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ORBITAL OPERATIONS STUDY

VOLUME II - INTERFACING ACTIVITIES ANALYSES

PART 3 - DATA MANAGEMENT ACTIVITY GROUP

FINAL REPORT

MAY 1972

APPROVED BY

L. R. Hogan

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TECHNICAL REPORT INDEX/ABSTRACT

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DESCRIPTIVE TERMS

*ELEMENT INTERFACES, *ALTERNATE APPROACHES, *DESIGN CONCEPTS, *OPERATIONAL PROCEDURES, *FUNCTIONAL REQUIREMENTS, *DESIGN INFLUENCES, *COMMUNICATIONS, *RENDEZVOUS, *STATIONKEEPING, *DETACHED ELEMENT OPERATIONS

ABSTRACT

THIS DOCUMENT IS VOLUME II, PART 3 OF THE FINAL REPORT OF THE ORBITAL OPERATIONS STUDY. ELEMENT INTERFACES, ALTERNATE APPROACHES, DESIGN CONCEPTS, OPERATIONAL PROCEDURES, FUNCTIONAL REQUIREMENTS, DESIGN INFLUENCES, AND APPROACH SELECTION ARE PRESENTED FOR EACH OF THE FOLLOWING INTERFACING ACTIVITIES: COMMUNICATIONS, RENDEZVOUS, STATIONKEEPING, DETACHED ELEMENT OPERATIONS.

FOREWORD

This report contains the results of the analyses conducted by the Space Division of North American Rockwell during the Orbital Operations Study, Contract NAS9-12068, and is submitted in accordance with line item 7 of the Data Requirements List (DRL 7).

The data are presented in three volumes and three appendixes for ease of presentation, handling, and readability. The report format is primarily study product oriented. This study product format was selected to provide maximum accessibility of the study results to the potential users. Several of the designated study tasks resulted in analysis data across elements and interfacing activities (summary level); and also analysis data for one specific element and/or interfacing activity (detailed level). Therefore, the final report was structured to present the study task analysis results at a consistent level of detail within each separate volume.

The accompanying figure illustrates the product buildup of the study and the report breakdown. The documents that comprise the reports are described below:

Volume I - MISSION ANALYSES, contains the following data:

- Generic mission models that identify the potential earth orbit mission events of all the elements considered in the study
- Potential element pair interactions during on-orbit operations
- Categorized element pair interactions into unique interfacing activities

Volume II - INTERFACING ACTIVITIES ANALYSIS, contains the following data:

- Cross reference to the mission models presented in Volume I
- Alternate approaches for the interfacing activities
- Design concept models that are adequate to implement the approaches
- Operational procedures to accomplish the approaches
- Functional requirements to accomplish the approaches
- Design influences and preferred approach selection by element pairs.

This volume is subdivided into four books or parts which are:

Part 1. INTRODUCTION AND SUMMARY - Condensed presentation of the significant results of the analyses for all interfacing activities

Part 2. STRUCTURAL AND MECHANICAL ACTIVITY GROUP

- Mating
- Orbital Assembly
- Separation
- EOS Payload Deployment
- EOS Payload Retraction and Stowage

Part 3. DATA MANAGEMENT ACTIVITY GROUP

- Communications
- Rendezvous
- Stationkeeping
- Detached Element Operations

Part 4. SUPPORT OPERATIONS ACTIVITY GROUP

- Crew Transfer
- Cargo Transfer
- Propellant Transfer
- Attached Element Operations
- Attached Element Transport

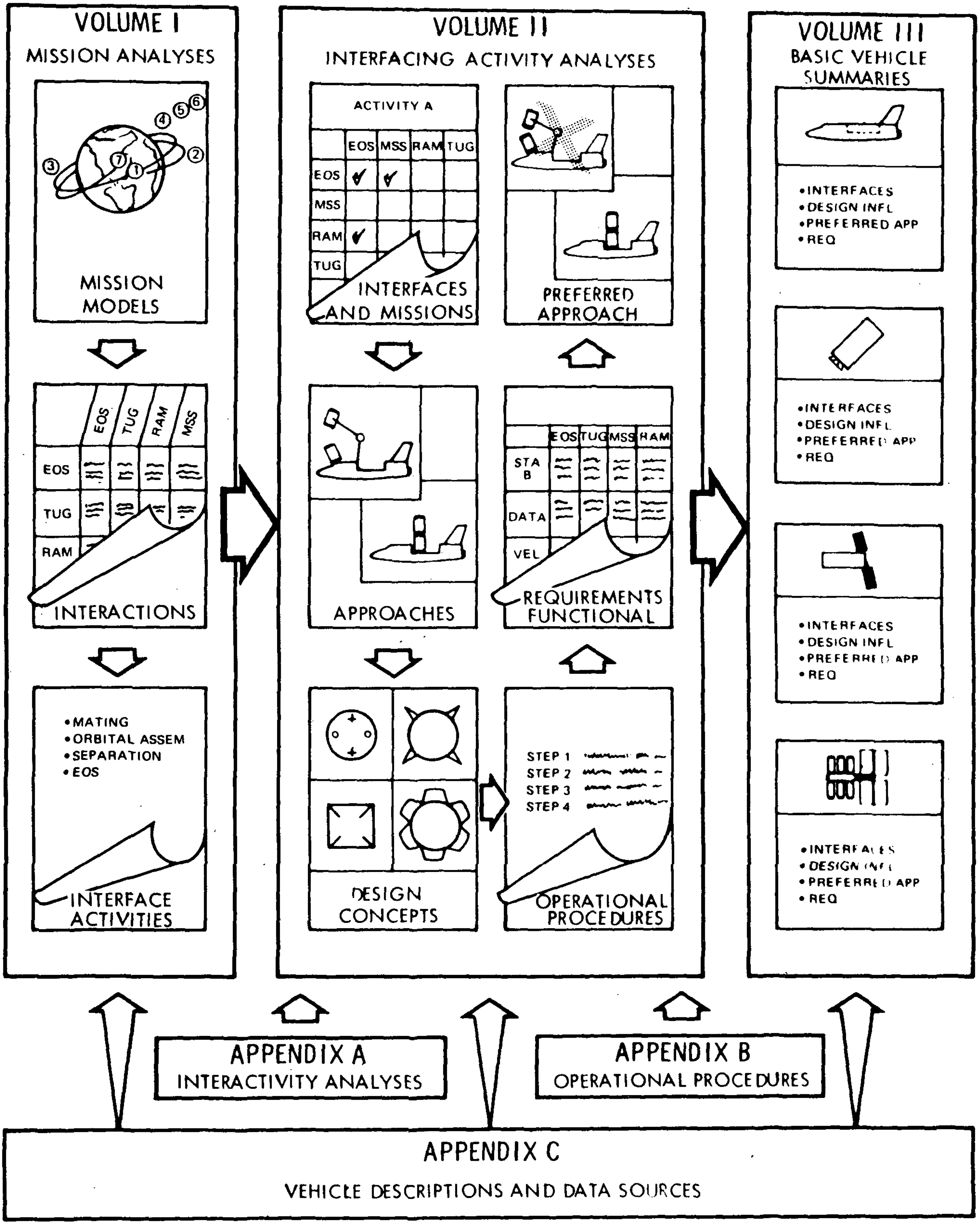
Volume III - BASIC VEHICLE SUMMARIES, contains a condensed summary of the study data pertaining to the following elements:

- Earth Orbital Shuttle
- Space Tug
- Research and Applications Modules
- Modular Space Station

Appendix A - INTERACTIVITY ANALYSES, contains many of the major trades and analyses conducted in support of the conclusions and recommendations of the study.

Appendix B - OPERATIONAL PROCEDURES, contains the detailed step-by-step sequence of events of each procedure developed during the analysis of an interfacing activity.

Appendix C - VEHICLE DESCRIPTIONS AND DATA SOURCES, presents a synopsis of the characteristics of the program elements that were included in the study (primarily an extraction of the data in Appendix I of the contract statement of work), and a bibliography of the published documentation used as reference material during the course of this study.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INTRODUCTION

This specific book is one part of the analyses conducted for each of fourteen interfacing activities. The results from four of the activities are documented in this book (Volume II Part 3). These activities are as follows:

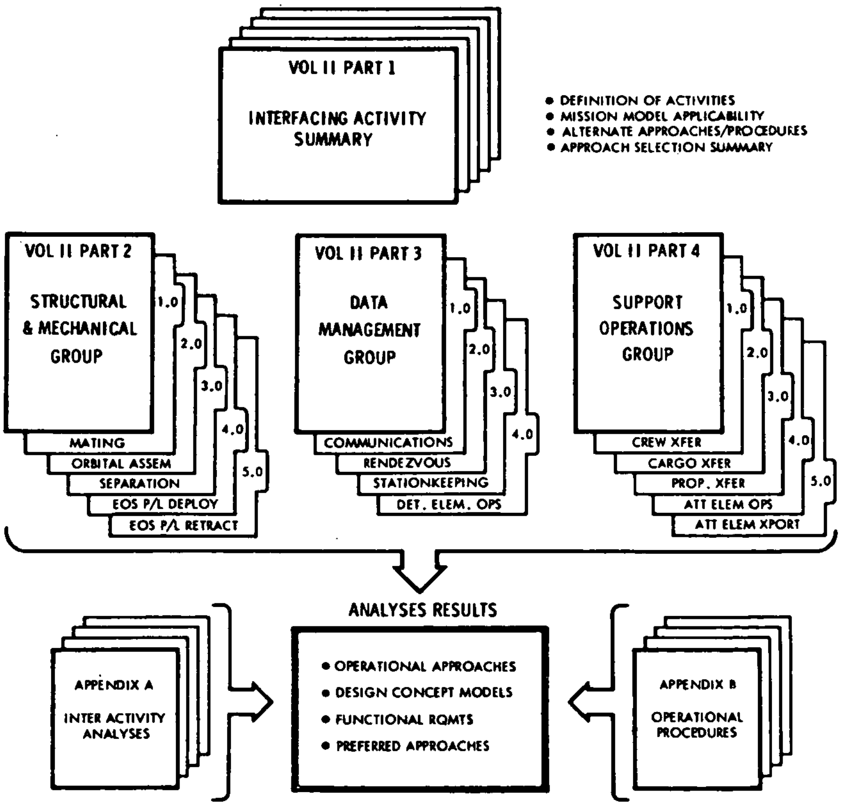
Section 1.0 COMMUNICATIONS

Section 2.0 RENDEZVOUS

Section 3.0 STATIONKEEPING

Section 4.0 DETACHED ELEMENT OPERATIONS

The following illustration shows the relationship of this book to the other related documents.



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ILLUSTRATIONS

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Figure Page

DETACHED ELEMENT OPS

TABLES

1.0 COMMUNICATIONS

The communications interfacing activity encompasses the methods of transfer of information between elements and to and from ground via communications links. Included in this information flow are voice, video, analog data, digital data, command/control digital signals, ranging signals, and tracking data. Each part of this information flow is an integral part of other interfacing activities and is used to accomplish a specific requirement of these other activities. Communications provide the tool to transfer the necessary information between elements.

1.1 SUMMARY

Communications is a support activity by itself. Reference to functional requirements in other activities shows that 11 of the remaining 13 impose communication requirements. Seventy communication interactions were identified from the 117 potential interactions displayed by Figure 1-1.

Three generic approaches were synthesized to structure operational procedures for the development of functional requirements. Each of the approaches (1) element-to-element, (2) element-to-TDRS, and (3) element-to-ground direct will probably be used during the operation of any mission.

Since a ground network and a TDRS model was established by NASA, all communication links were determined to be compatible with their characteristics. Ku, S, and VHF bands were chosen for all operations for this reason. Other frequencies, X, C, and UHF, were rejected for noncompatibility reasons.

An operations constraint of the TDRS should be pointed out. All communications utilizing TDRS must flow through the TDRS ground control center. This is true for any ground/element operation using TDRS as well as any element-to-element communications. Two elements out of line of sight with each other, but in sight of a single TDRS, must still communicate with each other through the TDRS ground control center. As presently conceived, TDRS does not have the capability to crosstrap channels directly through a single satellite or from one TDRS to another TDRS. It is easily practical, however, to configure the TDRS with the capability for channel crosstrapping.

The operations procedures for the three approaches were divided further into procedures for data transfer, tracking and ranging and command and control. Differences between operations for these procedures are mainly evident in the necessity for handover procedures for the element/ground (direct or TDRS) approach; otherwise the operations procedures are very similar. Location of command and control and the data processing center are different between ground/element and element/element operations.

A parametric study was performed and evaluates the communication and tracking capability of spacecraft orbiting the earth at altitudes between 100 and 500 nautical miles. Assumptions encountered throughout the analysis are briefly discussed and typically represent state-of-the-art communication system parameters. As such, data contained herein are not optimum as simultaneous manipulation of a half-dozen or more uniquely dependent link parameters will result in different operational requirements. The intent of this analysis is to provide generalized operational data applicable to all orbital elements, thereby maintaining equipment commonality necessary for efficient communications during orbital operation activities. An attempt has been made to provide tentative functional requirements for individual element pairs. These requirements are subject to modification due to differences in assumptions or link capability requirements. The tabular requirements should, however, provide a good reference and indication of the general requirements magnitude. In developing detailed functional requirements for terminal characteristics, a series of curves relating antenna size, range and power can be used. These curves and the use and modification for different parameter assumptions are discussed in the requirements analyses. From this basic data a complete set of tabular requirements was derived for element pairs and by individual element terminal.

The Design Concept Models paragraph summarizes the hardware concept in terms of performance capability and communications terminal performance. Performance is defined in terms of receiver, transmitter and antenna characteristics in each of the frequency bands implemented. VHF links can be accommodated with a 25-watt transmitter and an omni-directional antenna. An S-band system with 30 watts RF power output and an omni-directional antenna can satisfy most of the element-to-element links. Much lower powers would be sufficient for operation to ground.

Operation with TDRS, when higher data rates and greater continuity of contact with ground are necessary, necessitates the use of a Ku-band system with a 25-watt RF power output and a steerable high-gain, 5-foot-diameter antenna.

All three approaches are recommended for use in orbital operations planning. VHF can be used as an alternate or backup mode and is necessary for order wire service when using TDRS. S-band is recommended as the primary mode for either element-to-element or element-to-ground. When elements must transfer data at rates higher than 1 Mbps or need a continuity of communications not available with the ground network, Ku-band systems should be incorporated. The two-TDRS-system will allow better than 85 to 90 percent orbital coverage of lowest orbit type satellites. Data rates up to 50 Mbps can be accommodated. The RAM, MSS, and a number of satellites were identified as the minimum number of elements needing the services of TDRS.

1.2 ELEMENT INTERFACE AND MISSION MODEL MATRICES

The element-to-element orbital interfacing operations of each of the elements under consideration in this study were analyzed to determine element-to-element communications interfaces. These communications interactions are shown in matrix form in Figure 1-1. The identified communications functional requirements include voice, data transfer (including command and control signals), television, and tracking and ranging. As shown in Figure 1-1, 70 element-to-element communications interfaces (space links only) were identified. Most of these interfaces occur as interfaces with the earth orbit shuttle (EOS) orbiter (20 interactions), the ground-based tug (11 interactions), and the space-based tug (13 interactions).

Figure 1-1 does not include either (1) hardwire communications interfaces, which are covered in Part 4, Section 4, as a functional requirement of "Attached Element Operations," or (2) the need for laser scanning radar corner cube reflectors when they are required as mating aids only. This functional requirement is discussed in Part 2, Section 1. Interfaces between ground (either direct or via TDRS) and space elements are not covered in the matrix of Figure 1-1. These interfaces are necessary for ground control of space elements and for tracking, ranging and data transfer necessary between ground and space elements. Interactions shown in Figure 1-1 which require some clarification or are noteworthy are:

1. The only requirements for space link communications between the nonreturnable or returnable tugs are with the EOS orbiter. These vehicles are unmanned "kick" stages delivered to earth orbit in the orbiter cargo bay. Data transfer between the orbiter and these type of tugs is required for checkout and command and control purposes after the tugs are deployed in orbit from the orbiter cargo bay. The tugs also must be cooperative (i.e., transpond tracking and ranging signals back to the orbiter, hence, the requirement for tracking and ranging).

2. The interactions shown for a satellite interfacing with either a ground- or space-based tug occur when the tug in question is employed to retrieve, resupply, or inspect the satellite. The television requirement is for inspection when the tug is unmanned.

3. The voice requirement shown for the EOS orbiter-to-EOS plus third-stage satellite covers the case where the third stage in question is a manned tug.

4. No communications interfaces exist between the LSB and other orbital elements in earth orbit, because the LSB is never manned or made functionally active until it is assembled on the lunar surface.

5. All of the OPD interface requirements for television pertain to docking and propellant transfer observation.

		SPACE VEHICLE INVENTORY																								
		EOS	TUG				RAM				SATELLITE			EO RESUP MODS	MSS		CPS			RNS	LUNAR PROGRAM SYSTEMS					OPD
			NON RET	RTN	GRD BASED	SPACE BASED	ATT. EOS	DET. EOS	ATT. MSS	DET. MSS	EOS DELIV	EOS + 3RD ST	RETR, RESUP		LOW EO	GEO SYNCH	OIS	EO SHTL	CLS		OLS	TUG UNMAN	TUG MAN	RESUP MOD	LSB	
	EOS	DRV	DR	DR	DRV	DRV	DV	DRV	X	DRV	DR	DRV	DR	X	DRV	DRV	▨	DRV	DRV	DRV	DRV	D	DV	X	X	DRV
TUG	NON RET		▨	▨	▨	▨	▨	▨	▨	▨	▨	X	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
	RETURNABLE			▨	▨	▨	▨	▨	▨	▨	▨	X	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
	GRD BASED				A	A	▨	▨	X	A	▨	X	DRT	X	▨	A	▨	DRV	A	A	▨	DR	A	X	▨	A
	SPACE BASED					A	▨	▨	X	A	▨	X	DRT	X	A	A	DR	DRV	A	A	A	DR	A	X	X	A
RAM	ATT. EOS						▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
	DET. EOS							▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
	ATT. MSS								▨	▨	▨	▨	▨	▨			▨	X	▨	X	▨	▨	▨	▨	▨	▨
	DET. MSS									▨	▨	▨	▨	▨	A	A	▨	DR	▨	DR	▨	▨	▨	▨	▨	▨
SATEL	EOS DELIV										▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
	EOS + 3RD ST											▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
	RETR, RESUP												▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
	EO RESUP MODS													X	X	X	▨	X	X	X	▨	X	X	X	▨	X
MSS	LOW EO														X	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
	GEOSYNCH															X	▨	DRV	▨	DRV	▨	▨	▨	▨	▨	▨
CPS	OIS																▨	DR	DR	DR	DR	▨	▨	▨	▨	DRT
	EO SHTL																	A	▨	▨	▨	▨	▨	▨	▨	A
	CLS																		A	▨	DRV	DR	DRV	X	X	DRV
	RNS																			X	DRV	DR	A	X	X	A
LPS	OLS																				X	DR	A	X	▨	▨
	TUG UNMAN																					▨	▨	X	X	DRT
	TUG MAN																						▨	X	X	A
	RESUP MOD																							X	X	X
	LSB																								X	▨
	OPD																									X

LEGEND

Potential Interactions	117
Actual Interactions	70
D - Analog/Digital Data Xfer	70
R - Tracking and Ranging	67
V - Voice	49
T - Television	30
A - All four types above	26
X - Not Applicable	47

Figure 1-1. Communications Interactions

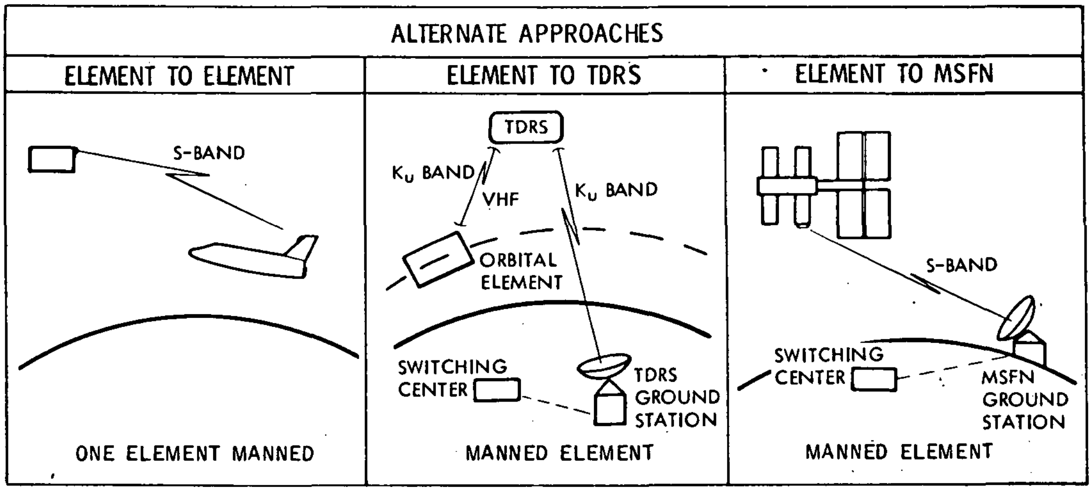
To provide traceability back to the mission models (see Volume I), another interface matrix is shown as Figure 1-2, which lists the mission models that involve a communications interaction between the elements in question. As expected, element-to-element communication interactions are involved in all 11 mission models.

		SPACE VEHICLE INVENTORY																								
		EOS	TUG				RAM				SATELLITE			EO RESUP MODS	MSS		CPS			RNS	LUNAR PROGRAM SYSTEMS					OPD
			NON RET	RTN	GRD BASED	SPACE BASED	ATT. EOS	DET. EOS	ATT. MSS	DET. MSS	EOS DELIV	EOS + 3RD ST	RETR, RESUP		LOW EO	GEO SYNCH	OIS	EO SHTL	CLS		OLS	TUG UNMAN	TUG MAN	RESUP MOD	LSB	
	EOS	2	1	2	2,5,7,8	1,2,4,5,8,10	3	1,2	☒	1,2,4,5,7,8	1	1,4,7	2,4,5,8	☒	1,2	1,5,7,8,11	▨	1,2,5,8,10,11	1,2,5,8,10,11	1,2,5,8,11	1,2,5	2,8	2,4,5,8,10,11	☒	2	1,2,5,10
TUG	NON RET		▨	▨	▨	▨	▨	▨	▨	▨	▨	☒	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
	RETURNABLE			▨	▨	▨	▨	▨	▨	▨	▨	☒	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
	GRD BASED				8	5,8	▨	▨	☒	7,8	▨	☒	8	☒	▨	7,8	▨	8,10,11	8,10,11	8,11	▨	8	8	☒	▨	8
	SPACE BASED					4,5	▨	▨	☒	4,5	▨	☒	4,5	☒	2,4,5,6	4,5,6,11	4,5,6,9	4,5,6,10,11	4,5,6,10,11	4,5,6,11	4,5	5	4,5,10,11	☒	5	2,4,5,6,9
RAM	ATT. EOS						▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
	DET. EOS							▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
	ATT. MSS								▨	▨	▨	▨	▨	▨	☒	☒	▨	☒	▨	☒	▨	▨	▨	▨	▨	▨
	DET. MSS									▨	▨	▨	▨	▨	1,2,5	4,5,7,8	▨	10,11	▨	11	▨	▨	▨	▨	▨	▨
SATEL	EOS DELIV										▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
	EOS + 3RD ST											▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
	RETR, RESUP												▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
	EO. RESUP MODS													☒	☒	☒	▨	☒	☒	☒	▨	☒	☒	☒	▨	☒
MSS	LOW EO														☒	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
	GEOSYNCH															☒	▨	4,5,8,10,11	▨	4,5,8,11	▨	▨	▨	▨	▨	▨
CPS	OIS																▨	9	9	9	9	▨	▨	▨	▨	9
	EO SHTL																	4,5,8,10	▨	▨	▨	▨	▨	▨	▨	4,5,10
	CLS																		4,5,8,10	▨	2,4,5,10,11	5,10,11	4,5,8,10,11	☒	5,10,11	4,5,8,10,11
	RNS																			☒	2,4,5,11	5,11	4,5,8,11	☒	5,11	4,5,8,11
LPS	OLS																				☒	2,5	2,4,5	☒	▨	▨
	TUG UNMAN																					▨	▨	☒	2,5	2,5,8
	TUG MAN																						▨	☒	2,5	2,4,5,8
	RESUP MOD																							☒	☒	☒
	LSB																								☒	▨
	OPD																									☒

Figure 1-2. Applicable Mission Models for Communication

1.3 ALTERNATE APPROACHES

Three fundamental communication link approaches are applicable for earth orbiting elements. They are (1) element to ground, (2) element to tracking and data relay satellite (TDRS), and (3) element-to-element. The first two approaches are dependent upon the characteristics of the Ground Network and TDRS. For the purpose of this study, the Ground Network and TDRS models developed by the Space Station Task Group (Reference Appendix C DS-504) will be used exclusively. Mission operations will probably utilize each of these alternates during a mission. It is likely that low (≤10 Kbps) and medium data rates (≤1 Mbps) will be handled by the Ground Network. TDRS could handle low data rates on VHF and up to 50 Mbps or Television on Ku Band. Requirements of individual elements will dictate which is used. TDRS can provide more nearly continuous communications than the Ground Network model.



ELEMENT-TO-GROUND AND ELEMENT-TO-TDRS LINKS

The links between orbital elements and the Ground Network or TDRS are illustrated in Figure 1-3. As indicated, the Ground Network uses S-band for communications. TDRS uses VHF for voice and low data rates normally associated with command signals and Ku-band for high data rates including television transmission. To ensure compatibility with the Ground Network and TDRS, the corresponding frequency bands are considered a requirement for these two approaches.

