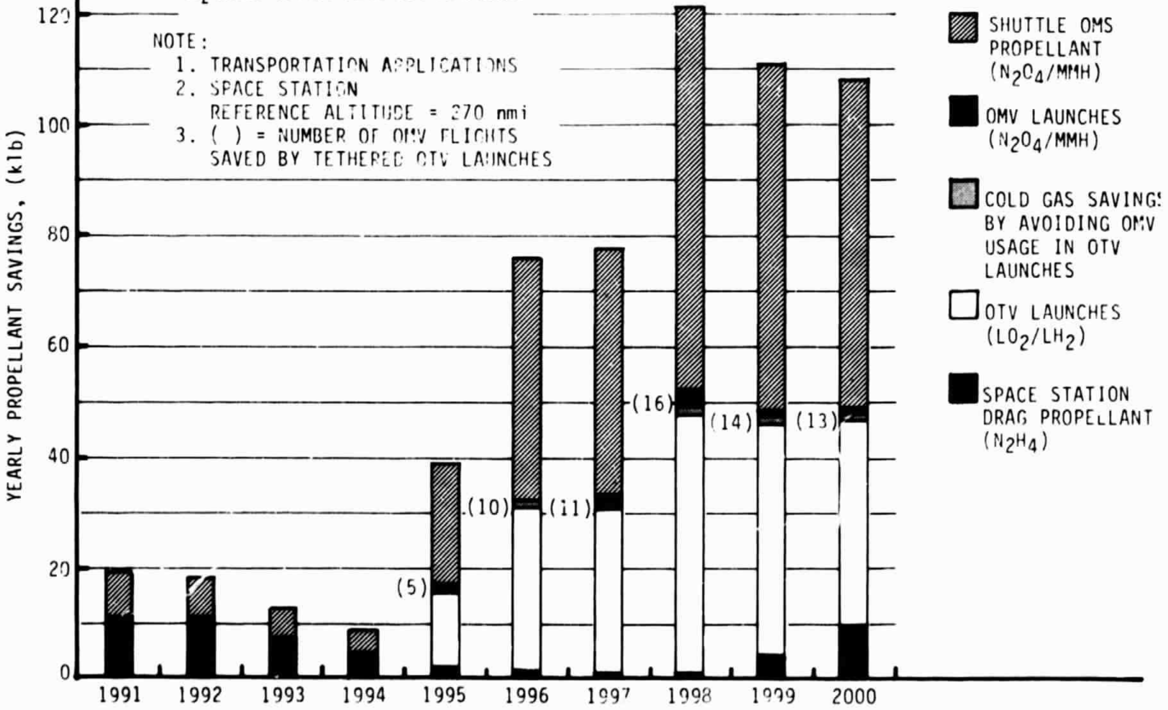


Figure 13 Potential Yearly Benefits from Space Station Tether Operations

altitude loss due to drag decay. The total of those two savings varies from 10,000 to 20,000 lb per year. From 1995 to 2000 the significantly increased savings are due to the OTV propellant saved by tether assisted launches and the correspondingly larger savings of OMS propellant scavenged during tether deorbit of Shuttle for momentum balance. In the later period, total propellant savings vary from 40,000 lb to 120,000 lb per year. In addition to those savings, 69 OMV missions (required for baseline OTV launches) are eliminated by the tether approach.

Other potential savings could be realized by transferring any excess Shuttle OMS propellant not needed for some missions to the Space Station. (This could occur for volume limited Shuttle flights to the Space Station when the full payload weight capability is not required).

3.0 CONCLUSIONS

The following general conclusions are based on the results of the Phase II study:

A. The application of tether technology has the potential to significantly increase the overall performance efficiency and capability of the integrated space operations and transportation systems thru the decade of the 90's.

B. The primary concepts for which significant economic benefits have been identified are dependent on the use of Space Station as a storage device for angular momentum and as an operating base for the tether systems.

C. These Space Station based concepts must be coupled into operational pairs that are functionally related such that one concept uses the angular momentum derived from the other.

D. The outstanding candidate concept for the source of angular momentum is the tethered deorbit of Shuttle from Space Station. An ancilliary benefit is the significant quantities of bipropellant scavenged from the Shuttle during the tether deorbit operation.

E. Two alternative candidates have been identified as leading contenders for the role of angular momentum consumers. First is a tether launch assist to an OTV mission which uses the angular momentum to reduce propellant requirements for OTV. Second is an electrodynamic power tether which gradually converts the scavenged angular momentum into electrical power for use on the Space Station.

F. Concurrent usage of the OTV launch assist and the electrodynamic power tether concepts are not feasible. Electrodynamic power tether usage could start with Space Station. Tether launch assist to OTV cannot commence until the advent of the space based OTV circa 1995.

G. Use of these functionally related concepts require that provision for them be incorporated into the Space Station design concept.

H. Certain operational impacts on the Space Station are inherent with these tether applications. The primary ones are the acceleration levels induced by tether deployments, and the orbit perturbations caused by tether mediated angular momentum transfers.

I. Tether deployment of masses such as the Shuttle or OTV mission stacks present significant energy management problems. Deployment generates significant quantities of energy which must be used, stored or rejected to space. Retrieval requires smaller but still significant quantities of energy to be supplied to the tether retrieval system.

J. Any overall strategy for tether usage must consider the compatibility aspects for those concepts using the Space Station as an operations base.

K. Economic benefits to be derived from the use of tethered platforms from Space Station has not been analyzed during this study phase. However, it should be noted that the use of such platforms would not be compatible with those concepts for which significant benefits have been identified.

L. Tethered OMV rendezvous concept for retrieval of returning OTV is not economically viable.

M. While tether insertion of AXAF from Shuttle does not present a unique performance capability and is not economically advantageous, other missions do exist where the orbit insertion capability is unique to the tether method.