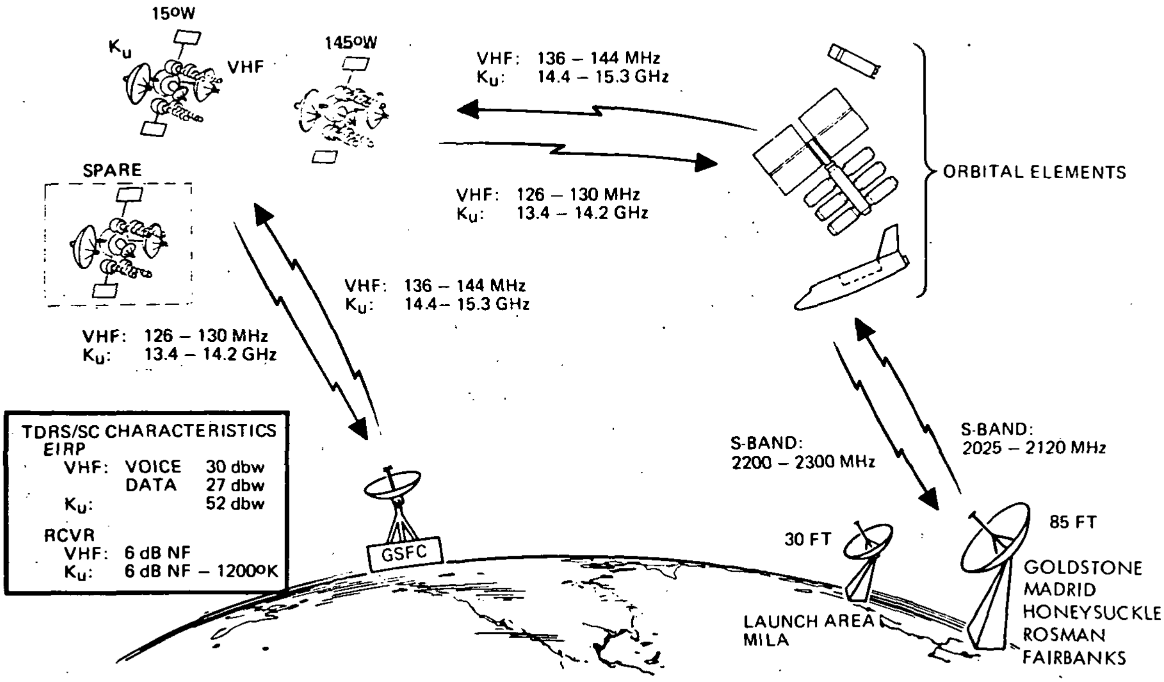


Figure 1-3. Ground Network and Synchronous Satellite Model (TDRS)

ELEMENT-TO-ELEMENT LINK

Appendix A delineates the trade study made that defines VHF, S band and Ku band as the most desirable frequencies for element-to-element communications link. This provides compatibility with the ground and TDRS and the required performance. A discussion of a modulation/demodulation techniques is included in Appendix A. It results in the recommendation for techniques compatible with Ground Network System. PRN range code directly PM (PSK) modulates the carrier., digital data is PM (PSK) modulated on a 1.024 MHz sub-carrier and voice FM modulates a 1.25 MHz sub-carrier. These sub-carriers PM modulate the RF carrier. Direct carrier PM (PSK) modulation is necessary for high data rates (1 to 50 Mbps). The PCM/PSK/PM technique described above can be used for simultaneous ranging and data transfer for medium data rates. These are the only techniques considered in this study. Adequate ranging and tracking, command and data links can be provided at these frequencies. In order to provide the necessary range and range-rate accuracies at close ranges (50 nautical miles to dock) for rendezvous, stationkeeping, and docking a laser radar system is recommended to supplement the PRN S-band range system.

1.4 DESIGN CONCEPT MODELS

Communications system design concepts were established on (1) compatibility with the ground network and TDRS, (2) compatibility with the data transfer requirements of the various interfacing activities supported by communications, (3) the available technology state of the art for receiver and transmitter characteristics, and (4) minimum complexity. Appendix A includes analyses that result in the establishment of three frequency bands for the communication links. These are (1) VHF, (2) S-band, and (3) Ku-band. Any of these bands could be used for element-to-element links according to the individual element pair requirements and the capability of the frequency band. Very high frequency (136 to 144 MHz) was chosen to be compatible with the TDRS low data rate link. Its limitations are defined in Table 1-1. S-band (2025 to 2300 MHz) is compatible with the NASA ground network model and can be used for medium data rates as defined in Table 1-1. High data rates (see Table 1-1) can be accommodated by Ku-band from element to TDRS to ground.

Table 1-1 Data Link Capabilities

	Forward Link (Up Link)	Return Link (Down Link)
S Band* (with ground)	1000 bps voice	1 Mbps voice television (FM baseband 1 MHz)
Ku Band*	100-1000 bps and data up to video plus voice	Greater than 1 Mbps up to 50 Mbps and/or video plus voice
VHF (with TDRS)	100-1000 bps plus voice	100-10,000 bps plus voice

*Both S and Ku band also provide the capability for PRN ranging simultaneously with other signals.

VHF is used for low data rates, voice links, TDRS order wire service, and element wake-up service. Omni-directional antennas (whip type) associated with a 25 watt, solid-state transmitter and an element 1200°K receiver system temperature provides sufficient performance for the required links. The link with TDRS requires a spread-spectrum modulation technique that was established to reduce multipath problems. The VHF link, either between elements or between element and TDRS is usable for single duplex voice channels, command digital signals, and low data rate (<10 kbps) telemetry signals.

S-band is used for medium data rates (up to 1 Mbps), voice links, and Apollo quality television service. Operation with ground stations requires relatively low power (less than 5 watts), omni-directional antennas and receiver noise temperatures of 1500° to 2000° K. Such a design is possible because of the ground station parameters that include an 85-foot diameter (51 db gain) antenna, a 10 or 20 kw transmitter power and ground receiver system noise temperature of 125° K. Element-to-element links, however, may require hi-gain directional antennas and transmitter powers up to 100 watts according to the service and separation range. In order to keep the transmitter power within reasonable state of the art for solid state equipment and enable use of omni-directional antennas it will be necessary to limit separation ranges to 150 nautical miles or less according to data transfer requirements. This would put a ceiling of approximately 30 kbps on digital data transfer. This assumes the use of a 30-watt solid-state transmitter (within present day technology) and an omindirectional antenna. When element-to-element requirements require higher data rates at longer ranges, a directional antenna can be used with a 30-watt transmitter. With a 5-foot parabolic antenna (28 db gain), 1 Mbps may be transferred over a range of 500 nautical miles. There are few cases where high data rates ($>$ 50 kbps) need be transferred over relatively long ranges ($>$ 150 nautical miles). RAM and MSS are the elements involved with these higher rates. In these cases, it is more effective to use a Ku-band system when the transfer of TV and data rates from 1 Mbps to 50 Mbps are involved.

Ku-band is used for high data rates, voice links, and good quality black and white or color TV. It is needed for operation to ground through the TDRS. One of the major advantages of TDRS is the capability to provide almost continuous orbital communications with low earth orbit elements. Communications with ground direct could result in contact gaps as well as relatively short (less than 15 minutes) contacts per orbit. This assumes the 5 station ground network established by NASA (reference DS-504). Ku-band does require a directional antenna whether it is being used for element-to-element communications or element-to-TDRS-to-ground. It is, therefore, only recommended when either the data rate or continuity of contact with ground makes it necessary. The longest range link is to TDRS (approximately 23,000 nautical miles). Utilization of a 25-watt transmitter with a 5-foot parabolic antenna (45 db gain) can satisfy up to 25 Mbps digital data transfer to the TDRS. A receiver with a Tunnel Diode Amplifier (TDA) providing approximately a 1200° K noise temperature with this 5-foot antenna is usable for all TDRS-to-element link requirements. The maximum demand in this direction is 500 kbps or 4.5 MHz color TV. Element-to-element Ku-band operation would probably be supported by the same equipment used for element-to-TDRS contact. Color TV (4.5 MHz) could be supported to 2000 nautical miles with a 25-watt transmitter, a 1200° K receiver noise temperature, and 20 db gain horn antennas on each end of the link. When Ku-band is needed, it is recommended that a 25-watt transmitter (with a traveling wave tube amplifier (TWTA)), a 5-foot (45 db gain) parabolic antenna, and a TDA receiver front end (1200° K noise temperature) be used. These are all within present technology as displayed in Appendix A. The directional antenna must be a tracking type because of the narrow beamwidth ($\cong 1°$ at 3 db points) and capable of either auto-track or computer programmed tracking.

As detailed in Appendix A, it is recommended that modulation techniques compatible with the ground network be utilized for both S- and Ku-band links for data transfer up to 1 Mbps. This uses subcarriers for voice and digital data and direct carrier phase modulation for the PRN ranging signal. For higher data rates (up to 50 Mbps) direct carrier PSK should be used for the digital data. High-quality TV, black and white or color, will direct FM modulate the carrier.

Tracking and ranging, for ranges over 75 nautical miles between elements, utilizes the standard PRN ranging system as mechanized by the existing NASA ground network. This system provides the necessary accuracy for ranging and range-rate measurements and can provide orbital parameters by making successive range measurements from the ground stations. This system requires a coherent transponder on the measured vehicle. It accepts the range code signal from the interrogating station and re-transmits the signal at another carrier frequency that is coherent with the incoming carrier and at a known fraction thereof. A further discussion of this system is included in the analysis section herein. Typical accuracies after 1-1/2 orbits with measurements from four NASA ground stations are:

Parameter	Errors (1σ)
Range	
T	370 ft.
N	360 ft.
R	320 ft.
Range Rate	
$\dot{T}$	0.37 ft/sec
$\dot{N}$	0.42 ft/sec
$\dot{R}$	0.53 ft/sec

T = Down Range   N = Cross Range   R = Altitude

Utilizing similar measurement techniques with TDRS on Ku-band decreases these accuracies by a factor of three or more according to the length of time taken for measurements. Even these accuracies are, however, satisfactory for measurements when space elements are more than 75 nautical miles apart. At ranges less than 75 nautical miles to docking, during either stationkeeping, rendezvous or docking maneuvers, where accuracies must improve by orders of magnitude, a scanning laser radar system can provide the required precision. The measuring vehicle requires the scanning laser radar and the measured vehicle a set of corner cube optical targets for reflection purposes. Proper use of reflector configuration can actually provide not only range and range rate measurements but locate the docking port and provide an attitude measurement. Detailed discussion of the scanning laser radar is found in Mating (Part 2, Section 1.0) and in the Rendezvous section (2.0). Typical accuracies as shown below have been demonstrated on models of the Scanning Laser Radar (SLR).

Range: less than 75 nautical miles, ±4 in. or ±0.02%, whichever is greater

Range-rate: ± 1/2 in./sec or ± 1 percent, whichever is greater

An element that would provide a full complement of external communications capability would contain the following:

1. Ku-Band Receiver and Transmitter with a 5-foot parabolic dish antenna. The receiver would have a noise temp. of 1200°K and the transmitter would provide 25 watts of RF power to the antenna.

2. S-Band Receiver and Transmitter with a semi-directive antenna. The receiver would have a noise temp. of 800°K and the transmitter would provide 30 watts of RF power to the antenna.

3. VHF Receiver and Transmitter with an omni-directional antenna. The receiver would have a noise temp. of 1200°K and the transmitter would provide 25 watts of RF power to the antenna.

4. Active Scanning Laser Radar (SLR) system and/or passive optical corner cube reflector. The SLS would have a manned range of 75 nautical miles.

These characteristics and the parameters thereof would be subject to modification according to link capacity requirements. The analysis section provides further details for an understanding of the choices for particular element pairs and elements.

Element transmitters should contain the capability to reduce power output in a step function. This is used in element-to-element communications as the range between elements decreases to avoid receiver overloading. When using S-band or VHF, omni-directional capability must be obtained without changing element attitude. This may require more than one antenna. This could mean either switching to several antennas or providing a receiver/transmitter at each antenna.

Complete system mechanization may mean more than one frequency operation in a particular band according to the number of different frequency links required or the number of simultaneous links necessary. The MSS, for instance, may require the capability to contact five different terminals; two RAM's, a ground station, the EOS, and the TDRS. Sequential operations can be accommodated simply by assigning unique "addresses" to each link. Assignment of specific frequencies within the passband to various element pair links can alleviate the potential receiver saturation problem of multiple simultaneous transmissions between two sets of elements. None of the individual element studies, including MSS evaluations, identified a requirement for simultaneous communications with two or more terminals.

1.5 OPERATIONAL PROCEDURES

Three sets of operational procedures were developed, one for each alternate approach. Each set contains subsets for the different types of communications activity; i.e., data transfer, tracking and ranging, and command and control. Modifications are also noted to account for unscheduled, urgent, and non-urgent operations in the ground-to-element interface (either direct ground via the ground network or by TDRS). Although the three approaches appear as alternates, it is probable that each alternate link will be used during element missions. This drives the requirement for element-to-element links to be compatible with ground network and/or TDRS links. It should also be noted that the ground network or TDRS communications links will require a handover procedure from one station to the next when the contact carries on beyond the element containment in the field of view of a single station. Handover accounts for the major difference between the procedures. Element-to-element links can be continuous, as necessary, since it is assumed that the two elements are always in line of sight of each other. The other delta--the processing and routing of data differs only in respect to the location of the data processing. It is likely that one of the space elements--in the element-to-element interface--will process the data and either display it on board or store it for future transmission to ground and subsequent routing to user. Such a case would occur in the case of a space station and RAM. The space station would collect data from the RAM, process it and either display it on board or store it and then transmit to the ground at the appropriate time.

Details of the assumptions, initial and final conditions are included with each of the operational procedures contained in Appendix B.

Communications is a supporting activity to other orbital operations activities. Examination of the Operational Procedures Applicability matrix (in Appendix B) indicates that only element-to-element orbital pairs are included. For these pairs, the element-to-element alternate communications is the only applicable operational procedure. There is, however, the requirement in most cases to communicate with ground, for data transfer and/or monitor and control of the orbiting element. Thus, most orbiting elements will need to interface with ground utilizing either a direct ground link or a link through TDRS to ground. Under certain circumstances, the element to ground link might also be used for element-to-element communications. This would occur if the orbital elements were out of communications line of sight with each other. The communications link would probably not be a direct relay, but rather an element-to-ground transmission, a deciphering by ground control, a ground control decision, and then finally a ground-to-element transmission. The basic area for examination of commonality is the communication frequency band or bands to be utilized for element-to-element interface that will account for compatibility with the element-to-ground frequency bands. As discussed in functional requirements (paragraph 1.6), this involves an iteration of requirements to ensure the proper choice of parameters to fulfill all the requirements with equipment commonality and complexity considerations. As indicated, communications links are for 33 element pairs (see applicability matrix in Appendix B).

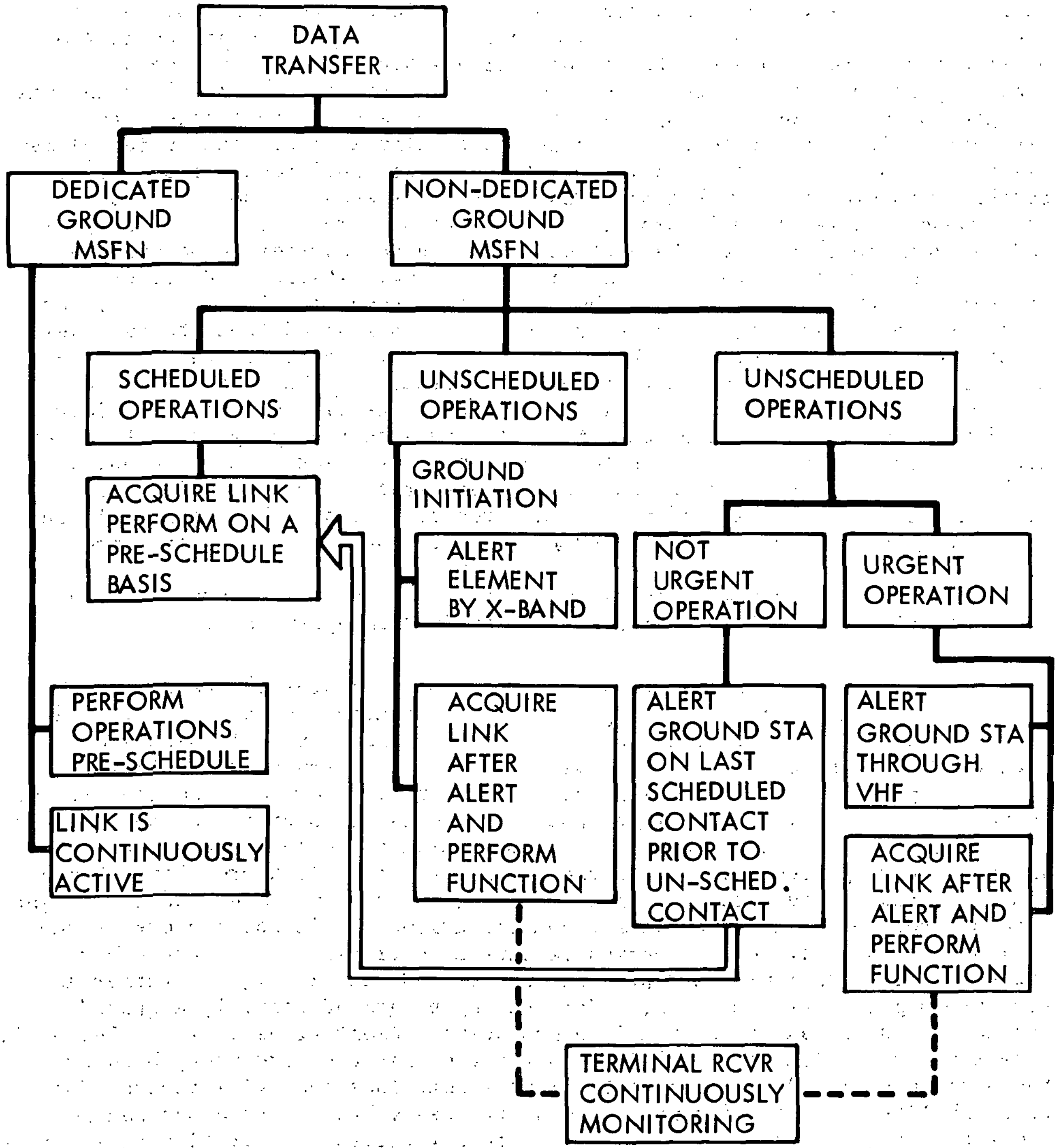


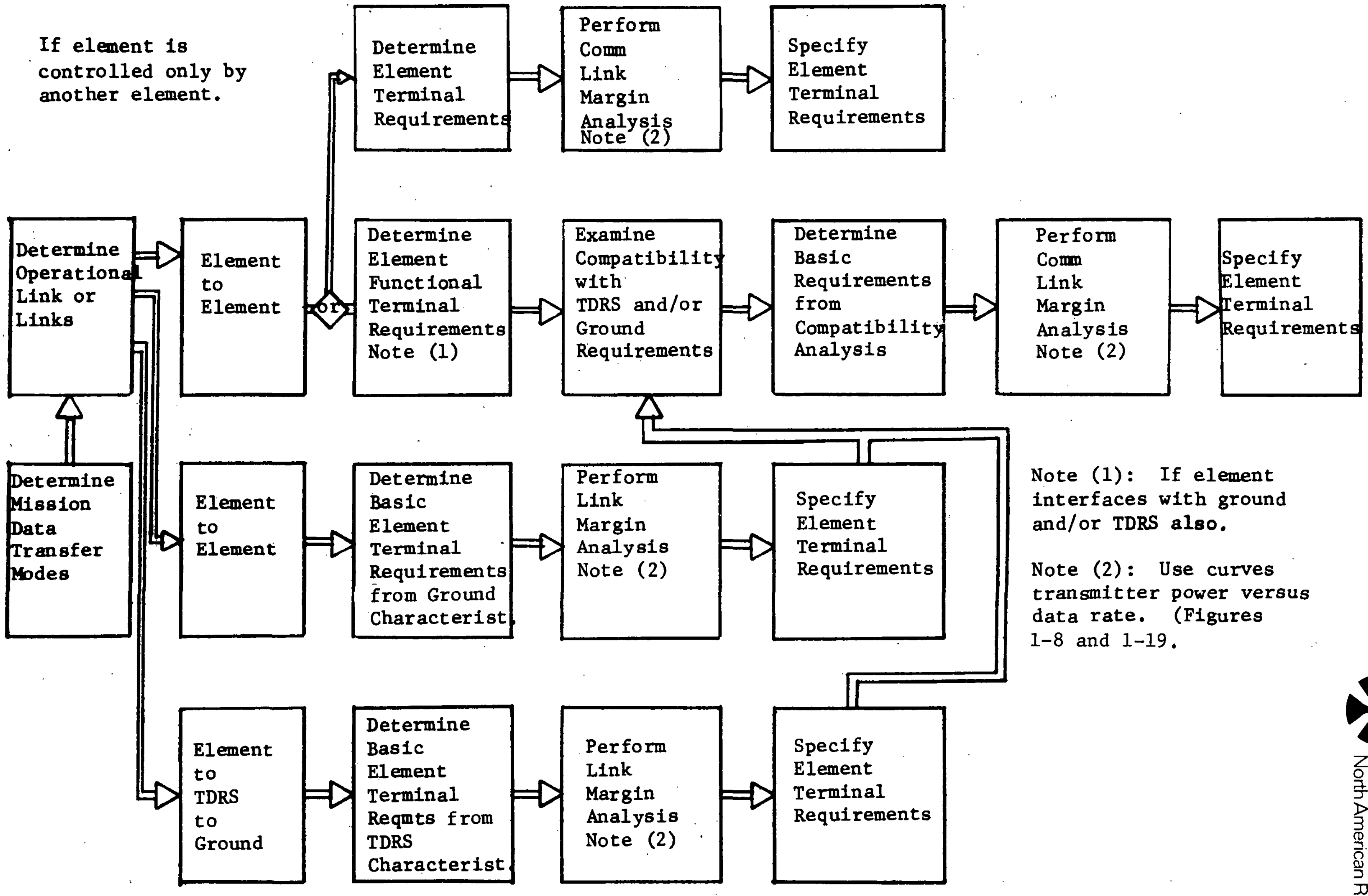
Figure 1-4. General Operations Flow

1.6 FUNCTIONAL REQUIREMENTS

Communications shall be capable of supporting data transfer, command and control, and tracking and ranging necessary during various operational activities between elements and between elements and ground. Each operation and each element involved must be examined for specific supporting requirements in terms of data rates, separation ranges, tracking and ranging accuracies, and modes of operation. When operation with ground is involved, certain constraints are imposed by the characteristics of the TDRS and the ground network as specified in the NASA model (reference Appendix C, DS-504). Utilizing these data and then performing an analysis to ensure compatibility between elements and elements and ground, a tentative set of functional requirements for element terminals can be derived. This derivation utilizes a series of curves developed from communication link margin analyses that assume certain parameters and then allows the choice of certain terminal characteristics versus types of data transmission. These resultant terminal characteristics, listed by element pairs, are subject to changes of basic data requirements and specific assumed parameters. A further discussion of methods to quickly effect changes is included under the analyses discussion.

Figure 1-5 defines the basic approach to determining detailed functional requirements for each element. In essence, it ensures a choice of parameters that will meet the performance requirements of any orbital element communication link for the particular element. Since the TDRS and ground network model impose certain requirements and need to be used for compatibility, Tables 1-2 and 1-3 are included to show the characteristics of these terminals utilized in the analyses herein.

This section first provides basic functional requirements in tabular format defining their application to the alternate approach procedures. These procedures are presented in Appendix B. This is followed by a set of matrices that define in detail, by element pairs, specific characteristics of the communications links. The last portion includes the analyses that were conducted to establish the specific requirements included in these matrices.



If element is controlled only by another element.

Note (1): If element interfaces with ground and/or TDRS also.

Note (2): Use curves transmitter power versus data rate. (Figures 1-8 and 1-19.

Figure 1-5. Requirements Definition Flow

Table 1-2. TDRS Characteristics

Forward Link TDRS To Element	Low Data Rate VHF Band	Medium/High Data Rate Ku Band
Frequency	126-130 MH_z	13.4-14.2 GH_z
Data Transmission Capability	1 voice channel plus 1.0 Kbps Digital Data	Up to 50 Mbps Digital Data or Up to Color Video TV Analog
Channels Available	2	2
EIRP	Voice = 30 dBW Command = 27 dBW	52 dBW
Return Link Element to TDRS		
Frequency	136-144 MH_z	14.4-15.35 GH_z
Receiver System Noise Figure (Incl. Earth Background)	6 dB	6 dB (1200°K)
Bandwidth (per channel)	2 MH_z (Spread Spectrum)	200 MH_z
Data Transmission Capability	Voice plus 10 Kbps Digital Analog	Up to 50 Mbps Digital or Up to Color TV -4.5 MH_z Video
Channels	20 Digital, 1 Voice	2
Antenna	16 dB Gain End Fire Array 26° Beamwidth, Cross-Polarized	2 - 5 ft. Parabolas 45 dB Gain

Table 1-3. Ground Network Stations
Communication Characteristics
Goldstone/Madrid/Honeysuckle Creek

Transmitter		**Receiver**	
Frequency	2090-2120 MH$_z$	Frequency	2270-2300 MH$_z$
Carrier EIRP	94 or 97 dBW	Receiver Noise Figure	1.7 dB
85 Foot		85 Foot	
Antenna Gain	51 dB	Antenna Gain	52 dB
Power Amplifier		IF Bandwidth	6.0 MH$_z$
Carrier Output	20 KW or 40 KW		
Carrier Modulation	PM (Coherent)	Carrier Modulation	PM (Coherent)
Voice Subcarrier	30 KH$_z$, FM	Carrier Frequency	2282.5
(100-2000 H$_z$)	±7.5 H$_z$ Deviation	Voice Subcarrier	1.25 MH$_z$, FM
Updata Subcarrier	70 KH$_z$, FM	Telemetry Subcarrier	1.024 MH$_z$, FM
	±5.0 KH$_z$ Deviation		1.6 Kbps, 51.2 Kbps
2 KH$_z$ Sine Wave, Bi-Phase Modulation		Television	FM
1 KH$_z$ Sync Tone			Direct on Carrier
		Carrier Frequency	2272.5 MH$_z$

FUNCTIONAL REQUIREMENTS TABULAR LIST

As previously mentioned, communications is a support activity to most all of the interfacing activities. Functional requirements are therefore established by the communications needs of each of these activities. An analysis of each activity and the elements involved results in the basic functional requirements to be provided by communications support. The tabular list reflects the generic requirements by the type of element (controlling and controlled) and their application to the three alternate approaches. Each element pair requires different quantitative criteria based upon its mission. This listing reflects the range of parameters. Following this are two tables (Table 1-4 and 1-5) delineating details of functional requirements for the communications terminals at both ends for each approach. Data transfer requirements encompass the scope of this study. Utilization of the curves referenced in the radiated power column and specific data transfer requirements for element pairs determines element power needs.

	Related Procedure		
	Element to		
	Gnd. 9-1	TDRS 9-2	Elmt. 9-3
1. The controlling element shall be capable of transmitting command digital signals, voice and other miscellaneous digital and analog data to the controlled element and/or to ground direct or via TDRS. It shall transmit the signals at sufficient power level to provide signals at the receiver that will result in high enough signal-to-noise ratio to ensure the required signal quality.	X	X	X
a. Voice and low data rates (up to 10 kbps) operation will be at VHF frequencies.		X	X
b. Voice, medium data rates (up to 1 Mbps) and TV up to 2.9 MHz video baseband operation will be at S-band.	X		X
c. Voice and medium data rates or high data rates (up to 50 Mbps) and 4.5 MHz video, operation will be at Ku-band.		X	X
2. The controlling element shall be capable of receiving, demodulating, and demultiplexing the data signals transmitted by the controlled element and/or ground direct or via TDRS, with low enough noise contribution to provide signal qualities within specifications.	X	X	X
a. Voice and low data rates (up to 1 kbps) operation will be at VHF frequencies.		X	X
b. Voice and medium data rates (up to 1 Mbps digital) shall be at S-band frequencies.	X		X
c. Voice and high data rates (up to 50 Mbps digital) shall be at Ku-band frequencies.		X	X
3. The controlled element shall be capable of transmitting an RF modulated signal that accommodates various combinations of analog and digital data as required by the particular element operations to the controlling element. The controlling element could be either another space element or ground. Ground may be contacted either direct or via TDRS. The controlled element shall radiate sufficient power to provide signal strength at the receiver that will result in high enough signal-to-noise ratios to ensure the required signal quality.	X	X	X

	Related Procedure Element to		
	Gnd. 9-1	TDRS 9-2	Elmt. 9-3
a. For voice and low data rates (up to 10 kbps) operation will be at VHF frequencies.		X	X
b. For voice, medium data rates (up to 1 Mbps digital), and TV either 2.9 MHz or 4.5 MHz, operation will be at S-band frequencies.	X		X
c. For voice and medium data rates or high data rates (up to 50 Mbps digital) and 4.5 MHz video, operation will be at Ku-band.		X	X
4. The controlled element shall have the capability to receive, demodulate demultiplex and route command digital signals, voice and other miscellaneous digital and analog data from any controlling element (TDRS, ground or element). It shall provide receiver system noise temperature low enough to result in signal qualities within specifications, when provided with signal levels as transmitted from the controlling elements.	X	X	X
a. Voice and low data rates (up to 10 kbps) operation will be at VHF frequencies.		X	X
b. Voice, medium data rates (up to 1 Mbps) and TV either 2.9 MHz or 4.5 MHz video.	X		X
c. Voice and medium data rates or high data rates (up to 50 Mbps) and 4.5 MHz video, operation will be at Ku-band.		X	X
5. The controlling or supporting element shall be capable of transmitting a PRN range code signal to the controlled element and receiving the turnaround signal for processing to determine range and range rate.	X	X	X
a. It shall be accomplished at an S-band operating frequency.	X		X
b. It shall be accomplished at a Ku-band operating frequency.		X	X

	Related Procedure Element to		
	Gnd. 9-1	TDRS 9-2	Elmt. 9-3
6. The controlled element shall be capable of receiving a PRN range code signal from the controlling element (space element, ground either direct or via TDRS) and coherently transponding the signal for transmission back to the controlling element. Ranging operation shall be compatible with ground network ranging signals.	X	X	X
a. It shall be accomplished at an S-band operating frequency.	X		X
b. It shall be accomplished at a Ku-band operating frequency.		X	X
7. When necessary, both the controlled element and the controlling element shall contain a Ku-band directive antenna with auto-track capability.		X	X
8. Order wire service shall be provided for the controlled element when it is necessary to request an unscheduled contact, either space or ground initiated. Voice or low data rate order wire channel shall be available at VHF (136 to 144 MHz). This transmission shall be compatible with TDRS.		X	
9. All space elements shall be provided with a receiver system that is continually activated during quiescent periods and that can receive low data rate commands (up to 1 kbps) signals from any direction regardless of its attitude orientation.	X	X	X
a. This service can be provided at VHF (136 to 148 MHz) frequencies compatible with TDRS operation.		X	X
b. This service can be provided at S-band frequencies where such omni-directional reception capability is already available.	X		X

	Related Procedure Element to		
	Gnd. 9-1	TDRS 9-2	Elmt. 9-3
10. The controlling element shall have the capability to measure range, range rate, pointing angles, and angular rate between it and the controlled element at ranges less than 75 nautical miles to the following accuracies: Range: ±6 in or .02% of range, whichever is greater Range rate: ±0.1 ft/sec or ±1% of range rate, whichever is greater Such accuracies are necessary for minimum fuel consumption and safety reasons. These can easily be satisfied by the capability of a Scanning Laser Radar system that can provide the following accuracies: Range: ±4 in. or ± 0.02%, whichever is greater Range rate: ±0.1 ft/sec or ±1%, whichever is greater			X

Table 1-4. Forward Link Communication Requirements

Link	Terminal	Frequency	Data Transfer Requirements	Communication Requirements	
				Terminal Requirements	Radiated Power
Ground to TDRS to Element	TDRS	VHF (126-144 MHz)	1 Voice Channel ≤1 Kbps	17 dB Gain, 26° FOV Directive Antenna Receiver NF = 6 dB *	Voice = 30 dBW Data = 27 dBW *
		Ku-Band (13.4-15.35 GHz)	4 Voice Channels ≤500 Kbps Digital ≤4.5 MHz TV, Ranging	45 dB Gain, 5 ft Ant. Receiver System Noise Temp. = 1200°K *	52 dBW *
Ground to Element (Direct)	Ground	S-Band (2025-2300 MHz)	4 Voice Channels ≤ 500 Kbps Digital ≤4.5 MHz TV 0.5 Mbps Ranging	51 dB Gain, 85 ft Ant. Receiver System Noise Temp. = 125°K *	94 dBW *
Element to Element	Controlling Element	S-Band (2025-2300 MHz)	1 Voice Channel ≤50 Kbps Digital 0.5 Mbps Ranging	28 dB Gain, 5 ft Ant. -- or -- 0 dB Gain, Semi-Direct. Receiver System Noise Temp. = 290°K or 800 K	See Curves 1-12 through 1-15 Data Modes vs Power
Element to Element	Controlling Element	Ku-Band (13.4-15.35 GHz)	1 Voice Channel ≤50 Kbps Digital 0.5 Mbps Ranging	37 dB Gain, 2 ft Ant. -- or -- 45 dB Gain, 5 ft Ant. Receiver System Noise Temp. = 1200°K	See Curves 1-16 through 1-19 Data Modes vs Power
Element to Element	Controlling Element	VHF (126-144 MHz)	1 Voice Channel ≤10 Kbps Digital	0 dB Gain, Omni-Ant. Receiver System Noise Temperature = 1200°K	25 Watts

* Characteristics defined by NASA model (reference DS-504)

Table 1-5. Return Link Communication Requirements

Link	Terminal	Frequency	Data Transfer Requirements	Communication Requirements	
				Terminal Requirements	Radiated Power
Element to TDRS to Ground	Element	VHF (126-144MHz)	1 Voice Channel 10 Kbps Digital	0 dB Gain, Omni-Ant.	25 Watts
		S-Band (13.4-15.35 GHz)	*Up to 50 Mbps Digital* TV (B&W or Color) 4 Voice, 0.5 MHz An. 0.5 Mbps, T-A Ranging	*37 dB Gain, 2 ft Ant.* -- or -- 45 dB Gain, 5 ft Ant. Receiver System Noise Temp. = 1200°K	See Curves 1-10 and 1-11 for Data Modes vs Power
Element to Ground (Direct)	Element	S-Band (2025-2300 MHz)	Up to 1 Mbps Digital TV (B&W) 4 Voice Channels 0.5 MHz Analog 0.5 Mbps T-A Ranging	0 dB Gain, Semi-Direct. Antenna Receiver System Noise Temp. = 1200°K	See Curves 1-8 and 1-9 for Data Modes vs Power
Element to Element	Controlled Element	S-Band (2025-2300 MHz)	Up to 50 Mbps Digital B&W TV (2.9 MHz) 1 Voice Channel 0.5 Mbps T-A Ranging	0 dB Gain, Semi-Direct. Antenna -- or -- 28 dB Gain, 5 ft Ant. Receiver System Noise Temp. = 290°K or 800 K	See Curves 1-12 through 1-15 for Data Modes vs Power
Element to Element	Controlled Element	Ku-Band (13.4-15.35 GHz)	Up to 50 Mbps Digital B&W TV (2.9 MHz) 1 Voice Channel 0.5 Mbps T-A Ranging	37 dB Gain, 2 ft Ant. -- or -- 45 dB Gain, 5 ft Ant. Receiver System Noise Temp. = 1200 K	See Curves 1-16 through 1-19 for Data Modes vs Power
Element to Element	Controlled Element	VHF (126-144 MHz)	1 Voice Channel ≤10 Kbps Digital	0 dB Gain, Omni Ant. Receiver System Noise Temp. = 1200°K	25 Watts

ELEMENT PAIR REQUIREMENTS MATRIX

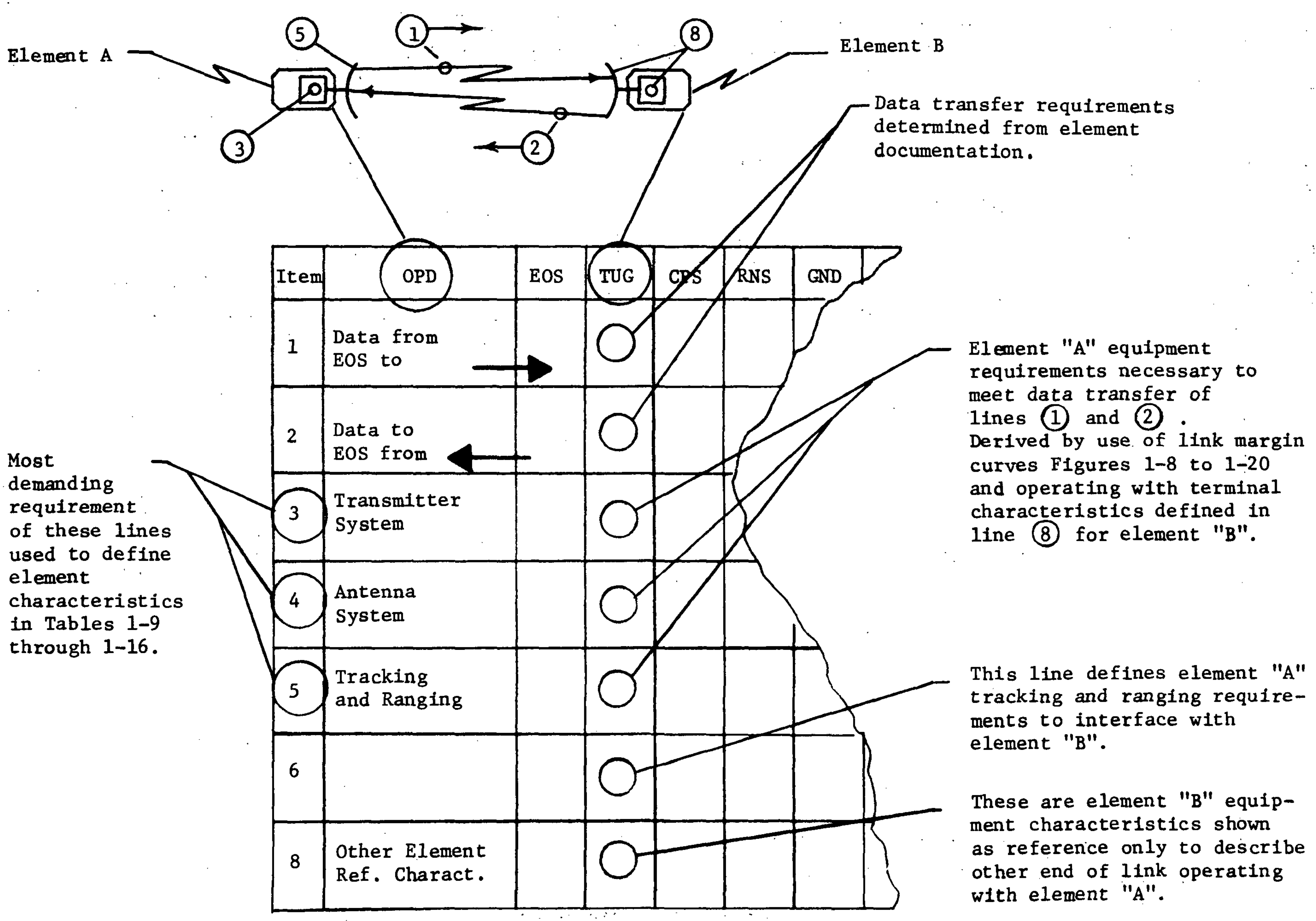
The element pair requirements matrices define the requirements in each case from the standpoint of an element terminal as impacted by the other half of the element pair. Examination, for instance, of the EOS matrix identifies the requirements on the EOS by each of the elements that will at some time be used as the second-half of the EOS element pairs. Data rates, types of data, antenna pointing, transmitter, receiver, antenna characteristics, and the tracking and ranging requirements encompass the majority of criteria. As an example, EOS interface with MSS is impacted by MSS requirements. This is delineated in the EOS matrix. Conversely, the MSS interface with EOS impacts the MSS. The MSS matrix defines that impact. An iterative process is necessary between these element pair definitions to assure the optimum choice of performance for both ends of the terminal. Transmitter power and its requirements on the element and its subsystem must be balanced with receiver antenna gain and noise figure to make each subsystem compatible with its own element. For example, incorporation of a directional antenna on the MSS would be preferred over the inclusion of the antenna on each of its associated RAMs.

After completing the matrix, the individual element characteristics are determined by examining each line item for the most demanding requirements. A table of individual element terminal characteristics is made from this commonality study and presented.

Derivation of the requirements listed in these matrices evolve from analyses of (1) each of the other interfacing activities and their communications demands, and (2) available source documentation on each of the orbital elements considered in this study. This determined first the element pair data transfer requirements and any necessary tracking and ranging needs. Secondly, the basic element mission and some knowledge of element configuration is utilized when looking at the balance between antenna type and size and receiver/transmitter systems that establish the interfacing communications link. Data transfer and the maximum range necessary to effect that transfer are the major drivers for the communications link parameters. The analyses following this section will define steps taken to define the quantitative results found in the enclosed matrices.

As mentioned above, the element pairs have been arranged by one element. Under each interfacing element, the requirements for performance with that element are tabulated. For instance, a look at the OPD matrix discloses first the data transfer to and from the OPD by its interfacing element. The functional requirements listed are based on these data transfers and are the requirements for the OPD to meet. Under EOS in the OPD matrix, item 3, Transmitter System, VHF, characteristics are given for this channel. The 25-watt, RF transmitter is an OPD requirement to meet the data transfer at the range indicated with the antenna described under item 5. Basic reference data that impacts these requirements is listed under item 8, where it is noted that the link will be with an EOS, 0 db gain antenna, and a 1200°K noise temperature receiver.

The following sketch illustrates the interrelationships of each entry in the matrices.



Element Characteristic Matrix Definition

COMMUNICATIONS ELEMENT PAIRS REQUIREMENTS MATRIX

	OPD	EOS	TUG	CPS	RNS	GND	TDRS	
1	Data from OPD to							
	. Voice (.3-3 KH$_z$)	X	X	X	X	X	X	
	No. Channels	1	1	1	1	1	1	
	. Television							
	. B&W (2.9 MH$_z$)	NA	NA	NA	NA	NA		
	. Color (4.5 MH$_z$)						X	
	. Digital Data							
	. Low 10 Kbps	10 Kbps	10 Kbps	10 Kbps	10 Kbps			
	. Med 1 Mbps					50 Kbps	50 Kbps	
	. High 50 Mbps							
	. Other							
	. Other							
	. Low Rate TV					Apollo Type 500 KH$_z$		
	.							
	.							
2	Data to OPD from							
	. Voice (.3-3 KH$_z$)	X	X	X	X	X	X	
	No. Channels	1	1	1	1	1	1	
	. Television							
	. B&W (2.9 MH$_z$)							
	. Color (4.5 MH$_z$)							
	. Digital Data							
	. Low 10 Kbps	2 Kbps	4 Kbps	10 Kbps	8.5 Kbps	10 Kbps	1 Kbps	

	OPD	EOS	TUG	CPS	RNS	GND	TDRS	
2	Data to OPD from (Cont)							
	. Digital Data (Cont)							
	. Med 1 Mbps							
	. High 50 Mbps							
	. Other							
	. Other . .							
3	Transmitter System							
	VHF			NA		NA		
	. Power Output	25 Watts	25 Watts				25 Watts	
	. Maximum Range	2,000 n.mi.	2,000 n.mi				23,000 nm	
	. Baseband Complex	10 Kbps + Voice	10 Kbps + Voice				10 Kbps + Voice	
	S-Band						NA	
	. Power Output	30 Watts	30 Watts	30 Watts	30 Watts	1 Watt		
	. Maximum Range	150 n.mi.	150 n.mi.	2,000 n.mi	2,000 n.mi	Slant Range to 500 n.mi. Altitude		
	. Baseband Complex	10 Kbps + Voice + PRN Range	10 Kbps + Voice + PRN Range	10 Kbps + Voice + PRN Range	10 Kbps + Voice + PRN Range	50 Kbps + Voice + PRN Range + TV		

	OPD	EOS	TUG	CPS	RNS	GND	TDRS	
3	Transmitter System (Cont)							
	K$_u$-Band . Power Output . Maximum Range . Baseband Complex	NA	NA	NA	NA	NA	10 Watts 23,000 nm 50 Kbps + TV + PRN Range	
4	Receiver System							
	VHF . Input Noise Temp. . Baseband Complex	1200°K 2 Kbps + Voice	1200°K 2 Kbps + Voice	NA	NA	NA	1200°K 1 Kbps + Voice	
	S-Band . Input Noise Temp. . Baseband Complex	800°K 2 Kbps + Voice + PRN Range	800°K 4 Kbps + Voice + PRN Range	800°K 10 Kbps + Voice + PRN Range	800°K 8.5 Kbps + Voice + PRN Range	800°K 10 Kbps + Voice + PRN Range	NA	
	K$_u$-Band . Input Noise Temp . Baseband Complex	NA	NA	NA	NA	NA	1200°K 1 Kbps + Voice + PRN Range	

	OPD	EOS	TUG	CPS	RNS	GND	TDRS	
5	Antenna System							
	VHF			NA	NA	NA		
	. Type	Whip	Whip			Whip		
	. Pattern	Omni	Omni			Omni		
	. Number							
	. Gain	0dB				0dB		
	. Polarization							
	S-Band							
	. Type					NA		
	. Pattern	Omni	Omni	Omni	Omni			
	. Number							
	. Gain	0dB	0dB	0dB	0dB			
	. Beamwidth							
	. Polarization	RHCP	RHCP	RHCP	RHCP	RHCP		
	K_u-Band	NA	NA	NA	NA	NA		
	. Type						5-Foot Parabolic	
	. Pattern							
	. Number							
	. Gain						45 dB	
	. Beamwidth						1° to 3 dB Points	
	. Polarization						RHCP	
6	Tracking/Ranging							
	. >75 N.Mi.							
	. Measure							
	. Respond	X	X	X	X	(X)		
	. Range Accuracy	± 1 n.mi.	± 1 n.mi.	± 1 n.mi.	± 1 n.mi.	± 1 n.mi.		

	OPD	EOS	TUG	CPS	RNS	GND	TDRS	
6	Tracking/Ranging (Cont)							
	. >75 N.Mi. - (Cont)							
	. Range Rate Accuracy	± 5 ft/sec	± 5 ft/sec	± 5 ft/sec	± 5 ft/sec	± 5 ft/sec	± 5 ft/sec	
	. Type System	PRN Range S-band	PRN Range S-band	PRN Range S-band	PRN Range S-band	PRN Range S-band	PRN Range K_u Band	
	. Less Than 75 N.Mi							
	. Measure							
	. Respond	X	X	X	X	NA	NA	
	. Range Accuracy	± 6" or ± .02% of Range Whichever is greater						
	. Range Rate Accuracy	± 0.1 ft/sec or ± 1% of Range Rate Whichever is greater						
	. Type System	SLR Passive Reflector Only	SLR Passive Reflector Only	SLR Passive Reflector Only	SLR Passive Reflector Only			
8	Other Element Reference Characteristics							
A	Transmitter							
	. Power Output							
	VHF	25 Watts	NA	NA	NA			
	K_u-Band	NA	NA	NA	NA			
	S-Band	30 Watts	30Watts	30 Watts	30 Watts			
B	Receiver							
	. Noise Temperature							
	VHF	1200°K	NA	NA				
	K_u-Band	NA	NA	NA	NA			
	S-Band	800°K	800°K	800°K	800°K			

	OPD	EOS	TUG	CPS	RNS	GND	TDRS	
8	Other Element Reference Characteristics (Cont)							
C	Antenna							
	. Gain							
	VHF	0dB	NA	NA	NA			
	K_u-Band	NA	NA	NA	NA			
	S-Band	0dB	0dB	23 dB	23 dB			

COMMUNICATIONS ELEMENT PAIRS REQUIREMENTS MATRIX

	RAM (FF) UNMANNED	EOS	MSS	TUG	GND	TDRS		
1	Data from RAM to							
	. Voice (.3-3 KH$_Z$) No. Channels	NA	NA	NA	NA	NA		
	. Television							
	. B&W (2.9 MH$_Z$)	NA	X	NA	X	X		
	. Color (4.5 MH$_Z$)							
	. Digital Data							
	. Low 10 Kbps	5 Kbps		5 Kbps				
	. Med 1 Mbps		50 Kbps		1 Mbps	35 Mbps		
	. High 50 Mbps							
	. Other							
	. Other							
	. Analog	NA	NA	NA	NA	7 MH$_Z$		
	.							
	.							
2	Data to RAM from							
	. Voice (.3-3 KH$_Z$) No. Channels	NA	NA	NA	NA	NA		
	. Television							
	. B&W (2.9 MH$_Z$)	NA	NA	NA	NA	NA		
	. Color (4.5 MH$_Z$)							
	. Digital Data							
	. Low 10 Kbps	2 Kbps	10 Kbps	4 Kbps	10 Kbps	10 Kbps		
	. Med 1 Mbps							
	. High 50 Mbps							
	. Other							

	RAM (FF) UNMANNED	EOS	MSS	TUG	GND	TDRS		
2	Data to RAM from (Cont)							
	. Other . .							
3	Transmitter System							
	VHF							
	. Power Output	NA	NA	NA	NA	25 Watts		
	. Maximum Range					23,000 nm		
	. Baseband Complex					10 Kbps		
	S-Band							
	. Power Output	30 Watts	30 Watts	30 Watts	1 Watt	NA		
	. Maximum Range	150 n.mi.	300 n.mi.	150 n.mi.	Slant Range to 500 n.mi. Altitude			
	. Baseband Complex	5 Kbps + PRN Range	50 Kbps + PRN Range + TV	5 Kbps + PRN Range	1 Mbps + PRN Range + TV			
	K_u-Band							
	. Power Output	NA	10 Watts	NA	NA	25 Watts		
	. Maximum Range		2000 n.mi.			23,000 nm		
	. Baseband Complex		50 Kbps + PRN Range & TV			35 Mbps or TV + PRN Range		

	RAM (FF) UNMANNED	EOS	MSS	TUG	GND	TDRS		
4	Receiver System							
	VHF	NA	NA	NA	NA	X		
	. Input Noise Temp.					1200°K		
	. Baseband Complex					1 Kbps		
	S-Band					NA		
	. Input Noise Temp.	800°K	800°K	800°K	800°K			
	. Baseband Complex	2 Kbps	10 Kbps	4 Kbps	10 Kbps			
	K_u-Band	NA		NA	NA			
	. Input Noise Temp.		1200°K			1200°K		
	. Baseband Complex		10 Kbps			1 Kbps + PRN Range		
5	Antenna System							
	VHF	NA	NA	NA	NA			
	. Type					Whip		
	. Pattern					Omni		
	. Number							
	. Gain					0dB		
	. Polarization							
	S-Band							
	. Type	Omni	5-Foot Parabolic	Omni	Omni	NA		
	. Pattern							
	. Number							
	. Gain		28 dB		0dB			
	. Beamwidth		7° to 3dB Points					
	. Polarization	RHCP	RHCP	RHCP	RHCP			

	RAM (FF) UNMANNED	EOS	MSS	TUG	GND	TDRS		
5	Antenna System (Cont)							
	K_u-Band							
	. Type	NA	2-Foot Parabolic	NA	NA	5-Foot Parabolic		
	. Pattern							
	. Number							
	. Gain		36 dB			45 dB		
	. Beamwidth		2.4°			1°		
	. Polarization		RHCP			RHCP		
6	Tracking/Ranging							
	. >75 N.Mi.							
	. Measure							
	. Respond	X	X	X	X	X		
	. Range Accuracy	± 1 n.mi.	± 1 n.mi.	± 1 n.mi.	± 1 n.mi.	± 1 n.mi.		
	. Range Rate Accuracy	± 5 ft/sec	± 5 ft/sec	± 5 ft/sec	± 5 ft/sec	± 5 ft/sec		
	. Type System	PRN S-Band	PRN S-Band	PRN S-Band	PRN S-Band	PRN K_u-Band		
	. <75 N.Mi.				NA	NA		
	. Measure							
	. Respond	X	X	X				
	. Range Accuracy	± 6" or ± .02% of Range						
	. Range Rate Accuracy	± 0.1 ft/sec or ± 1% of Range Rate						
	. Type System	SLR Passive Reflector	SLR Passive Reflector	SLR Passive Reflector				

	RAM (FF) UNMANNED	EOS	MSS	TUG				
8	Other Element Reference Characteristics							
A	Transmitter							
	. Power Output							
	VHF	NA	NA	NA				
	K_u-Band	NA	20 Watts	NA				
	S-Band	30 Watts	30 Watts	30 Watts				
B	Receiver							
	. Noice Temperature							
	VHF	NA	NA	NA				
	K_u-Band	NA	1200°K	NA				
	S-Band	800°K	800°K	800°K				
C	Antenna							
	. Gain							
	VHF	NA	NA	NA				
	K_u-Band	NA	45 dB	NA				
	S-Band	0dB	0dB	0dB				

COMMUNICATIONS ELEMENT PAIRS REQUIREMENTS MATRIX

	SAT	EOS	TUG	GND	TDRS			
1	Data from Sat to							
	. Voice (.3-3 KH_z) No. Channels	NA	NA	NA	NA			
	. Television . B&W (2.9 MH_z) . Color (4.5 MH_z)	NA	NA	X	X			
	. Digital Data . Low 10 Kbps . Med 1 Mbps . High 50 Mbps . Other	27.5 Kbps	27.5 Kbps	1.6 Mbps	1.6 Mbps			
	. Other . .							
2	Data to Sat from							
	. Voice (.3-3 KH_z) No. Channels	NA	NA	NA	NA			
	. Television . B&W (2.9 MH_z) . Color (4.5 MH_z)	NA	NA	NA	NA			
	. Digital Data . Low 10 Kbps . Med 1 Mbps . High 50 Mbps . Other	2 Kbps	4 Kbps	1 Kbps	1 Kbps			

	SAT	EOS	TUG	GND	TDRS			
2	Data to Sat from (Cont) . Other . . .							
3	Transmitter System							
	VHF . Power Output . Maximum Range . Baseband Complex	NA	NA	NA	25 Watt 23,000 nm 10 Kbps Digital			
	S-Band . Power Output . Maximum Range . Baseband Complex	30 Watts 130 n.mi. 27.5 Kbps + T-A Ranging	30 Watts 130 n.mi. 27.5 Kbps + T-A Ranging	1 Watt 1.6 Mbps or T-A PRN Range or 2.9 MH_z TV	NA			
	K_u-Band . Power Output . Maximum Range . Baseband Complex	NA	NA	NA	10 Watts 23,000 nm 1.6 Mbps or PRN Range or TV			

	SAT	EOS	TUG	GND	TDRS			
4	Receiver System							
	VHF			NA	X			
	. Input Noise Temp.	NA	NA		1200°K			
	. Baseband Complex				1 Kbps			
	S-Band							
	. Input Noise Temp	800°K	800°K	800°K	NA			
	. Baseband Complex	2 Kbps + PRN Range	4 Kbps + PRN Range	1 Kbps + PRN Range				
	K$_u$-Band	NA	NA	NA				
	. Input Noise Temp				1200°K			
	. Baseband Complex				1 Kbps + PRN Range			
5	Antenna System							
	VHF							
	. Type	NA	NA	NA	Whip			
	. Pattern				Omni			
	. Number				1			
	. Gain				0dB			
	. Polarization							
	S-Band				NA			
	. Type							
	. Pattern	Omni	Omni	Omni				
	. Number							

	SAT	EOS	TUG	GND	TDRS			
5	Antenna System (Cont)							
	S-Band (Cont)				NA			
	. Gain	OdB	OdB	OdB				
	. Beamwidth							
	. Polarization	RHCP	RHCP	RHCP				
	K_u-Band	NA	NA	NA	X			
	. Type				5' Parabolic			
	. Pattern							
	. Number				1			
	. Gain				45 dB			
	. Beamwidth				1° Bet. 3 dB Points			
	. Polarization				RHCP			
6	Tracking/Ranging							
	. ≥75 N.Miles							
	. Measure	NA	NA	NA	NA			
	. Respond	X	X	X	X			
	. Accuracy							
	. Range	± 1 N.Mi.	± 1 N.Mi.	± 1 N.Mi.	± 1 N.Mi.			
	. Range Rate	± 5 Ft/Sec	± 5 Ft/Sec	± 5 Ft/Sec	± 5 Ft/Sec			
	. Type System	S-Band PRN	S-Band PRN	S-Band PRN	K_u-Band			
	. ≤75 N.Miles							
	. Measure	NA	NA	NA	NA			
	. Respond	X	X					

	SAT	EOS	TUG	GND	TDRS			
6	Tracking/Ranging (Cont)							
	. Accuracy							
	. Range	± 6" or ± .02% ·R whichever is greater						
	. . Range Rate	± 0.1 FPS or ± 1% of $\overline{R}$						
	. Type System	SLR Passive Reflector	SLR Passive Reflector					
8	Other Element Reference Characteristics							
A	Transmitter							
	. Power Output							
	VHF	NA	NA					
	K_u-Band	NA	NA					
	S-Band	30 Watts	30 Watts					
B	Receiver Noise Temp.							
	VHF	NA	NA					
	K_u-Band	NA	NA					
	S-Band	800°K	800°K					
C	Antenna Gain							
	VHF	NA	NA					
	K_u-Band	NA	NA					
	S-Band	OdB	OdB					

COMMUNICATIONS ELEMENT PAIRS REQUIREMENTS MATRIX

	CPS (CLS)	CPS (CLS)	EOS	TUG	OPD		GND	TDRS
1	Data from CPS to							
	. Voice (.3-3 KH_z) No. Channels	X 1	X 1	X 1	X 1		X 1	X 1
	. Television . B&W (2.9 MH_z) . Color (4.5 MH_z)	NA	NA	NA	NA		X	X
	. Digital Data . Low 10 Kbps . Med 1 Mbps . High 50 Mbps . Other	10 Kbps	10 Kbps	10 Kbps	10 Kbps		1 Mbps	1 Mbps
	. Other . . .							
2	Data to CPS from							
	. Voice (.3-3 KH_z) No. Channels	X 1	X 1	X 1	X 1		X 1	X 1
	. Television . B&W (2.9 MH_z) . Color (4.5 MH_z)	NA	NA	NA	NA		NA	NA
	. Digital Data . Low 10 Kbps . Med 1 Mbps . High 50 Mbps . Other	2 Kbps	2 Kbps	4 Kbps	10 Kbps		30 Kbps	30 Kbps

	CPS (CLS)	CPS (CLS)	EOS	TUG	OPD	RNS	GND	TDRS
2	Data to CPS from (Cont) . Other . . .							
3	Transmitter System							
	VHF . Power Output . Maximum Range . Baseband Complex	NA	NA	NA	NA	NA	NA	X 25 Watts 23,000 nm 10 Kbps + Voice
	S-Band . Power Output . Maximum Range	30 Watts 2,000 nm	30 Watts 2,000 nm	30 Watts 2,000 nm	30 Watts 2,000 nm	30 Watts 2,000 nm	1 Watt Slant Range to 500 n.mi. Altitude	NA
	. Baseband Complex	10 Kbps + Voice + PRN Range	10 Kbps + Voice + PRN Range	10 Kbps + Voice + PRN Range	10 Kbps + Voice + PRN Range	10 Kbps + Voice + PRN Range	Voice + TV + PRN Range or 1 Mbps	
	K_u-Band . Power Output . Maximum Range . Baseband Complex	NA	NA	NA	NA	NA	NA	X 10 Watts 23,000 nm 1 Mbps + Voice + TV + PRN Range

	CPS (CLS)	CPS (CLS)	EOS	TUG	OPD	RNS	GND	TDRS
4	Receiver System							
	VHF	NA	NA	NA	NA	NA	NA	
	. Input Noise Temp.							1200°K
	. Baseband Complex							1 Kbps + Voice
	S-Band							
	. Input Noise Temp.	800°K	800°K	800°K	800°K	800°K	800°K	NA
	. Baseband Complex	Voice + 2 Kbps	Voice + 2 Kbps	Voice + 4 Kbps	Voice + 10 Kbps	Voice + 2 Kbps	Voice + 30 Kbps	
	K_u-Band	NA	NA	NA	NA	NA	NA	
	. Input Noise Temp.							1200°K
	. Baseband Complex							30 Kbps + Voice
5	Antenna System							
	VHF	NA	NA	NA	NA	NA	NA	
	. Type							Whip
	. Pattern							Omni
	. Number							
	. Gain							0dB
	. Polarization							
	S-Band							
	. Type	3-Foot Parabolic	3-Foot Parabolic	3-Foot Parabolic	3-Foot Parabolic	3-Foot Parabolic		NA
	. Pattern						Omni	
	. Number							
	. Gain	23 dB	23 dB	23 dB	23 dB	23 dB	0dB	

	CPS (CLS)	CPS (CLS)	EOS	TUG	OPD	RNS	GND	TDRS
5	Antenna System (Cont)							
	S-Band (Cont)							
	. Beamwidth	7° to 3 dB Points	7° to 3 dB Points	7° to 3 dB Points	7° to 3 dB Points	7° to 3 dB Points		
	. Polarization	RHCP	RHCP	RHCP	RHCP	RHCP	RHCP	
	K_u-Band							
	. Type	NA	NA	NA	NA	NA	NA	5 Foot Parabolic
	. Pattern							1° FOV
	. Number							
	. Gain							45 dB
	. Beamwidth							1° to 3 dB Points
	. Polarization							RHCP
6	Tracking/Ranging							
	. >75 N. Miles							
	. Measure	X			X	X		
	. Respond	X	X	X		X	X	X
	. Accuracy							
	. Range	± 1 n.mi.	± 1 n.mi.	± 1 n.mi.	± 1 n.mi.	± 1 n.mi.	± 1 n.mi.	± 1 n.mi.
	. Range Rate	± 5 ft/sec	± 5 ft/sec	± 5 ft/sec	± 5 ft/sec	± 5 ft/sec	± 5 ft/sec	± 5 ft/sec
	. Type System	PRN S-Band	PRN S-Band	PRN S-Band	PRN S-Band	PRN S-Band	PRN S-Band	PRN K_u-Band
	. <75 N. Miles							
	. Measure	X			X	X		

	CPS (CLS)	CPS (CLS)	EOS	TUG	OPD	RNS	GND	TDRS
6	Tracking/Ranging (Cont)							
	. Respond	X	X	X		X		
	. Accuracy							
	. Range ± 6" or ± .02% of Range whichever is greater							
	. Range Rate ± 0.1 ft/sec or ± 1% of Range Rate whichever is greater							
	. Type System	Active SLR + Passive Reflector	SLR Passive Reflector	SLR Passive Reflector	Active SLR			
8	Other Element Reference Characteristics							
A	Transmitter							
	. Power Output							
	VHF	NA	25 Watts	25 Watts	NA	NA		
	K_u-Band	NA	NA	NA	NA	NA		
	S-Band	30 Watts	30 Watts	30 Watts	30 Watts	30 Watts		

	CPS (CLS)	CPS (CLS)	EOS	TUG	OPD	RNS	GND	TDRS
8	Other Element Reference Characteristics (Cont)							
B	Receiver							
	. Noise Temperature							
	VHF	NA	1200°K	1200°K	NA	NA		
	K_u-Band	NA	NA	NA	NA	NA		
	S-Band	800°K	800°K	800°K	800°K	800°K		
C	Antenna							
	. Gain							
	VHF	NA	0dB	0dB	NA	NA		
	K_u-Band	NA	NA	NA	NA	NA		
	S-Band	23 dB	0dB	0dB	0dB	23 dB		

COMMUNICATIONS ELEMENT PAIRS REQUIREMENTS MATRIX

	MSS	EOS	TUG	RAM (FF)	GND	TDRS		
1	Data from MSS to							
	. Voice (.3-4 KH$_z$)	X	X	NA	X	X		
	No. Channels	1	1		3	3		
	. Television	NA	NA	NA				
	. B&W (2.9 MH$_z$)	NA						
	. Color (4.5 MH$_z$)	NA			4.5 MH$_z$	4.5 MH$_z$		
	. Digital Data							
	. Low 10 Kbps		10 Kbps	10 Kbps				
	. Med 1 Mbps	51.2 Kbps						
	. High 50 Mbps				2.0 Mbps	2.0 Mbps		
	. Other							
	. Other							
	. Facsimile	NA	NA	NA	0.5 MH$_z$	0.5 MH$_z$		
	.							
	.							
2	Data to MSS from							
	. Voice (.3-3 KH$_z$)	X	X	NA	X	X		
	No. Channels	1	1		3	3		
	. Television	NA		X	NA	NA		
	. B&W (2.9 MH$_z$)		2.9 MH$_z$	2.9 MH$_z$				
	. Color (4.5 MH$_z$)							
	. Digital Data							
	. Low 10 Kbps	2 Kbps	4 Kbps					
	. Med 1 Mbps			50 Kbps	500Kbps	500 Kbps		
	. High 50 Mbps							
	. Other							

	MSS	EOS	TUG	RAM (FF)	GND	TDRS		
2	Data to MSS from (Cont)							
	. Other							
	. Audio/Hi/Fi	NA	NA	NA	.03-10 KH$_z$	.03-10 KH$_z$		
	. .							
3	Transmitter System							
	VHF							
	. Power Output . Maximum Range . Baseband Complex	25 Watts 2,000 n.mi 10 Kbps + Voice	NA	NA	NA	25 Watts 23,000 nm 10 Kbps + Voice + PRN Range		
	S-Band							
	. Power Output . Maximum Range	30 Watts 95 n.mi.	30 Watts 150 n.mi.	30 Watts 3500 n.mi.	1 Watt Slant Range to 500 n.mi. Altitude	NA		
	. Baseband Complex	51.2 Kbps + Voice + PRN Range	10 Kbps + Voice + PRN Range + TV	10 Kbps + PRN Range	2.0 Mbps or 3 Voice + PRN Range or TV or 0.5 MH$_z$ Facsimile			

	MSS	EOS	TUG	RAM (FF)	GND	TDRS		
3	Transmitter System (Cont)							
	K_u-Band	NA	NA		NA			
	. Power Output			20 Watts		20 Watts		
	. Maximum Range			4000 n.mi.		23,000 nm		
	. Baseband Complex			10 Kbps + PRN Range		2 Mbps or 3 Voice + PRN Range + TV + 0.5 MH_z Facsimile		
4	Receiver System							
	VHF	NA	NA	NA	NA			
	. Input Noise Temp.	1200°K				1200°K		
	. Baseband	1 Kbps + Voice				1 Kbps + Voice		
	S-Band					NA		
	. Input Noise Temp.	800°K	800°K	800°K	800°K			
	. Baseband Complex	2 Kbps + Voice + PRN Range	4 Kbps + Voice + 2.9 MH_z TV + PRN Range	50 Kbps TV 2.9 MH_z + PRN Range	500 Kbps + 3 Voice + Hi-Fi Audio + PRN Range			
	K_u-Band							
	. Input Noise Temp	NA	NA	1200°K	NA	1200°K		

	MSS	EOS	TUG	RAM (FF)	GND	TDRS		
4	Receiver System (Cont)							
	K_u-Band (Cont)							
	. Baseband Complex			50 Kbps + TV 2.9 MH_z + PRN Range		500 Kbps + 3 Voice + Hi-Fi Audio + PRN Range		
5	Antenna System							
	VHF							
	. Type	Whip	NA	NA	NA	Whip		
	. Pattern	Omni				Omni		
	. Number							
	. Gain	0dB				0dB		
	. Polarization							
	S-Band					NA		
	. Type							
	. Pattern	Omni	Omni	Omni	Omni			
	. Number							
	. Gain	0dB	0dB	0dB	0dB			
	. Beamwidth							
	. Polarization	RHCP	RHCP	RHCP	RHCP			
	K_u-Band	NA	NA		NA			
	. Type			5-Foot Parabolic		5-Foot Parabolic		
	. Pattern							
	. Number							
	. Gain			45 dB		45 dB		

	MSS	EOS	TUG	RAM (FF)	GND	TDRS		
5	Antenna System (cont.)							
	. Beamwidth			1° to 3 db point		1° to 3 db point		
	. Polarization			RHCP		RHCP		
6	Tracking/Ranging							
	> 75 n mi.							
	. Measure	X	X	X				
	. Respond	X	X		X	X		
	. Range accuracy	±1 n mi.	±1 n mi.	±1 n mi.	±1 n mi.	±1n mi.		
	. Range rate accuracy	-5 ft/sec	-5 ft/sec	-5 ft/sec	-5 ft/sec	-5 ft/sec		
	. Type system	PRN	PRN	PRN	PRN	PRN		

	MSS	EOS	TUG	RAM (FF)	GND	TDRS		
6	Tracking/Ranging (cont.)							
	< 75 n mi.							
	. Measure	X	X	X	NA	NA		
	. Respond	Respond	Respond					
	. Range accuracy	±6 in. or ±.02% of range whichever is greater						
	. Range rate accuracy	±0.1 in. FPS or ±1% of range rate whichever is greater						
	. Type system	Passive reflector for SLR	Passive reflector for SLR	Active SLR				
8	Other Element Reference Characteristics							
A	Transmitter							
	. Power output							
	VHF	25 watts	NA	NA				
	Ku-band	NA	NA	10 watts				
	S-band	30 watts	30 watts	30 watts				
B	Receiver							
	. Noise temperature							
	VHF	1200° K	NA	NA				
	Ku-band	NA	NA	1200° K				
	S-band	800° K	800° K	800° K				
C	Antenna							
	. Gain							
	VHF	0 db	NA	NA				
	Ku-band	NA	NA	36 db				
	S-band	0 db	0 db	28 db				

	RNS	EOS	TUG	CPS	OPD	GROUND	TDRS	
1	DATA FROM RNS TO	✓	✓	✓	✓	✓	Not Required	
	Voice (0.3 - 3 kHz)	✓	✓	✓	✓	✓		
	No. Channels	1	1	1	1	1		
	Television							
	. B&W (2.9 MHz)	✓	✓		✓	✓		
	. Color (4.5 MHz)	NR	NR	NR	NR	✓		
	Digital Data							
	. Low ≳10 kbps	8.5 kbps	8.5 kbps	8.5 kbps	8.5 kbps	8.5 kbps		
	. Med ≳1 Mbps							
	. High ≳ 50 Mbps							
	. Other							
	Other						Not Required	
2	DATA TO RNS FROM						Not Required	
	Voice (0.3 - 3 kHz)	✓	✓	✓	✓	✓		
	No. Channels	1	1	1	1	1		
	Television							
	. B&W (2.9 MHz)	-	-	-	-	-		
	. Color (4.5 MHz)							
	Digital Data							
	. Low ≳10 kbps	2 kbps	4 kbps	2 kbps	10 kbps	2 kbps		
	. Med ≳1 Mbps							
	. High ≳50 Mbps							
	. Other							
	Other						Not Required	

	RNS	EOS	TUG	CPS	OPD	GROUND	TDRS	
3	TRANSMITTER SYSTEM							
	VHF	NA	NA	NA	NA	NA	X	
	. Power output						25 watts	
	. Maximum range						23,000 n mi.	
	. Baseband complex						10 kbps + voice	
	S-Band							
	. Power output	30 watts	30 watts	30 watts	30 watts	1 watt	NA	
	. Maximum range	2000 n mi	2000 n mi	20000 nmi	2000 n mi	Slant range to 500 n mi altitude		
	. Baseband complex	8.5 kbps + voice + PRN ranging	8.5 kbps + voice + PRN ranging	8.5 kbps + voice + PRN ranging	8.5 kbps + voice + PRN ranging	8.5 kbps + voice + PRN ranging + TV		
	Ku-Band	NA	NA	NA	NA	NA	NA	
	. Power output							
	. Maximum range							
	. Baseband complex							
4	RECEIVER SYSTEM							
	VHF	NA	NA	NA	NA	NA		
	. Input noise temp.						1200° K	
	. Baseband complex						1 kbps + voice	

	RNS	EOS	TUG	CPS	OPD	GROUND	TDRS	
4	RECEIVER SYSTEM (cont.)							
	S-Band						NA	
	. Input noise temp.	800 K	800 K	800 K	800 K	800 K		
	. Baseband complex	2 kbps + voice + PRN ranging	4 kbps + voice + PRN ranging	2 kbps + voice + PRN ranging	10 kbps + voice + PRN ranging	2 kbps + voice + PRN ranging		
	Ku-Band	NA	NA	NA	NA	NA	NA	
	. Input noise temp.							
	. Baseband complex							
5	ANTENNA SYSTEM							
	VHF	NA	NA	NA	NA	NA		
	. Type						WHIP	
	. Pattern						Omni	
	. Number							
	. Gain						0 db	
	. Polarization							
	S-Band						NA	
	. Type	3-foot parabolic	3-foot parabolic	3-foot parabolic	3-foot parabolic			
	. Pattern					Omni		
	. Number							
	. Gain	23 db	23 db	23 db	23 db	0 db		
	. Beamwidth	7° to 3 db	7° to 3 db	7° to 3 db	7° to 3 db			
	. Polarization	RHCP	RHCP	RHCP	RHCP	RHCP		

	RNS	EOS	TUG	CPS	OPD	GROUND	TDRS	
5	ANTENNA SYSTEM (cont.)							
	Ku-Band	NA	NA	NA	NA	NA	NA	
	. Type							
	. Pattern							
	. Number							
	. Gain							
	. Beamwidth							
	. Polarization							
6	TRACKING/RANGING							
	>75 *nautical miles*							
	. Measure							
	. Respond	✓	✓	✓	✓	✓	NA	
	. Accuracy range	±1 n mi	± 1 n mi	±1 n mi	±1 n mi	±1 n mi		
	. Range rate accuracy	±5 ft/sec	±5 ft/sec	±5 ft/sec	±5 ft/sec	±5 ft/sec		
	. Type system	PRN S-band	PRN S-band	PRN S-band	PRN S-band	PRN S-band		
	<75 nautical miles					NA	NA	
	. Measure				✓			
	. Respond	✓	✓	✓				
	. Range accuracy	±6 in. or ±.02% of range whichever is greater						
	. Range rate accuracy	±0.1 ft/sec or ±1% of range rate whichever is greater						
	. Type System	SLR Passive Reflector	SLR Passive Reflector	SLR Passive Reflector	Active SLR			

	RNS	EOS	TUG	CPS	OPD			
8	OTHER ELEMENT REFERENCE CHARACTERISTICS							
A	Transmitter							
	Power Output							
	. VHF	NA	NA	NA	NA			
	. Ku-band	NA	NA	NA	NA			
	. S-band	30 watts	30 watts	30 watts	30 watts			
B	Receiver							
	Noise Temperature							
	. VHF	NA	NA	NA	NA			
	. Ku-band	NA	NA	NA	NA			
	. S-band	800 K	800 K	800 K	800 K			
C	Antenna							
	Gain							
	. VHF	NA	NA	NA	NA			
	. Ku-band	NA	NA	NA	NA			
	. S-band	0 db	0 db	23 db	0 db			

COMMUNICATIONS ELEMENT PAIRS REQUIREMENTS MATRIX

	TUG$_1$	EOS	TUG$_2$	RAM (FF)	SAT	MSS	CPS	RNS
1	Data from TUG$_1$ to							
	. Voice (.3-3 KH$_Z$)	X	X	NA	NA	X	X	X
	No. Channels	1	1			1	1	1
	. Television							
	. B&W (2.9 MH$_Z$)	NA	NA	NA	NA	NA	NA	NA
	. Color (4.5 MH$_Z$)							
	. Digital Data							
	. Low $\overline{<}$ 10 Kbps	4 Kbps	4 Kbps	4 Kbps	4 Kbps	4 Kbps	4 Kbps	4 Kbps
	. Med $\overline{<}$ 1 Mbps							
	. High $\overline{<}$ 50 Mbps							
	. Other							
	. Other							
	.							
	.							
	.							
2	Data to TUG$_1$ from							
	. Voice (.3-3 KH$_Z$)	X	X	NA	NA	X	X	X
	No. Channels	1	1			1	1	1
	. Television	NA	NA	NA	NA	NA	NA	NA
	. B&W (2.9 MH$_Z$)							
	. Color (4.5 MH$_Z$)							
	. Digital Data							
	. Low $\overline{<}$ 10 Kbps	2 Kbps	10 Kbps	5 Kbps	27.5 Kbps	10 Kbps	10 Kbps	8.5 Kbps
	. Med $\overline{<}$ 1 Mbps							
	. High $\overline{<}$ 50 Mbps							
	. Other							

COMMUNICATIONS ELEMENT PAIRS REQUIREMENTS MATRIX

	TUG_1	OPD	GND	TDRS				
1	Data from TUG_1 to							
	. Voice (.3-3 KH_z)	X	X	X				
	No Channels	1	1	1				
	. Television							
	. B&W (2.9 MH_z)	NA	X	X				
	. Color (4.5 MH_z)							
	. Digital Data							
	. Low ≲ 10 Kbps	4 Kbps						
	. Med ≲ 1 Mbps		50 Kbps	50 Kbps				
	. High ≲ 50 Mbps							
	. Other							
	. Other							
	.							
	.							
	.							
2	Data to TUG_1 from							
	. Voice (.3-3 KH_z)	X	X	X				
	No. Channels	1	1	1				
	. Television	NA	NA	NA				
	. B&W (2.9 MH_z)							
	. Color (4.5 MH_z)							
	. Digital Data							
	. Low ≲ 10 Kbps	10 Kbps	2 Kbps	2 Kbps				
	. Med ≲ 1 Mbps							
	. High ≲ 50 Mbps							
	. Other							

	TUG$_1$	EOS	TUG$_2$	RAM (FF)	SAT	MSS	CPS	RNS
2	Data to TUG$_1$ from (Cont)							
	. Other . . .	NA	NA	NA	NA	NA	NA	NA
3	Transmitter System							
	VHF . Power Output . Maximum Range . Baseband Complex	25 Watts 2,000 n.mi 4 Kbps + Voice	25 Watts 2,000 n.mi 4 Kbps + Voice	NA	NA	NA	NA	NA
	S-Band . Power Output . Maximum Range . Baseband Complex	30 Watts 150 n.mi. 4 Kbps + Voice + TA PRN Ranging	30 Watts 150 n.mi. 4 Kbps + Voice + PRN Ranging	30 Watts 150 n.mi. 4 Kbps + PRN Ranging	30 Watts 150 n.mi. 4 Kbps + PRN Ranging	30 Watts 150 n.mi. 4 Kbps + Voice + PRN Ranging	30 Watts 2000 n mi. 4 Kbps + Voice + PRN Ranging	30 Watts 2000 m mi 4 Kbps + Voice + PRN Ranging or TV
	K$_u$-Band . Power Output . Maximum Range . Baseband Complex	NA	NA	NA	NA	NA	NA	NA

	TUG$_1$	OPD	GND	TDRS				
2	Data to TUG$_1$ from (Cont)							
	. Other . . .	NA	NA	NA				
3	Transmitter System							
	VHF . Power Output . Maximum Range . Baseband Complex	NA	NA	25 Watts 23,000 nm 10 Kbps + Voice				
	S-Band . Power Output . Maximum Range	30 Watts 150 n.mi.	1 Watt Slant Range from 500 nm Altitude	NA				
	. Baseband Complex	4 Kbps + Voice + PRN Ranging	50 Kbps + Voice + PRN Ranging or TV					
	K$_u$-Band . Power Output . Maximum Range . Baseband Complex	NA	NA	X 10 Watts 23,000 nm 50 Kbps + Voice + PRN Range + TV				

	TUG_1	EOS	TUG_2	RAM (FF)	SAT	MSS	CPS	RNS
4	Receiver System							
	VHF			NA	NA	NA	NA	NA
	. Input Noise Temp.	1200°K	1200°K					
	. Baseband Complex	2 Kbps + Voice	10 Kbps + Voice					
	S-Band							
	. Input Noise Temp.	800°K	800°K	800°K	800°K	800°K	800°K	800°K
	. Baseband Complex	2 Kbps + Voice + PRN Range	10 Kbps + Voice + PRN Range	5 Kbps + PRN Range	27.5 Kbps + PRN Range	10 Kbps + Voice + PRN Range	10 Kbps + Voice + PRN Range	8.5 Kbps + Voice + PRN Range
	K_u-Band							
	. Input Noise Temp.	NA	NA	NA	NA	NA	NA	NA
	. Baseband Complex							
5	Antenna System							
	VHF		X	NA	NA	NA	NA	NA
	. Type	Whip	Whip					
	. Pattern	*Omni*	*Omni*					
	. Number							
	. Gain	0dB	0dB					
	. Polarization							
	S-Band							
	. Type							
	. Pattern	Omni	Omni	Omni	Omni	Omni	Omni	Omni
	. Number							
	. Gain	0dB	0dB	0dB	0dB	0dB	0dB	0dB

	TUG$_1$	OPD	GND	TDRS				
4	Receiver System							
	VHF	NA	NA					
	. Input Noise Temp.			1200°K				
	. Baseband Complex			2 Kbps + Voice				
	S-Band							
	. Input Noise Temp	800°K	800°K	NA				
	. Baseband Complex	10 Kbps + Voice + PRN Range	2 Kbps + Voice + PRN Range					
	K$_u$-Band							
	. Input Noise Temp.	NA	NA	1200°K				
	. Baseband Complex			2 Kbps + Voice				
5	Antenna System							
	VHF	NA	NA	X				
	. Type			Whip				
	. Pattern			Omni				
	. Number							
	. Gain			0dB				
	. Polarization							
	S-Band							
	. Type							
	. Pattern	Omni	Omni	NA				
	. Number							
	. Gain	0dB	0dB	NA				

	TUG$_1$	EOS	TUG$_2$	RAM (FF)	SAT	MSS	CPS	RNS
5	Antenna System (Cont)							
	S-Band (Cont)							
	. Beamwidth							
	. Polarization	RHCP	RHCP	RHCP	RHCP	RHCP	RHCP	RHCP
	K$_u$-Band							
	. Type	NA	NA	NA	NA	NA	NA	NA
	. Pattern							
	. Number							
	. Gain							
	. Beamwidth							
	. Polarization							
6	Tracking/Ranging							
	. >75 N. Miles							
	. Measure		X	X	X	X	X	X
	. Respond	X	X					
	. Accuracy							
	. Range	± 1 n.mi.	± 1 n.mi.	± 1 n.mi.	± 1 n.mi.	± 1 n.mi.	± 1 n.mi.	± 1 n.mi.
	. Range Rate	± 5 ft/sec	± 5 ft/sec	± 5 ft/sec	± 5 ft/sec	± 5 ft/sec	± 5 ft/sec	± 5 ft/sec
	. Type System	PRN S-Band	PRN S-Band	PRN S-Band	PRN S-Band	PRN S-Band	PRN S-Band	PRN S-Band
	. < 75 N. Miles							
	. Measure		X	X	X	X	X	X
	. Respond	X	X					
	. Accuracy							
	. Range	± 6" or ± .02% of Range Whichever is greater						
	. Range Rate	± 0.1 FPS or ± 1% of Range Rate whichever is greater						
	. Type System	Passive Reflector	Active SLR + Passive Reflector	Active SLR	Active SLR	Active SLR	Active SLR	Active SLR

	TUG$_1$	OPD	GND	TDRS				
5	Antenna System (Cont)							
	S-Band (Cont)							
	. Beamwidth							
	. Polarization	RHCP	RHCP					
	K$_u$-Band							
	. Type	NA	NA	5-Foot Parabolic				
	. Pattern			1° FOV				
	. Number			1				
	. Gain			45 dB				
	. Beamwidth			1° to 3 dB Points				
	. Polarization			RHCP				
6	Tracking/Ranging							
	. >75 N. Miles							
	. Measure	X						
	. Respond		X	X				
	. Accuracy							
	. Range	± 1 n.mi.	± 1 n.mi.	± 1 n.mi.				
	. Range Rate	± 5 ft/sec	± 5 ft/sec	± 5 ft/sec				
	. Type System	PRN S-Band	PRN S-Band	PRN Ku-Band				
	. < 75 N. Miles							
	. Measure	X	NA	NA				
	. Respond							
	. Accuracy							
	. Range							
	. Range Rate							
	. Type System	Active SLR						

	TUG$_1$	EOS	TUG$_2$	RAM (FF)	SAT	MSS	CPS	RNS
8	Other Element Reference Characteristics							
A	Transmitter							
	. Power Output							
	VHF	25 Watts	25 Watts	NA	NA	NA	NA	NA
	K$_u$-Band	NA	NA	NA	NA	NA	NA	NA
	S-Band	30 Watts	30 Watts	30 Watts	30 Watts	30 Watts	30 Watts	30 Watts
B	Receiver							
	. Noise Temperature							
	VHF	1200°K	1200°K	NA	NA	NA	NA	NA
	K$_u$-Band	NA	NA	NA	NA	NA	NA	NA
	S-Band	800°K	800°K	800°K	800°K	800°K	800°K	800°K
C	Antenna							
	. Gain							
	VHF	0dB	0dB	NA	NA	NA	NA	NA
	K$_u$-Band	NA	NA	NA	NA	NA	NA	NA
	S-Band	0dB	0dB	0dB	0dB	0dB	23 dB	23 dB

	TUG_1	OPD	GND	TDRS				
8	Other Element Reference Characteristics							
A	Transmitter							
	. Power Output							
	VHF	25 Watts						
	K_u-Band	NA						
	S-Band	800°K						
B	Receiver							
	. Noise Temperature							
	VHF	1200°K						
	K_u-Band	NA						
	S-Band	800°K						
C	Antenna							
	. Gain							
	VHF	0dB						
	K_u-Band	NA						
	S-Band	0dB						

COMMUNICATIONS ELEMENT PAIRS REQUIREMENTS MATRIX

	EOS_1	EOS_2	TUG	RAM (FF)	SAT	MSS	CPS	RNS
1	Data from EOS_1 to							
	. Voice (.3-3 KH_z)	X	X	NA	NA	X	X	X
	No. Channels	1	1			1	1	1
	. Television	NA	NA	NA	NA	NA	NA	NA
	. B&W (2.9 MH_z)							
	. Color (4.5 MH_z)							
	. Digital Data							
	. Low $\lesssim$ 10 Kbps	2 Kbps	2 Kbps	2 Kbps	2 Kbps	2 Kbps	2 Kbps	2 Kbps
	. Med $\lesssim$ 1 Mbps							
	. High $\lesssim$ 50 Mbps							
	. Other							
	. Other . . .							
2	Data to EOS_1 from							
	. Voice (.3-3 KH_z)	X	X	NA	NA	X	X	X
	No. Channels	1	1			1	1	1
	. Television	NA	NA	NA	NA	NA	NA	NA
	. B&W (2.9 MH_z)							
	. Color (4.5 MH_z)							
	. Digital Data							
	. Low $\lesssim$ 10 Kbps	10 Kbps	4 Kbps	5 Kbps	27.5 Kbps		10 Kbps	8.5 Kbps
	. Med $\lesssim$ 1 Mbps					51.2 Kbps		
	. High $\lesssim$ 50 Mbps							
	. Other							

COMMUNICATIONS ELEMENT PAIRS REQUIREMENTS MATRIX

	EOS_1	OPD	GND	TDRS				
1	Data from EOS_1 to							
	. Voice (.3-3 KH_z)	X	X					
	No. Channels	1	2					
	. Television	NA	NA					
	. B&W (2.9 MH_z)							
	. Color (4.5 MH_z)							
	. Digital Data							
	. Low $\leq$ 10 Kbps	2 Kbps						
	. Med $\leq$ 1 Mbps		51.2 Kbps					
	. High $\leq$ 50 Mbps							
	. Other							
	. Other							
	.							
	.							
	.							
2	Data to EOS_1 from							
	. Voice (.3-3 KH_z)	X	X					
	No. Channels	1	2					
	. Television	NA	NA					
	. B&W (2.9 MH_z)							
	. Color (4.5 MH_z)							
	. Digital Data							
	. Low $\leq$ 10 Kbps	10 Kbps	10 Kbps					
	. Med $\leq$ 1 Mbps							
	. High $\leq$ 50 Mbps							
	. Other							

	EOS_1	EOS_2	TUG	RAM (FF)	SAT	MSS	CPS	RNS
2	Data to EOS_1 from (Cont) . Other . . .							
3	Transmitter System							
	VHF . Power Output . Maximum Range . Baseband Complex	25 Watts 2000 n.mi. 2 Kbps + Voice	25 Watts 2000 n.mi. 2 Kbps + Voice	NA	NA	25 Watts 2000 n.mi. 2 Kbps + Voice	25 Watts 2000 n.mi. 2 Kbps + Voice	25 Watts 2000 n.mi. 2 Kbps + Voice
	S-Band . Power Output . Maximum Range . Baseband Complex	30 Watts 150 n.mi. 51.2 Kbps + Voice + PRN Range	30 Watts 150 n.mi. 2 Kbps + Voice + PRN Range	30 Watts 150 n.mi. 2 Kbps + PRN Range	30 Watts 150 n.mi. 2 Kbps + PRN Range	30 Watts 150 n.mi. 2 Kbps + Voice + PRN Range	30 Watts 2000 n.mi. 2 Kbps + Voice + PRN Range	30 Watts 2000 n.mi 2 Kbps + Voice + PRN Range
	K_u-Band . Power Output . Maximum Range . Baseband Complex	NA	NA	NA	NA	NA	NA	NA
4	Receiver System							
	VHF . Input Noise Temp	1200°K	1200°K	NA	NA	1200°K	1200°K	1200°K

	EOS_1	OPD	GND	TDRS				
2	Data to EOS_1 from (Cont)							
	. Other . . .							
3	Transmitter System							
	VHF . Power Output . Maximum Range . Baseband Complex	25 Watts 2000 n.mi. 2 Kbps + Voice	NA	25 Watts 23,000 nm 10 Kbps + Voice				
	S-Band . Power Output . Maximum Range	30 Watts 150 n.mi.	1 Watt Slant Range to 500 n.mi. Altitude	NA				
	. Baseband Complex	2 Kbps + Voice + PRN Range	51.2 Kbps + Voice + TA PRN Range					
	K_u-Band . Power Output . Maximum Range . Baseband Complex	NA	NA	NA				
4	Receiver System							
	VHF . Input Noise Temp.	1200°K	NA	25 Watts				

	EOS$_1$	EOS$_2$	TUG	RAM (FF)	SAT	MSS	CPS	RNS
4	Receiver System (Cont)							
	VHF (Cont)							
	. Maximum Range							
	. Baseband Complex	10 Kbps + Voice	4 Kbps + Voice			51.2 Kbps + Voice	10 Kbps + Voice	8.5 Kbps + Voice
	S-Band							
	. Input Noise Temp	800°K	800°K	800°K	800°K	800°K	800°K	800°K
	. Baseband Complex		4 Kbps + Voice + PRN Range	5 Kbps + PRN Range	27.5 Kbps + PRN Range	51.2 Kbps + Voice + PRN Range	10 Kbps + Voice + PRN Range	8.5 Kbps + Voice + PRN Range
	K$_u$-Band	NA	NA	NA	NA	NA	NA	NA
	. Input Noise Temp.							
	. Baseband Complex							
5	Antenna System							
	VHF							
	. Type							
	. Pattern	Omni	Omni	NA	NA	Omni	Omni	Omni
	. Number							
	. Gain	0dB	0dB			0dB	0dB	0dB
	. Polarization							
	S-Band							
	. Type							
	. Pattern	Omni	Omni	Omni	Omni	Omni	Omni	Omni
	. Number							
	. Gain	0dB	0dB	0dB	0dB	0dB	0dB	0dB
	. Beamwidth							
	. Polarization	RHCP	RHCP	RHCP	RHCP	RHCP	RHCP	RHCP

	EOS_1	OPD	GND	TDRS				
4	Receiver System (Cont)							
	VHF (Cont)							
	. Maximum Range			23,000 nm				
	. Baseband Complex	10 Kbps + Voice		10 Kbps + Voice				
	S-Band							
	. Input Noise Temp.	800°K	2000°K	NA				
	. Baseband Complex	10 Kbps + Voice + PRN Range	2 Kbps + Voice PRN Range					
	K_u-Band	NA	NA	NA				
	. Input Noise Temp.							
	. Baseband Complex							
5	Antenna System							
	VHF							
	. Type							
	. Pattern	Omni	NA	Omni				
	. Number							
	. Gain	0dB		0dB				
	. Polarization							
	S-Band							
	. Type							
	. Pattern	Omni	Omni					
	. Number							
	. Gain	0dB	0dB					
	. Beamwidth							
	. Polarization	RHCP	RHCP					

	EOS$_1$	EOS$_2$	TUG	RAM (FF)	SAT	MSS	CPS	RNS
5	Antenna System (Cont)							
	Ku-Band	NA	NA	NA	NA	NA	NA	NA
	. Type							
	. Pattern							
	. Number							
	. Gain							
	. Beamwidth							
	. Polarization							
6	Tracking/Ranging							
	. > 75 N.Miles							
	. Measure	X	X	X	X	X	X	X
	. Respond	X				X		
	. Accuracy							
	. Range	± 1 n.mi.	± 1 n.mi.	± 1 n.mi.	± 1 n.mi.	± 1 n.mi.	± 1 n.mi.	± 1 n.mi.
	. Range Rate	± 5 ft/sec	± 5 ft/sec	± 5 ft/sec	± 5 ft/sec	± 5 ft/sec	± 5 ft/sec	± 5 ft/sec
	. Type System	PRN S-Band	PRN S-Band	PRN S-Band	PRN S-Band	PRN S-Band	PRN S-Band	PRN S-Band
	. < 75 N.Miles							
	. Measure	X		X		X		
	. Respond	X						
	. Accuracy							
	. Range	± 6" or ± .02% of Range whichever is greater						
	. Range Rate	± 0.1 FPS or 1% of Range Rate whichever is greater						
	. Type System	Active SLR + Passive Reflector		Active SLR		Active SLR		

	EOS_1	OPD	GND	TDRS				
5	Antenna System (Cont)							
	Ku-Band	NA	NA	NA				
	. Type							
	. Pattern							
	. Number							
	. Gain							
	. Beamwidth							
	. Polarization							
6	Tracking/Ranging							
	. >75 N.Miles			NA				
	. Measure	X						
	. Respond		X					
	. Accuracy							
	. Range	± 1 n.mi.	± 1 n.mi.					
	. Range Rate	± 5 ft/sec	± 5 ft/sec					
	. Type System	PRN S-Band	PRN S-Band					
	. < 75 N.Miles							
	. Measure	X	NA	NA				
	. Respond							
	. Accuracy							
	. Range	±6" or .02% of range						
	. Range Rate	±0.1 FPS or 1% of range-rate whichever is greater						
	. Type System	Active SLR						

	EOS$_1$	EOS$_2$	TUG	RAM (FF)	SAT	MSS	CPS	RNS
8	Other Element Reference Characteristics							
A	Transmitter							
	. Power Output							
	VHF	25 Watts	25 Watts	NA	NA	25 Watts	1200°K	
	K$_u$-Band	NA	NA	NA	NA	NA	NA	NA
	S-Band	30 Watts	30 Watts	30 Watts	30 Watts	30 Watts	30 Watts	30 Watts
B	Receiver							
	. Noise Temperature							
	VHF	1200°K	1200°K	NA	NA	1200°K	1200°K	1200°K
	K$_u$-Band	NA	NA	NA	NA	NA	NA	NA
	S-Band	800°K	800°K	800°K	800°K	800°K	800°K	800°K
C	Antenna							
	. Gain							
	VHF	0dB	0dB	NA	NA	0dB	0dB	0dB
	K$_u$-Band	NA	NA	NA	NA	NA	NA	NA
	S-Band	0dB	0dB	0dB	0dB	0dB	23 dB	23 dB

	EOS_1	OPD						
8	Other Element Reference Characteristics							
A	Transmitter							
	• Power Output							
	VHF	25 Watts						
	K_u-Band	NA						
	S-Band	30 Watts						
B	Receiver							
	• Noise Temperature							
	VHF	1200°K						
	K_u-Band	NA						
	S-Band	800°K						
C	Antenna							
	• Gain							
	VHF	0dB						
	K_u-Band	NA						
	S-Band	0dB						

FUNCTIONAL REQUIREMENTS ANALYSES

As mentioned above, the first step in the analysis was to determine the maximum data transfer requirements for each element and its interfacing element. This involved researching source documentation for performance requirements established by the particular element program. Then, it was necessary to examine each other interfacing activity in the Orbital Operations study for their demands on the communications system. It must be re-iterated that communications is a support service. By application of data correlation and judgement, a set of data requirements was evolved. The next step was to determine some basic constraints or system parameters that must be applied due to the limits of cost and technology. This determined items such as an S-band receiver system noise figure of 800° K, the use of moderate size antennas (3 to 5 feet), when directional antennas were necessary, and the limits of S- and Ku-band transmitter RF power outputs to 30 and 25 watts, respectively. Other constraints are imposed by the use of the VHF, S-band and Ku-band frequencies to provide compatbility with the NASA ground network and TDRS system model (reference DS-504). Tables 1-2 and 1-3 identify the frequency ranges and data rates that can be accommodated by TDRS and the ground network. Although other frequencies and limits could be used for element-to-element communications, these should be used as the basis for element-to-element operations in order to provide systems compatibility. A series of parametric curves were then derived from computations using standard communications link margin techniques. These curves were derived for both analog FM and PSK modulation as well as the combination of PRN, PM ranging and subcarrier PM/PSK modulation. The curves were based on specific antenna sizes and separation ranges for transmitter power output versus data rate at both S- and Ku-band. Element-to-element operation and element-to-ground or TDRS curves are available for use as applicable. Figures 1-8 to 1-19 cover these communication links.

When antenna sizes and receiver noise temperatures coincide with these curves, they can be used directly to determine RF transmitter power. It was found, however, that at S-band another curve would be helpful when antenna size and receiver temperature might be different than assumed. Figure 1-20 plots separation range against effective radiated power (EIRP) in dbw for several different data rates most commonly encountered in the program. Reference lines for 30 and 100 watts RF radiated power (EIRP) and 30 watts transmitter power and 3- and 5-foot antennas are shown. This curve also assumes an 800 K noise temperature receiver and a 0 db receiver antenna gain. Having established a data rate, say 50 kbps, examine this curve and find the EIRP for a given range; i.e., 42.4 dbw at 2200 nautical miles. This can be satisfied with a transmitter power output of 14.8 dbw (30 watts) and 5-foot parabolic antenna (28 db gain). If the element is limited to an omni-directional antenna (0 db gain), the range is limited to either 170 nautical miles with a 100-watt (20 dbw) transmitter or 95 nautical miles with a 30-watt (14.8 dbw) transmitter.

In a similar manner, the curves displaying data rates versus transmitter power may be used directly to determine transmitter power in watts for the conditions shown on the curve.

Corrections to the basic curves for different receiver noise temperatures or antenna gains can be made by applying their impact on the major analysis calculation. Noise temperatures other than those indicated on the curve are impacted by 10 log T in db where T is noise temperature in degrees Kelvin. The change from 290°K to 800°K, for instance, means the addition of 4.4 dbw of power necessary to preserve the link signal-to-noise ratio. Since the curves give power in watts, this must first be converted to dbw and this difference in db added. Thus, a 10-watt power or 10 dbw requirement would be increased to 14.4 dbw or 28 watts by the change from 290° K to 800° K. Similarly, variations in antenna gain can be used to modify the results. Tables 1-6 and 1-7 can be used to help make these modifications. These are (Table 1-6) noise spectral density versus receiver noise temperature and (Table 1-7) antenna power gains and beamwidths for both S- and Ku-bands. Another aid is the variation of space loss due to separation range. This component in the margin analyses is 20 log d (d being separation range in nautical miles). Changes from the ranges shown on the curves can be accomplished using this factor.

Table 1-6. Noise Spectral Density vs. Receiver Noise Temperature

Receiver Noise Temperature (degrees Kelvin)	Noise Spectral Density (dbw/Hz)	Relative to 290° K (db variation)
125	206.0	+ 2.0
200	205.6	+ 1.6
290	204.0	0.0
500	201.6	- 2.4
800	199.6	- 4.4
1000	198.6	- 5.4
1200	197.8	- 6.2
4000	192.6	-11.4
7000	190.1	-13.9

Table 1-7. Antenna Size vs. Gain and Beamwidth

Size	S-Band - 2 GHz		Ku-Band - 15 GHz	
	Gain (db)	Beamwidth (degrees)	Gain (db)	Beamwidth (degrees)
2	19.0	18.0	37.0	2.4
3	23.0	12.0	40.5	1.6
4	25.5	9.0	43.0	1.2
5	27.5	7.0	45.0	1.0
6	29.0	6.0	46.5	0.8
7	30.5	5.0	48.0	0.7
8	31.5	4.5	49.0	0.6

Figure 1-6 defines the maximum ranges between elements for various orbital altitudes. Derivation of the maximum range of 23,000 nautical miles between TDRS and element is shown in Figure 1-7. These range numbers can be used to determine maximum expected link separations for various element-to-element combinations.

VHF is usable for low data rates and voice signals. When TDRS is used, VHF is a necessity to provide order wire capability. Order wire on VHF provides the alert in either direction with TDRS to activate communications. VHF is also usable for the wake-up of quiescent elements by active alements. A 25-watt VHF transmitter with an omni-directional antenna (0 db gain) will support all low data rate links either with TDRS or element to element. This was confirmed by a margin calculation.

Communications support to data transfer, command and control, and tracking and ranging were considered in the analyses. Data transfer supports the transfer of analog and digital data in both link directions. Signal-to-noise ratios were used to provide quality signal outputs after demodulation. All digital links were assumed to provide a bit-error-rate (BER) of 1×10^{-6}. This BER is considered adequate for the most demanding requirement; i.e., command transfer. Ground-to-element either direct or via TDRS links were briefly analyzed to assure that the combination of receiver noise temperatures and antenna configurations assumed would support the uplink quality requirements. All cases showed no problem. Omni-directional VHF antennas, and 1200°K noise temperature receivers are sufficient to receive commands from TDRS with SNR to provide a BER of 1×10^{-6}. At S-band, the ground radiated power available provides sufficient signal strength at an element with an omni-directional antenna and a 1200 °K noise temperature receiver. The advantage of the large high-gain antenna (85-foot) and receiver system low noise temperature (125° K) at the ground stations is evident in the low S-band element powers necessary.

Ranging is provided by systems compatible with that used by the ground network stations. The measuring (controlling) element must have the capability to generate and transmit a PRN (pseudo random noise) code to the measured element. The measured (controlled) element has the capability to receive and transmit the signal back to the measuring element. The measuring element must have the capability to perform a code correlation and measure the round trip time. With knowledge of the internal delay time in the measured vehicle, the range can be computed.

The transponder that is used on the measured vehicle must be a coherent system; i.e., the transmitter carrier is coherent with the received carrier. By measurement of the carrier doppler frequency shift, range rate is computed. All elements must have transponder systems capable of operating with a ground network PRN range and range rate system. This establishes as a functional requirement an S-band PRN ranging transponder for operation with ground and Ku-band for TDRS operation. RF power necessary to provide accurate ranging is small compared to that necessary for data transfer. Figures 1-14, 1-15, 1-18, and 1-19 define the transmitter power necessary. Certain other assumptions, in addition to those of Tables 1-4 and 1-5, were made for the ranging modes. Carrier tracking noise bandwidths of 800 Hz were assumed, and a 1 Hz clock noise bandwidth was assumed for PRN. A carrier tracking threshold of 6 db without subcarriers and 12 db with subcarriers was assumed. These are typical of Apollo detection requirements. A signal-to-noise ratio of 32 db is required for PRN threshold. These systems are capable of measurement accuracies in the order of 30-foot RMS range and 0.2 fps range rate. Successive range measurements of range can provide data for calculation of accurate orbital parameters and ephemerides.

Tracking data (angular position data) when necessary can be obtained by outputs from auto-track systems on high-gain directive antenna systems. Ground network stations use either 30 or 85-foot tracking antennas at S-band using a simultaneous lobing tracking system. Element tracking utilizing similar techniques could be used when either Ku- or S-band directive systems are available on the element. By application of range, range-rate and tracking data to the computer, state vectors and orbital parameters can be calculated. Successive measurements of range and range-rate provides sufficient data to result in the required accuracy of state vectors and orbital parameters.

Range, range-rate and state vector measurement accuracy requirements are determined by support to rendezvous, stationkeeping, docking, and mission support requirements. Studies of source documentation indicate that fulfillment of rendezvous, stationkeeping and docking can be met by application of the following requirements:

Range	Accuracy	
	Range	Range-Rate
0-100 ft	± 6 inches	±0.1 ft/sec
100-1500 ft	± 1 foot	±0.1 ft/sec
1500 ft-5 n mi	± 10 feet	±0.5 ft/sec
5 n mi-30 n mi	± 100 feet	±0.5 ft/sec
30 n mi-60 n mi	± 500 feet	±5.0 ft/sec
Over 60 n mi	± 1 n mi	±10 ft/sec

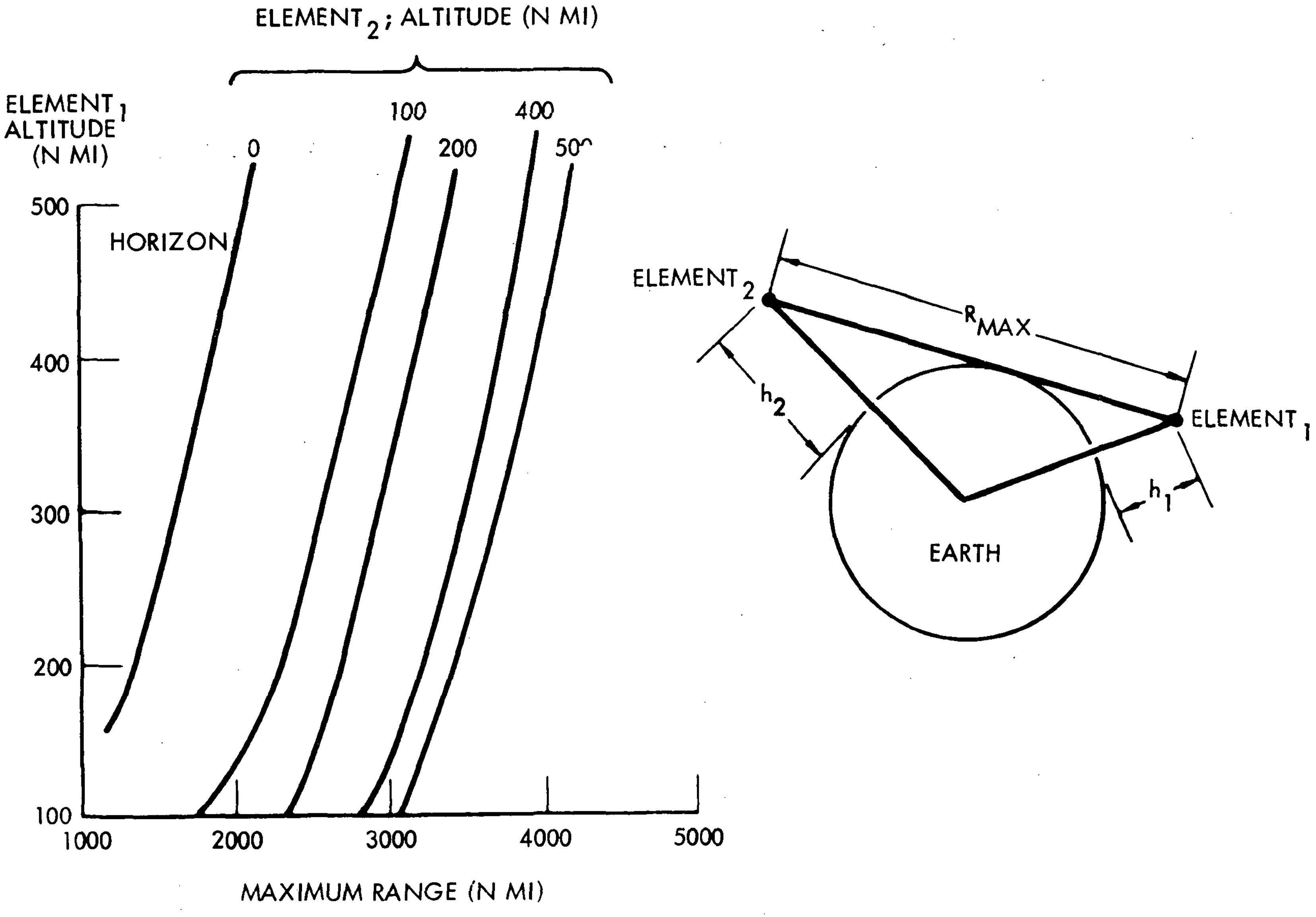


Figure 1-6. Maximum Line-of-Sight Range Versus Program Element Altitudes

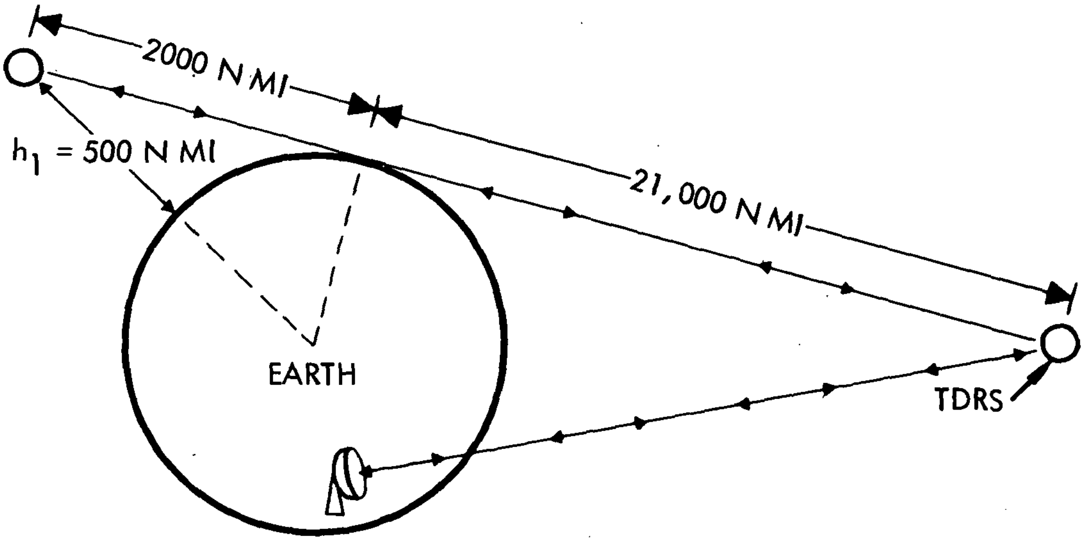


Figure 1-7. Maximum Line-of-Sight Range for an Element-to-Synchronous Satellite Relay

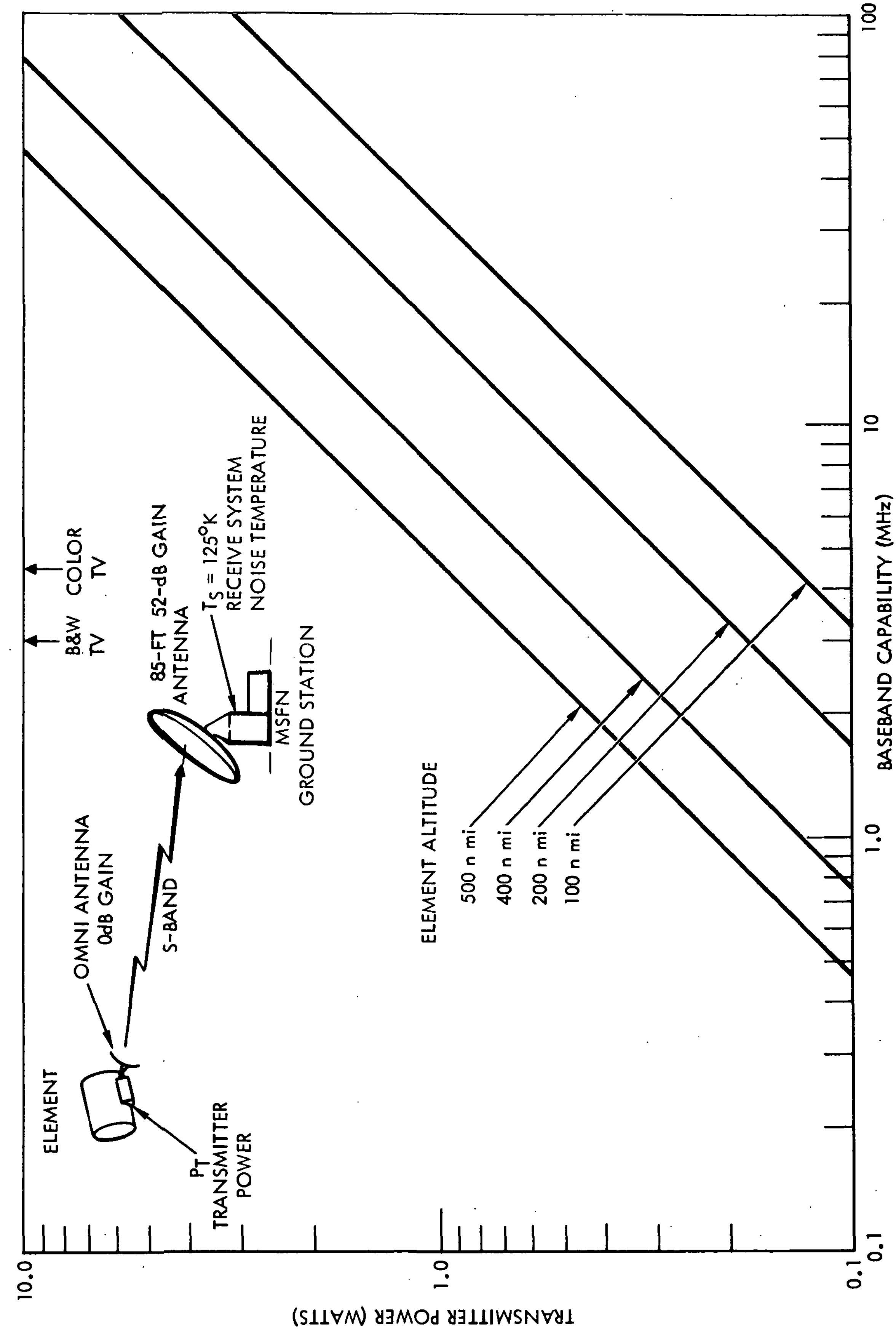


Figure 1-8. Direct-to-Ground FM Modes Link Analysis (S-Band)

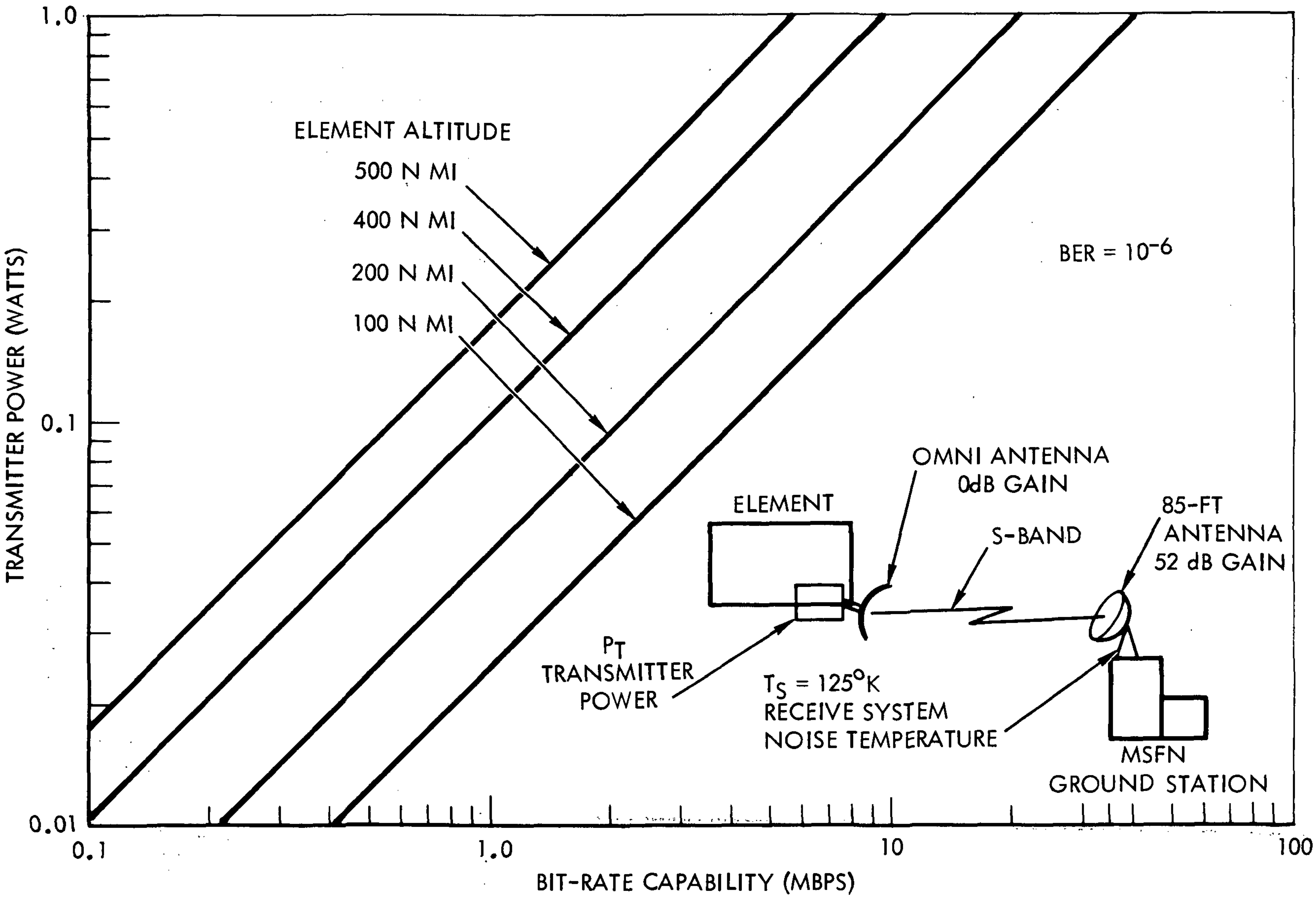


Figure 1-9. Direct-to-Ground PSK Data Link Analysis (S-Band)

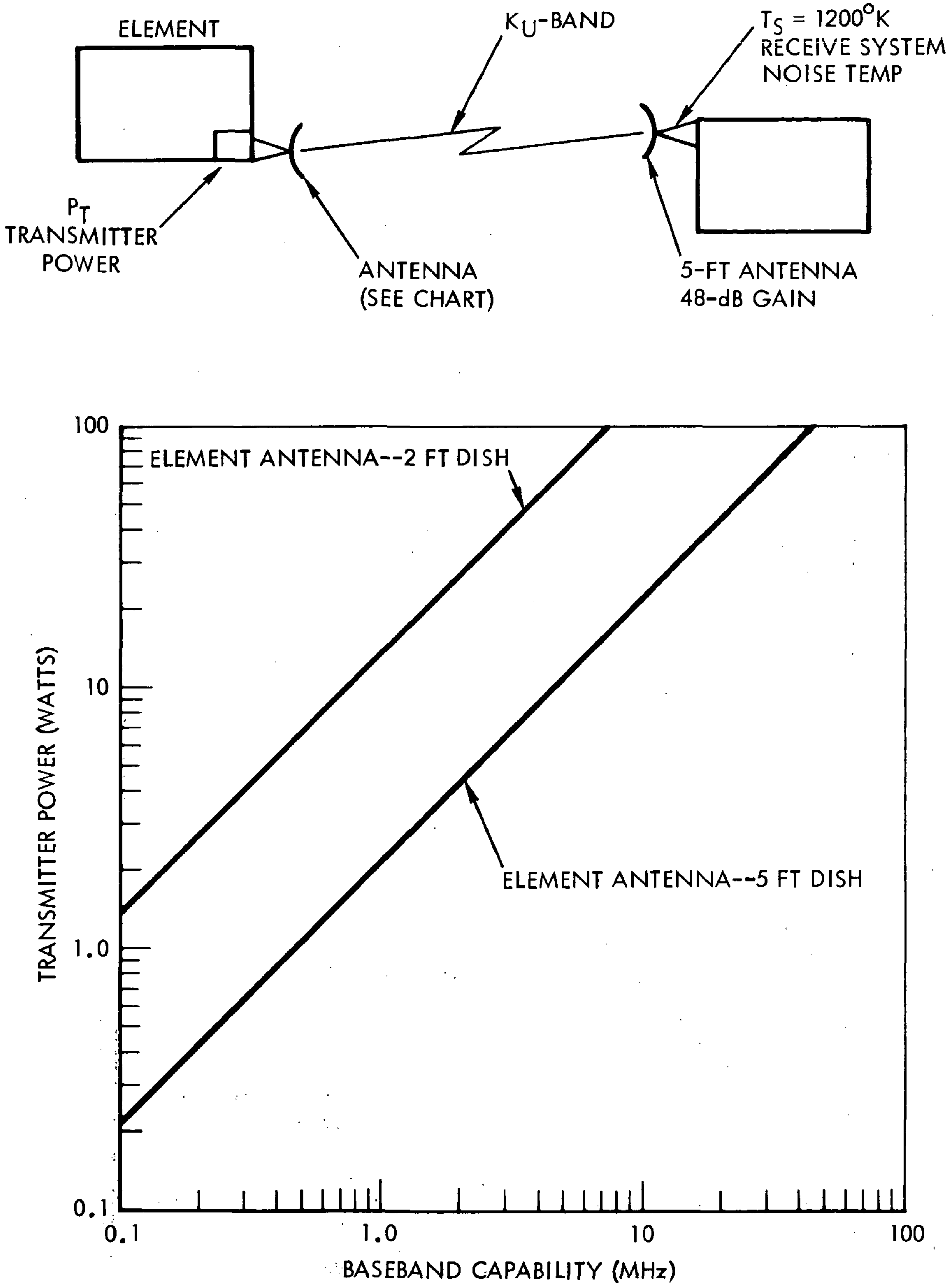


Figure 1-10. Element-to-TDRS FM Modes Link Analysis (K_u-Band)

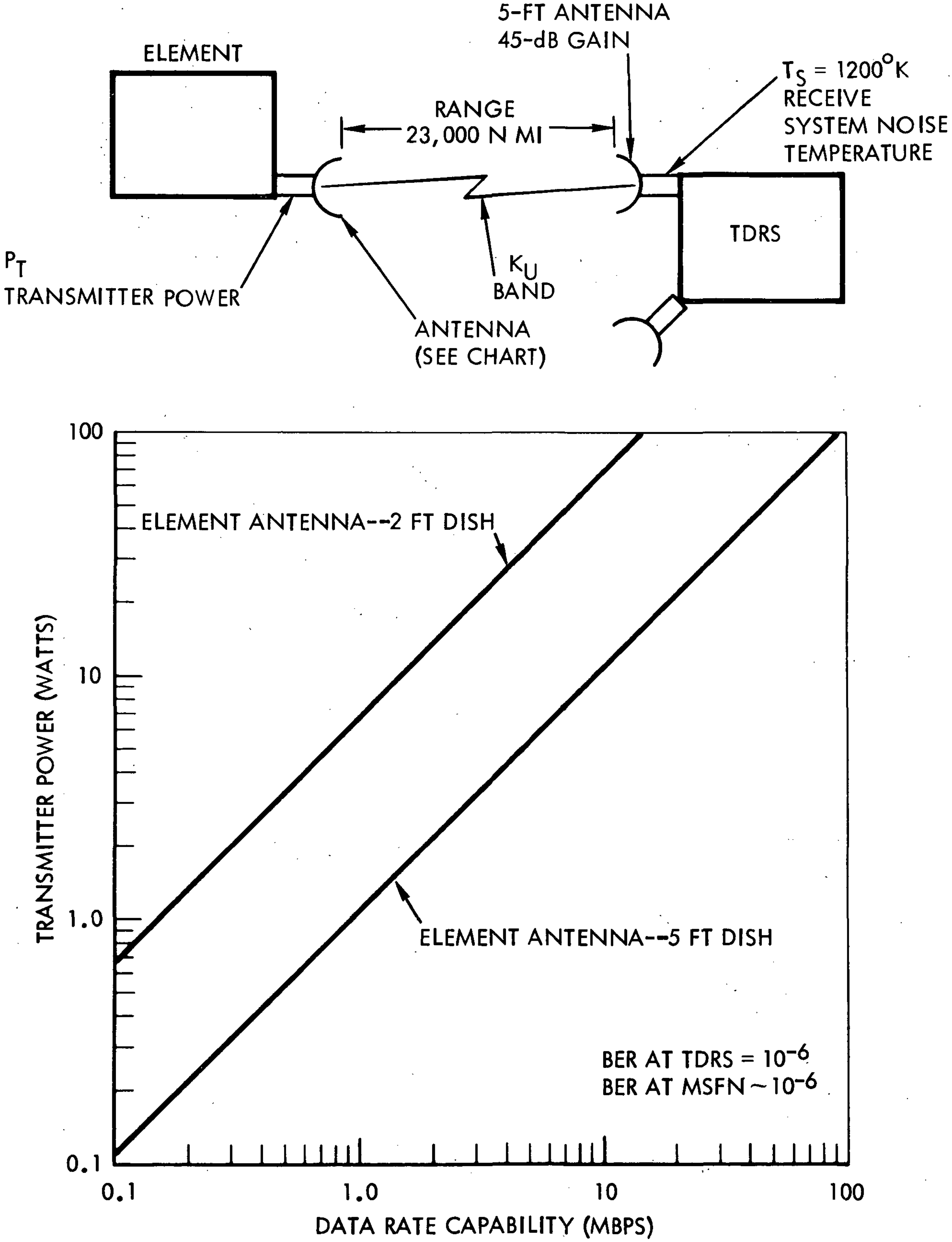


Figure 1-11. Element-to-TDRS PSK Data Link Analysis (K_u-Band)

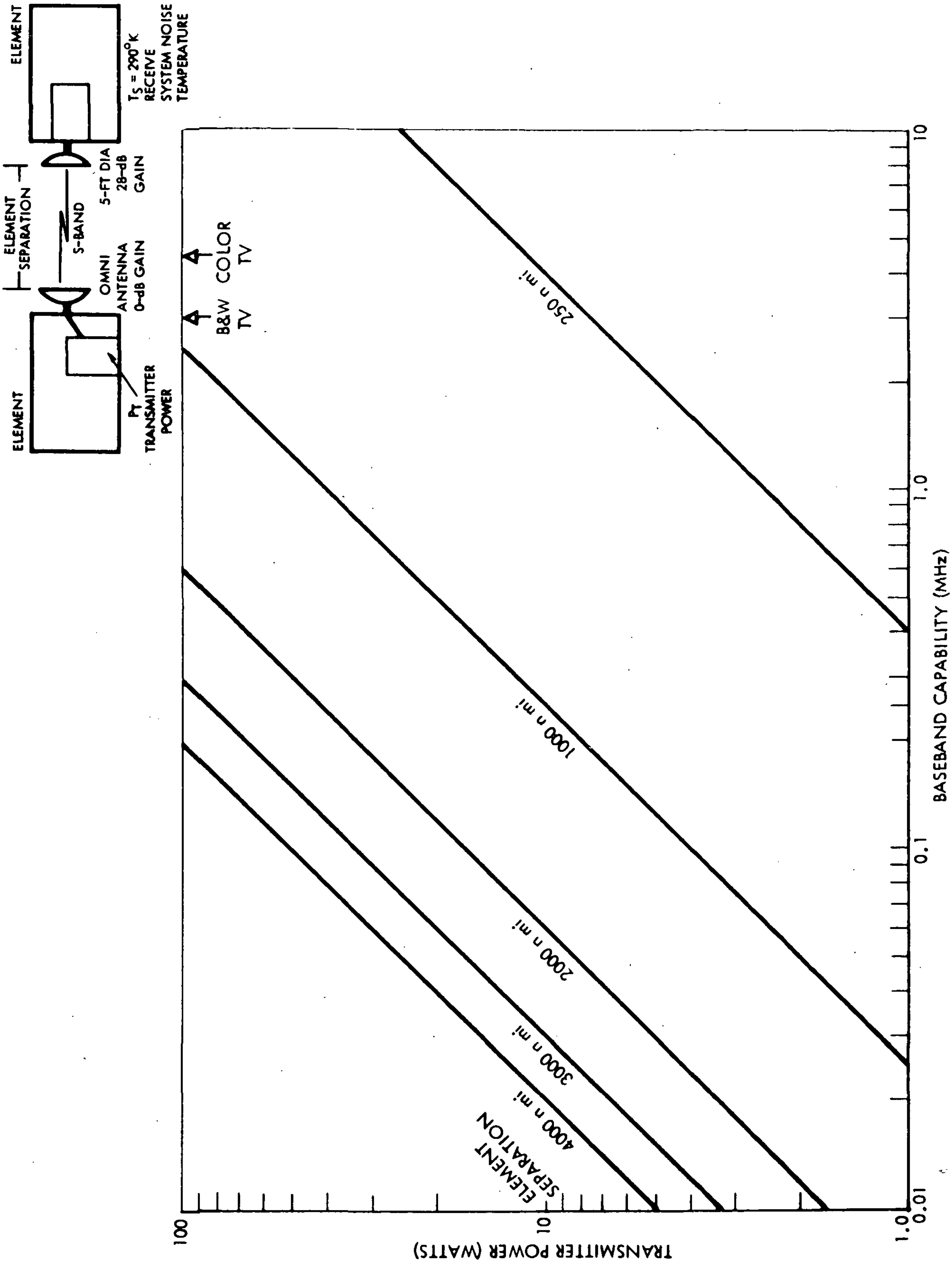


Figure 1-12. Element-to-Element FM Modes Link Analysis (S-Band)

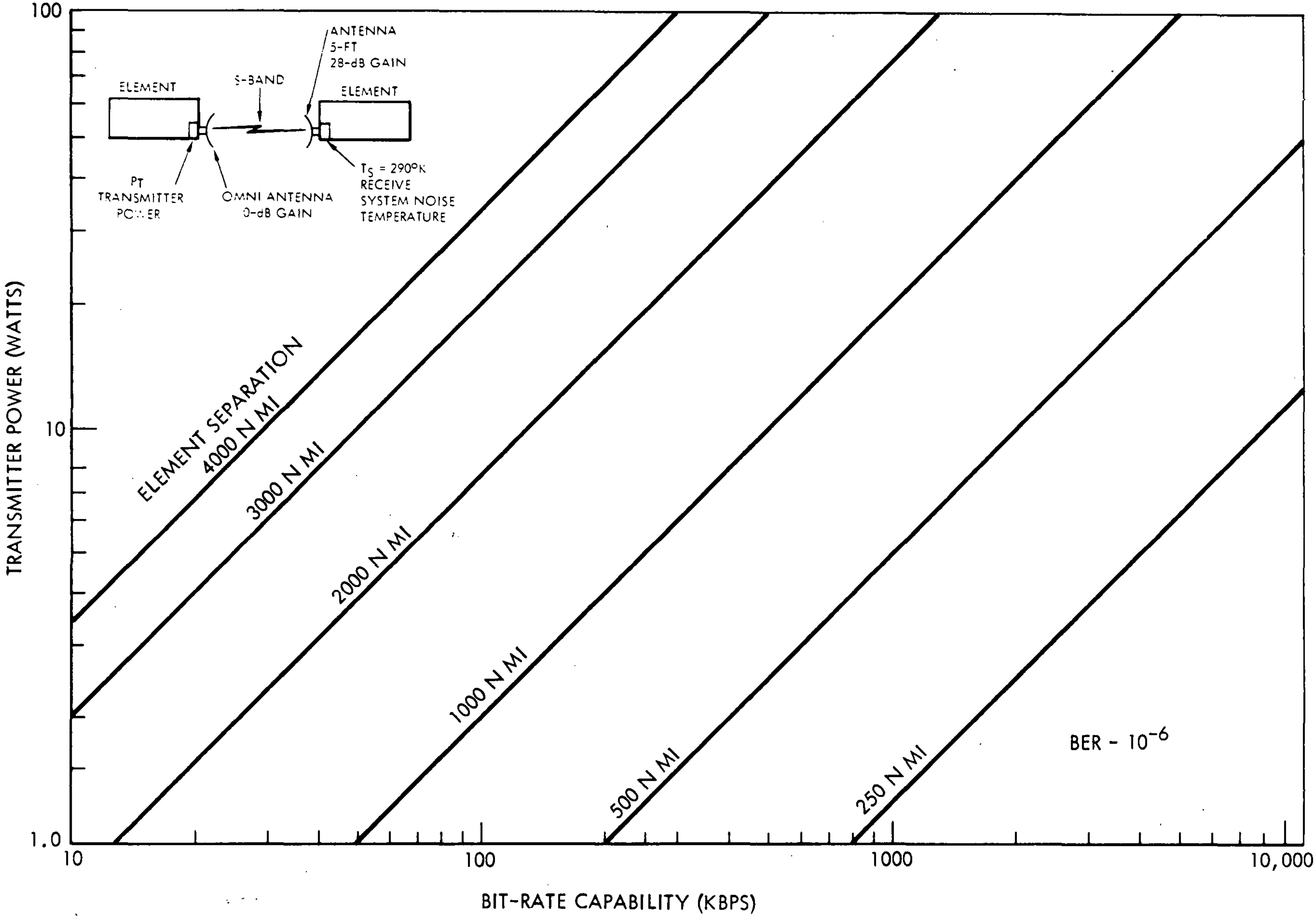


Figure 1-13. Element-to-Element PSK Data Link Analysis (S-Band)

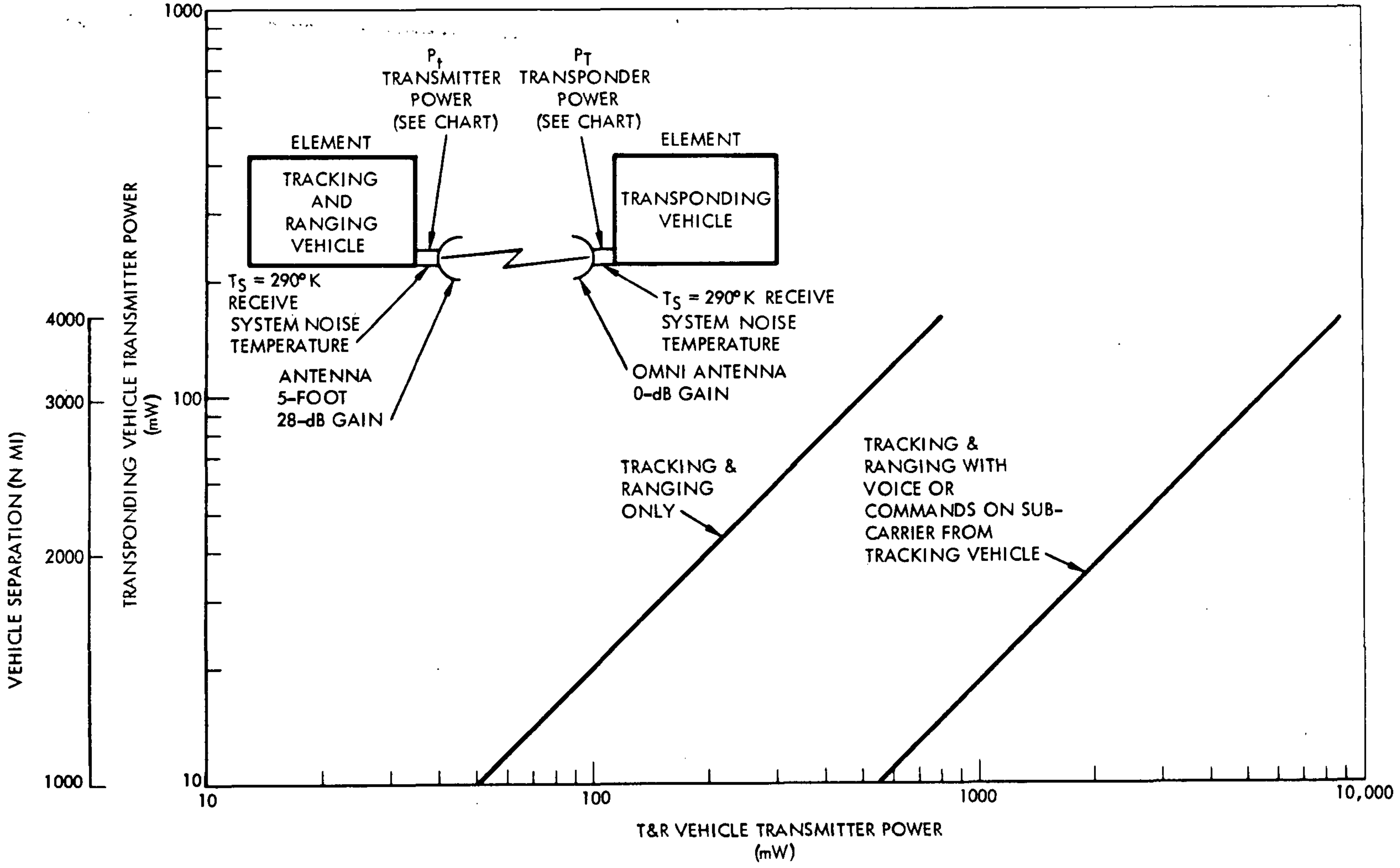


Figure 1-14. Element-to-Element Tracking and Ranging (S-Band)

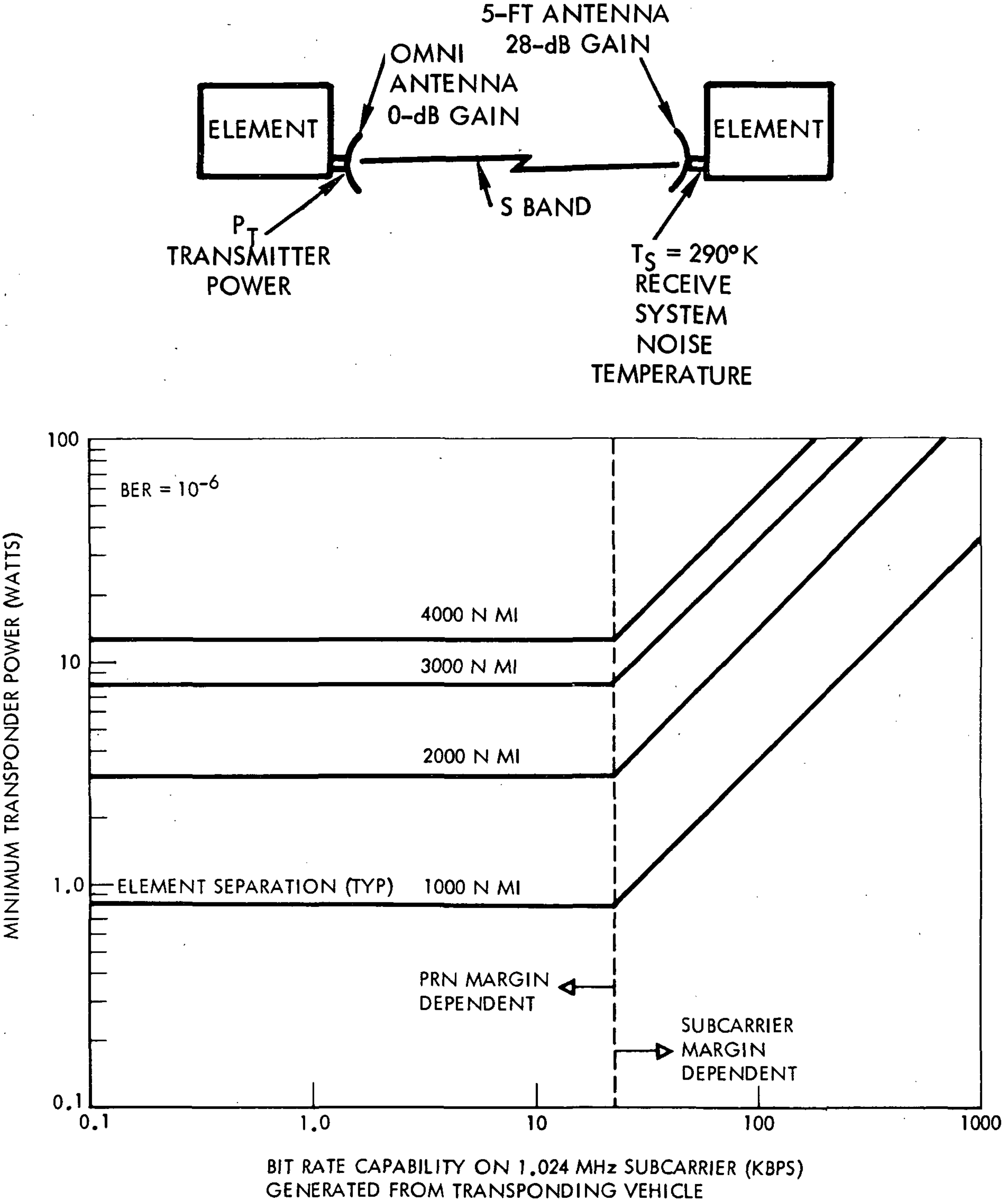


Figure 1-15. Data and Turned Around PRN Ranging Element-to-Element PCM/PSK/PM Link Analysis (S-Band)

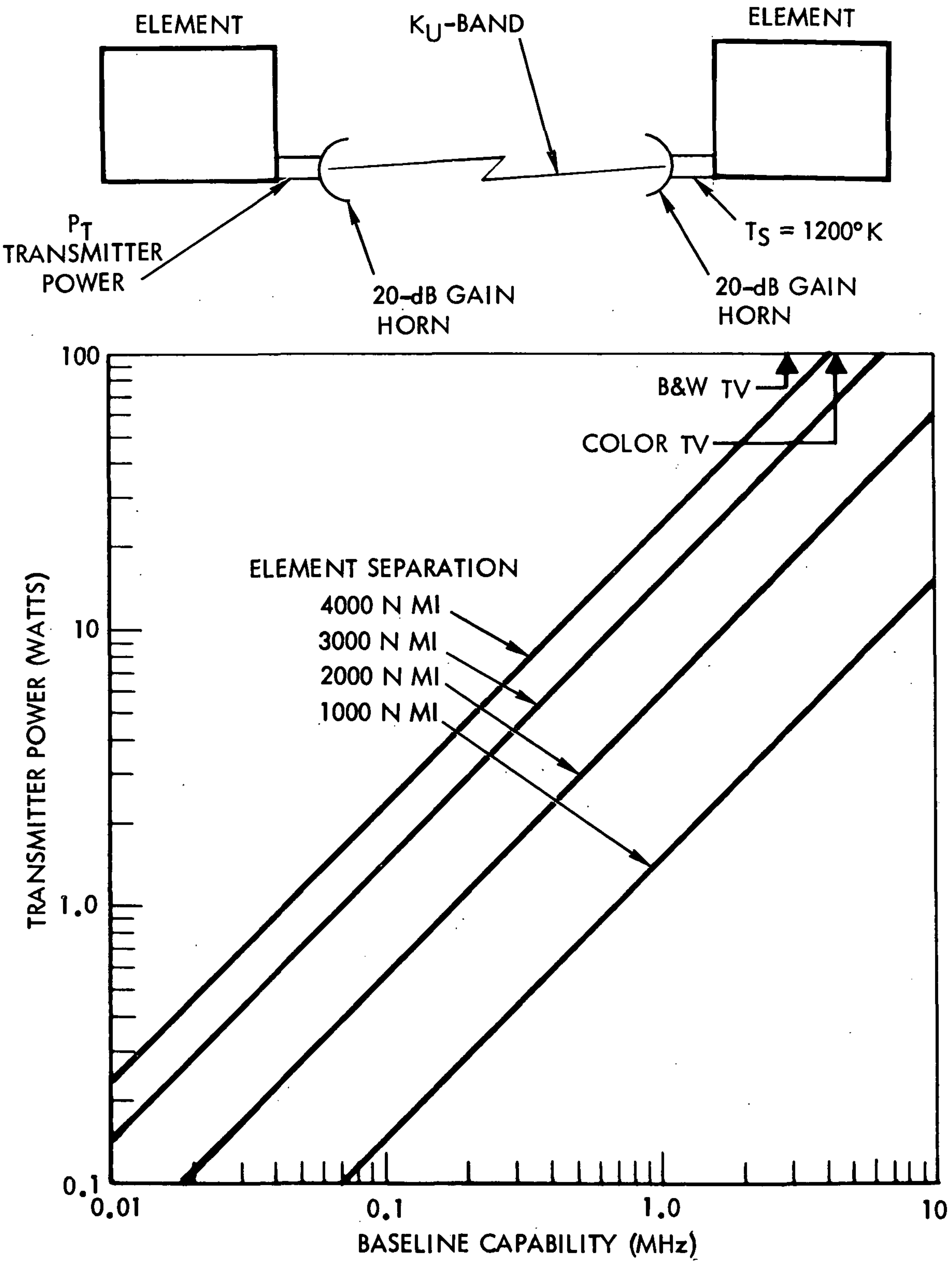


Figure 1-16. Element-to-Element FM Modes Link Analysis (K_u-Band)

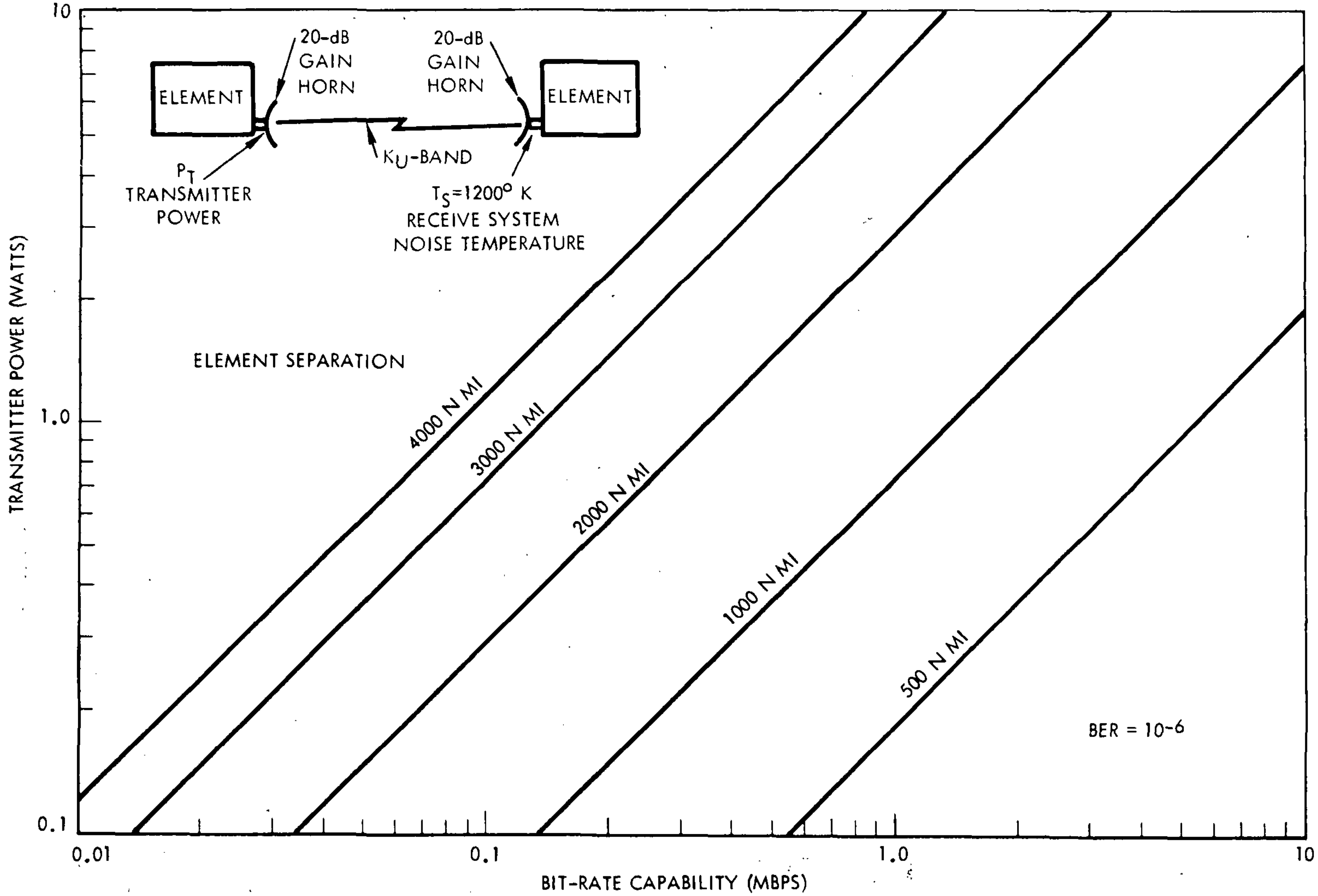


Figure 1-17. Element-to-Element PSK Data Link Analysis (K_u-Band)

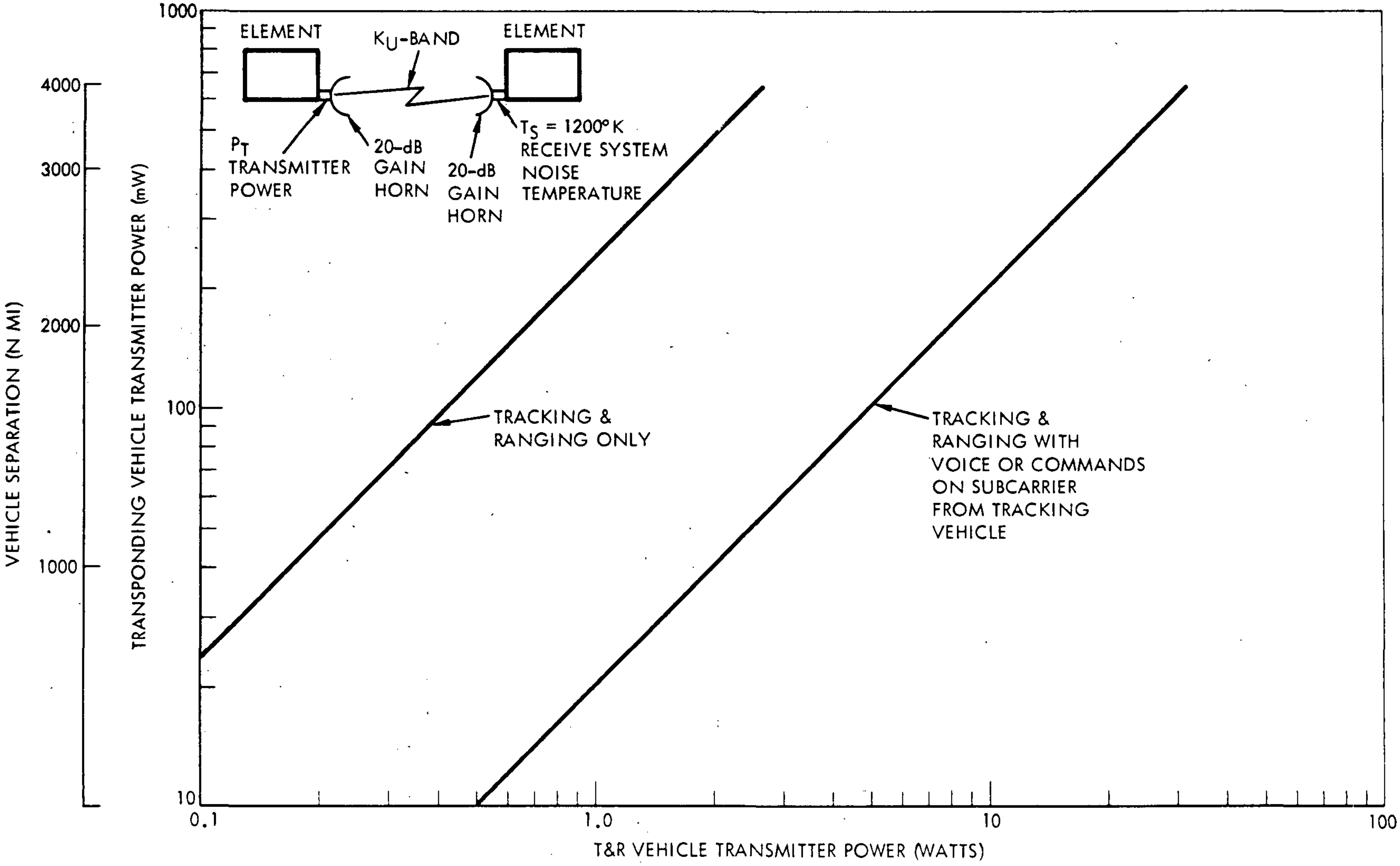
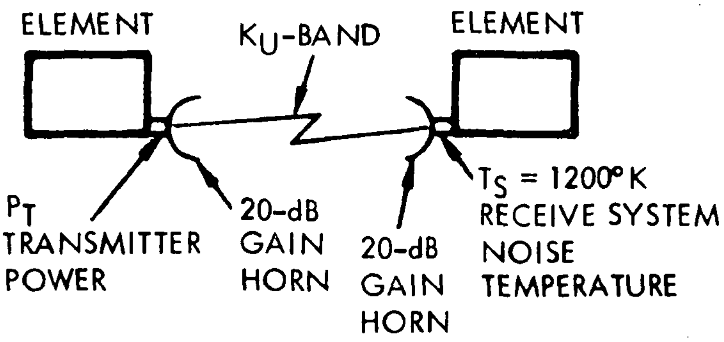


Figure 1-18. Element-to-Element Tracking and Ranging With Turnaround Ranging Only (K_u-Band)



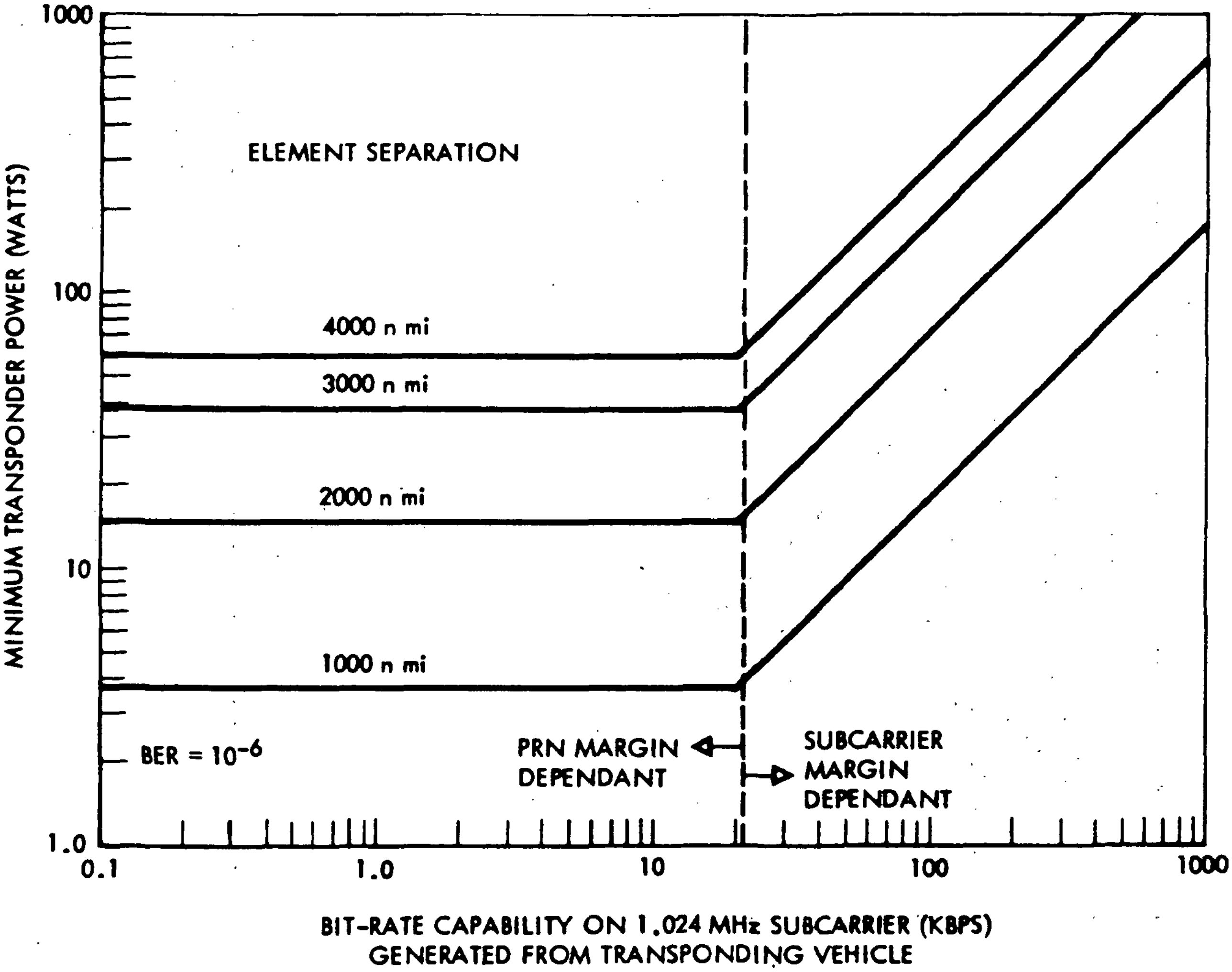


Figure 1-19. Data and Turned Around Ranging Element-to-Element PCM/PSK/PM Link Analysis (K_u-Band)

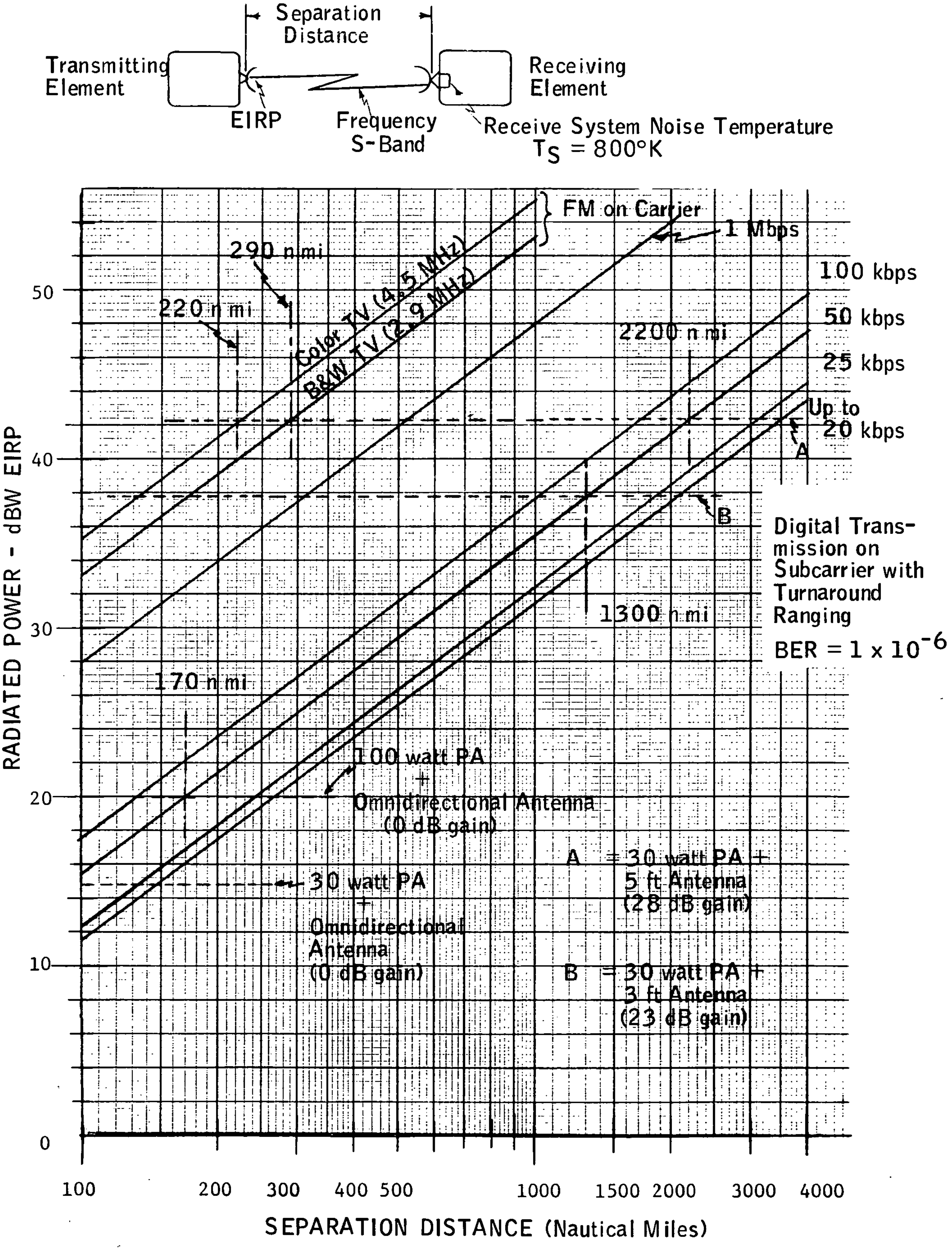


Figure 1-20. Element-to-Element Communications Link Characteristics at S-Band

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1.7 DESIGN INFLUENCES AND PREFERRED APPROACH SELECTION

For the communications activity, choice of a preferred approach, i.e., element-to-element, element-to-ground direct or element-to-ground via TDRS is appropriate only for the choice between the ground links. During any element mission, communications links must be established between the element and another element or between the element and ground. An element-to-element link can only be effectively accomplished by a direct link. The present TDRS system does not have the capability to support a link between two elements directly through the TDRS. All element communication to TDRS must flow through the TDRS ground control center. Thus, the signal from one element must be to TDRS, TDRS to ground, switched from ground to TDRS, and then to the other element pair. Similar attempts to provide such a link through the ground network could be more complicated. It would be necessary in many cases to utilize two ground stations and ground communications link between ground stations. Thus, a direct element-to-element RF communications link is considered the only approach when two elements must have direct contact. All elements or element pairs utilize this link during rendezvous, stationkeeping, detached element operations, and to support mission activities. Although each element was not required to use a TDRS to ground link, it is considered highly desirable to implement for that use. Either Ku or VHF can be used. Data rate or baseband bandwidth would determine which. Previous tables have indicated these limits. Use of TDRS provides a larger percentage of communications continuity than the ground network. Very small dark periods occur with the two satellite TDRS system of the model. The worst condition would be at low orbital altitudes. For example, the dark period would approach 10 percent of an orbit for orbits of 200 nautical miles. At a 700-nautical mile orbit this would decrease to approximately 3 percent.

In several cases, where high data rates (1 to 50 Mbps) or analog signals such as standard broadcast quality TV (4.5 MHz) must be transmitted to ground, TDRS at Ku-band will become a necessary relay. Present ground network stations at S-band, defined in the NASA model, cannot handle these bandwidths. With the ground network model of five stations, contact time to ground may be severely limited. Some orbits would have short time (6 minutes) or even zero coverage. Each element and its orbital history should be examined for coverage when direct to ground communications is used. It is also highly desirable to utilize the direct to ground approach as an alternate to ground via TDRS. The TDRS system (two satellites) is limited to 4 Ku-band users and 40 VHF users. Scheduling of use and as needed availability could become a problem. Availability of the ground net would help by providing additional channels. Tracking and ranging of satellites is more accurate from ground stations. The ground network has considerable operational history and element terminals would utilize existing technology and equipment. Although its data capability and continuity of communications are not as high as the TDRS, it would suffice for many element operations. In conclusion, it is recommended that each element be equipped to provide communication to other interfacing elements direct, to ground direct, and to TDRS when necessary for bandwidth or continuity reasons. The selection of all three approaches provides the major reason for the recommendation of VHF, S- and Ku-bands as the only alternate frequencies to consider for communications. By using these frequencies for element-to-element links, a commonality of equipment is accomplished. These frequencies, tracking/ranging, and modulation techniques are compatible with the ground use, either direct or via TDRS. Appendix A defines the trades made to establish this recommendation.

It would be highly desirable from a commonality standpoint to standardize on data format, especially for the telemetry and command signals. This standardization would result in commonality of much of the communication hardware. By limiting the frequency ranges to be used to VHF, S-band and Ku-band, a commonality of RF equipment can be achieved. Adding the standardization of data format would provide further commonality in the MODEM and data processing equipment.

A review of advantages accrued by this overall approach indicates many other supporting factors. No breakthrough in technology is required to implement the necessary element communications terminals. S-band equipment compatible with existing ground network systems is presently available. The addition of RF power to 30 to 35 watts may require new design for space application, but solid-state 30-watt S-band equipment has already been built and requires no new development. Ku-band equipment is not in general use but receiver and transmitter components presently exist to support the development and design of receivers with the noise figures estimated in this study (1200° K) and transmitters with power outputs to 25 watts. See Appendix A for further details. The development of TDRS will hasten the availability of Ku-band equipment and stimulate performance improvements. VHF is obviously a tried and developed frequency band. The spread spectrum modulation technique of TDRS will be developed during that program. PRN ranging is standard and requires no new developments. Checkout and maintenance of this equipment is well defined and much knowledge already exists to ensure high reliability. The major cost drivers in the different equipments will be the development of Ku-band transmitter and receivers and any high-gain antennas necessary. S-band and VHF costs would be low compared to any other possible alternates. The equipment is highly developed; most of the cost would be involved in production and development of the spread spectrum VHF equipment and the S-band power amplifiers. Development risks would be negligible. High-gain antennas, when necessary, would be needed even if X- or C-bands were used. The cost differential between that and Ku-band or S-band would be small. Ku-band requires tighter antenna surface tolerances, but a maximum of 5-foot size keeps this problem minimal. Ku-band equipment development costs would compare favorably with X- or C-band. One of the advantages of utilizing commonality between approaches is the provision of backup links. The capability to work with either TDRS or ground improves the reliability of mission operations. Safety is enhanced by providing the second link in the case of unforeseen problems.

The requirement for accurate knowledge of relative position, relative range-rate and angles between elements for rendezvous, stationkeeping, and docking leads to the choice of a scanning laser radar (SLR) system. Because of the precision of measurement accuracy, it is capable of support of these activities as well as an automatic docking operation between two unmanned satellites. Although the scanning laser radar is useful to a maximum of 75 nautical miles, it provides measurement accuracies at this range better than necessary but also has the precision for docking operations or close-in rendezvous and stationkeeping. At ranges greater than 75 nautical miles, the S-band PRN range system is sufficiently accurate, either by element-to-element relative measurement or from a ground station.

The possibility of microwave radar was examined. At ranges less than 50 feet, the microwave radar is not usable. Even at longer ranges it cannot approach the accuracy projected for the SLR, either in range or range-rate measurement. The system recommended needs only one active terminal. The target element uses corner cube reflectors to enhance the laser reflection signal. See Appendix A for further description and Part 2, Section 1 for its use in automatic docking. The SLR is presently under development. Hardware has been tested, confirming the projected accuracies. Use of this system for rendezvous, stationkeeping, and detached element operations for ranges less than 75 nautical miles as well as for docking would provide a tool common between elements, simple to use, and low in development risk. It also provides a precision instrument for measuring docking parameters that heretofore were only supported by a pilot's visual capability. No direct measurements of range or range-rate were available. They were pilot observations supported by visual target devices. The use of the scanning laser radar would enhance many operations.

No EVA communications requirements were identified as an interface activity for this study.

An examination of the orbital elements (by groupings) discloses that only two require Ku-band/TDRS operation. These are the RAM and MSS elements. All others can perform all necessary communications by S-band direct to ground or by VHF through TDRS to ground. RAM and MSS elements require the Ku-band link of TDRS to ground to provide the necessary bandwidth for the high data rates generated for real time and data dump from these elements. RAM will have some experiments that generate up to 35 Mbps data. Storage on board will relieve some of the demand but not sufficient to allow S-band direct to ground for high data rate and wideband TV. This is limited by bandwidth as well as reduced contact time. Color television and data rates of at least 2 Mbps from MSS along with high daily data dumps need the Ku-band channel bandwidth on TDRS. Although continuity of contact may be a problem for other elements in certain missions, a TDRS/VHF link can satisfy their normal low data rates and voice channels to provide high percentage of orbit contact time even at low orbits. The result is that most elements can satisfy communication needs with only S-band and VHF equipment, both with omni-directional antennas. By using PRN transponders for both ranging and communications, all long range (greater than 75 nautical miles) tracking/ranging requirements can be met. Ground stations can track to 75 nautical miles separation. When necessary for rendezvous, stationkeeping or other operations, a scanning laser radar system is used to provide more precision range, range-rate and angular element-to-element information. Each of the approaches (element-to-element, element-to-ground direct and element-to-TDRS-to-ground) is used during the life of an element mission. Consideration was only given to earth orbital operations. Lunar missions will add requirements to the RNS and CPS. These were not considered in this study. Table 1-8 is a compilation of all element approaches by major category. Tables 1-9 through 1-16 list in more detail the characteristics of each element for earth orbital operations, including the close-range scanning laser radar requirements. Both of these tables do indicate the additional capability that will probably be available for RNS and CPS lunar missions. This capability can be used to advantage for providing longer range element-to-element links from RNS and CPS. These data are shown in the functional requirements tables.

In using the element characteristics tables, Apollo-type TV is used to define the 10-frame per second/320 lines per frame system used on Apollo. The ground network is presently configured to handle this low baseband (500 kHz) signal. It is possible that the ground stations may be upgraded to provide higher resolution, broadcast-type television service. If so, S-band could be used for this improved operation.

Table 1-8. Approach Selection

	Element	Operates With	Ku-Band 25-watt	S-Band		VHF 25-watt Omni
				30-w Transmitter		
			5 ft Ant	3 ft Ant	Omni	
	EOS	EOS, Tug, RAM, MSS, CPS, RNS, OPD, Sat	-	-	X	X
	Tug	EOS, Tug, RAM, Sat, MSS, CPS, RNS, OPD	-	-	X	X
	RAM	EOS, MSS, Tug	X	-	X	X
	MSS	EOS, Tug, RAM	X	-	X	X
	RNS	EOS, Tug, OPD	-	X *	X	X
	CPS	CPS, EOS, Tug, OPD	-	X *	X	X
	OPD	EOS, Tug, CPS, RNS	-	-	X	X
	Sat	EOS, Tug	X	-	X	X
Approaches	Element	Element	X	X	X	X
	Element	Ground direct	-	X	X	X
	Element	TDRS to ground	X	-	-	X

* Shown to indicate that this capability will probably be available to support lunar missions. Omni capability will support all earth orbit operations.

Table 1-9. Element Characteristics

TUG

Operation with

EOS, Tug_2, RAM, Sat, MSS, CPS, RNS, OPD,
Ground Station, TDRS

Frequency Band	Ku	S	VHF
Frequency Ret.	14.4 - 15.35 gHz	2200 - 2300 MHz	136 - 144 MHz
Frequency Fw.	13.4 - 14.2 gHz	2025 - 2120 MHz	126 - 130 MHz
Data - Transmit	Not Used		
Analog - voice	↓	1 channel	1 channel
Analog - TV		Apollo type	--
Digital		50 kbps	10 kbps
Data - Receive			
Analog - voice		1 channel	1 channel
Analog - TV		--	--
Digital		10 kbps	1 kbps
Antenna type		Omni	Omni
Gain		0 db	0 db
Size			
Receiver noise temp.		800°K	1200°K
Transmitter			
Power output		30 watts	25 watts
Tracking/Ranging		PRN code transponder	
Measure		X	--
Respond		X	--
Use both active SLR and passive optical reflectors for docking maneuvers			

Use of Apollo type TV deletes need for TDRS Ku-band use - Continuity of communications is supported by TDRS-VHF link

Table 1-10. Element Characteristics

MSS

Operation with
EOS, Tug, RAM, Ground Station, TDRS

Frequency Band	Ku	S	VHF
Frequency Band Ret. Fw.	14.4 - 15.35 gHz 13.4 - 14.2 gHz	2200 - 2300 MHz 2025 - 2120 MHz	136 - 144 MHz 126 - 130 MHz
Data - Transmit	Note (1)	Note (1)	
Analog - voice	3 channels	3 channels	1 channel
Analog - TV	Color, 4.5 MHz	--	--
Digital	2.0 Mbps	1 Mbps	10 kbps
Data - Receive	Note (2)	Note (2)	
Analog - voice	3 channels	3 channels	1 channel
Analog - TV	--	--	--
Digital	500 kbps	500 kbps	1 kbps
Antenna Type	Parabolic	Omni	Omni
Gain	45 db	0 db	0 db
Size	5 ft dia		
Receiver noise figure	1200°K	800°K	1200°K
Transmitter Power output	25 watts	30 watts	25 watts
Tracking/Ranging			
Measure	--	X	--
Respond	X	X	--
SLR active system, and passive reflectors, at docking ports			

(1) Additional down data for facsimile - 0.5 MHz bandwidth

(2) Additional up channel for entertainment
Audio - 30 Hz - 10 kHz baseband

Table 1-11. Element Characteristics

EOS

Operation with
EOS_2, Tug, RAM, Sat, MSS, CPS, RNS, OPD, Ground Station and TDRS

Frequency Band	Ku	S	VHF
Frequency Ret. Fw.	14.4 - 15.35 gHz 13.4 - 14.2 gHz	2200 - 2300 MHz 2025 - 2120 MHz	136 - 144 MHz 126 - 130 MHz
Data - Transmit	Not Used		
Analog - voice		1 channel	1 channel
Analog - TV		--	--
Digital		51.2 kbps	10 kbps
Data - Receive			
Analog - voice		1 channel	1 channel
Analog - TV		--	--
Digital		10 kbps	1 kbps
Antenna Type		Omni	Omni
Gain		0 db	0 db
Size			
Receiver noise figure		800°K	1200°K
Transmitter Power output		30 watts	25 watts
Tracking/Ranging			
Measure		X	--
Respond		X	--
Active SLR and passive optical reflectors for rendezvous and docking			

Table 1-12. Element Characteristics

RAM

Operation with
EOS, MSS, Tug, Ground Station, TDRS

Frequency Band	Ku	S	VHF
Frequency Ret.	14.4 - 15.35 gHz	2200 - 2300 MHz	136 - 144 MHz
Frequency Fw.	13.4 - 14.2 gHz	2025 - 2120 MHz	126 - 130 MHz
Data - Transmit			
Analog - voice	--	--	--
Analog - TV	B&W - 2.9 MHz		--
Digital	35 Mbps	1 Mbps	10 kbps
Data - Receive			
Analog - voice	--	--	--
Analog - TV	--	--	--
Digital	10 kbps	10 kbps	1 kbps
Antenna Type	Parabolic	Omni	Omni
Gain	45 db	0 db	0 db
Size	5-foot		
Receiver noise temp	1200°K	800°K	1200°K
Transmitter Power output	25 watts	30 watts	25 watts
Tracking/Ranging			
Measure	--	--	--
Respond	X	X	--
Passive optical reflectors for SLR for rendezvous and docking			

Table 1-13. Element Characteristics

CPS

Operation with
CPS, EOS, Tug, OPD, Ground Station, TDRS

Frequency Band		Ku	S	VHF
Frequency	Ret.	14.4 - 15.35 gHz	2200 - 2300 MHz	136 - 144 MHz
	Fw.	13.4 - 14.2 gHz	2025 - 2120 MHz	126 - 130 MHz
Data - Transmit		Not Used		
Analog - voice		↓	1 channel	1 channel
Analog - TV		↓	Apollo TV	--
Digital		↓	1 Mbps	10 kbps
Data - Receive		↓		
Analog - voice		↓	1 channel	1 channel
Analog - TV		↓	--	--
Digital		↓	30 kbps	1 kbps
Antenna Type		↓	Parabolic	Omni
Gain		↓	23 dB	0 db
Size		↓	3 feet (1)	
Transmitter		↓		
Power output		↓	30 watts	25 watts
Tracking/Ranging		↓		
Measure		↓	X	--
Respond		↓	X	--
SLR active system and passive optical reflectors				

(1) Although available for earth orbit operations - since it is needed for lunar operations - an omni-directional antenna system would be sufficient for earth orbital missions.

Table 1-14. Element Characteristics

RNS

Operation with
EOS, Tug, OPD, Ground Station, TDRS

Frequency Band		Ku	S	VHF
Frequency	Ret.	14.4 - 15.35 gHz	2200 - 2300 MHz	136 - 144 MHz
	Fw.	13.4 - 14.2 gHz	2025 - 2120 MHz	126 - 130 MHz
Data - Transmit		Not Used		
Analog - voice			1 channel	1 channel
Analog - TV			Apollo type	--
Digital			10 kbps	10 kbps
Data Receive				
Analog - voice			1 channel	1 channel
Analog - TV			--	--
Digital			10 kbps	1 kbps
Antenna Type			Parabolic	Omni
Gain			23 dB	0 db
Size			3 feet (1)	
Transmitter				
Power output			30 watts	25 watts
Tracking/Ranging				
Measure				
Respond			X	--
Use both active SLR system and passive optical reflectors				

(1) Although available for earth orbit operations - since it is needed for lunar operations - an omni-directional antenna system would be sufficient for earth orbital missions.

Table 1-15. Element Characteristics

OPD

Operation with
EOS, Tug, CPS, RNS, Ground Station, TDRS

Frequency Band	Ku	S	VHF
Frequency Ret.	14.4 - 15.35 gHz	2200 - 2300 MHz	136 - 144 MHz
Frequency Fw.	13.4 - 14.2 gHz	2025 - 2120 MHz	126 - 130 MHz
Data - Transmit	Not Used ↓		
Analog - voice		1 channel	1 channel
Analog - TV		Apollo type	--
Digital		50 kbps	10 kbps
Data - Receive			
Analog - voice		1 channel	1 channel
Analog - TV		--	--
Digital		10 kbps	1 kbps
Antenna Type		Omni	Omni
Gain		0 db	0 db
Size			
Transmitter			
Power output		30 watts	25 watts
Tracking/Ranging			
Measure		--	--
Respond		X	--
Passive optical reflectors needed at docking ports for SLR use			

Table 1-16. Element Characteristics

Satellites
Note (1)

Operation with
EOS, Tug, Ground Station, TDRS

Frequency Band		Ku	S	VHF
Frequency	Ret. Fw.	14.4 - 15.35 gHz 13.4 - 14.2 gHz	2200 - 2300 MHz 2025 - 2120 MHz	136 - 144 MHz 126 - 130 MHz
Data - Transmit				
Analog - voice		--	--	--
Analog - TV		B&W - 2.9 MHz	B&W - 2.9 MHz*	--
Digital		1.6 Mbps	1 Mbps	10 kbps
Data - Receive				
Analog - voice		--	--	--
Analog - TV		--	--	--
Digital			1 kbps	1 kbps
Antenna Type		Parabolic	Omni	Omni
Gain		45 db	0 db	0 db
Size		5-foot		
Transmitter				
Power output		10 watts	30 watts	25 watts
Tracking/Ranging				
Measure		--	--	--
Respond		X	X	--
SLR passive optical reflectors only				

Note (1) Each satellite has different data requirements - model shown is for maximum case.

* If MSFN is upgraded - otherwise, Apollo-type TV must be used.

2.0 RENDEZVOUS

The purpose of the rendezvous activity is to conduct orbital maneuvers (other than orbital maintenance) to either establish or alter a prescribed range /range rate relationship between two orbiting elements. The predominant operational mode is to conduct thrusting maneuvers on one element to position that element within close proximity of another element.

Under a broad definition of rendezvous, the injection and placement of an element at a prescribed spatial location could be defined as rendezvousing with a point in space. This operational mode involves only one orbital element and therefore is not considered further in this study.

Rendezvous operations may either commence from a stationkeeping mode or terminate in a stationkeeping mode. Thus the range dispersion between elements varies from a few thousand feet to several thousand miles. The rendezvousing elements may or may not maintain line of sight during the operation.

2.1 SUMMARY

Evaluation of the mission models and corresponding element-to-element interface matrix indicated that there are 51 element pair rendezvous interactions. Exclusive of these are 7 involving orbit-to-orbit shuttles (OIS, CPS, RNS) and 2 involving the MSS and free-flying RAM's. Only the emplacement and sortie missions do not include element-to-element rendezvous interfaces.

Three alternate approaches were evaluated. They are:

1. Independent - All operations performed by the rendezvousing elements independent of external information
2. Ground Control - Command and control functions performed by a ground control center
3. Space Control - Command and control functions performed by a third orbital element

The significant difference in the three approaches is the location of the rendezvous control center and the resultant equipment complement on the orbital elements.

The key functions that must be accomplished are: (1) attitude determination, (2) state vector update, (3) flight control computation, (4) relative range and velocity determination and (5) command, control and data transfer links. The design concept model selected for the accomplishment of attitude and state vector determination by orbital elements was a star tracker/horizon scanner/inertial platform. All of these components are currently operational on space vehicles. This combination concept model can adequately achieve the performance requirements of rendezvous. Computer delta requirements for the state vector update function are estimated at 10K to 15K words (32 bit word).

The ground network and TDRS models used in this study can also provide the necessary state vector accuracies for rendezvous.

The requirements associated with flight control computation are reflected in the computer size and complexity also. A delta capacity of approximately 2K words (32 bit word) is required for this function.

Range and velocity determination is a function of the range between the rendezvousing elements. At long range either currently operational VHF or S-band ranging with omni antennas and transponders on the orbiting elements is adequate. At close proximity (≤ 5 nautical miles) a laser scanning radar (LSR) system is recommended, especially in the case of rendezvous between unmanned elements. (This SLR is also recommended for stationkeeping and mating operations).

The data link requirements between elements and control center are well within the capability of the communication link requirements established by other interfacing activities or independent element operations. VHF, S-band or K_u-band can readily handle the 1-10 KBPS command, control and data transfer requirements for rendezvous.

Operational procedures for the alternate approaches were developed. The procedures assisted in the identification of more detailed functional requirements and definition of the orbital element equipment required for each approach. Iteration of the procedures resulted in the development of three procedures that do not correspond directly to the approaches. Two procedures are associated with the independent approach and are characterized by the status of the controlling element -- whether it is passive (target vehicle) or active (maneuvering vehicle). The third procedure is applicable to both the ground control and the space control approach.

The preferred approach selection was primarily influenced by the type of rendezvous missions that were applicable to the various elements. As a result a hybrid of approaches was selected for various element pairs.

EOS missions are relatively short duration, manned, and would be planned in detail prior to launch. The preferred approach for EOS element pairs is the independent option for the terminal phase. Ephemeride determination of the elements to be rendezvoused with would be performed by ground flight control operations prior to launch, or initiation of maneuver planning.

Similarly all thrust vector maneuvers would be preplanned by ground control. State vector updates during the rendezvous mission are required. Normally, ground control would accomplish this function also. EOS would control only the terminal phase of the rendezvous operation in a truly independent mode.

The potential diverse short term operations/trajectories that the Tug will be required to perform do not lend themselves to an independent type of approach without added complexity and weight. A ground control approach is preferred except for terminal phase operations. If the Tug is manned the independent approach would be preferred for the terminal phase.

Because of the long durations involved and the inherent independent nature of rendezvous operations involving the MSS and other orbital stationed elements either an independent or space controlled approach is preferred. For example, MSS-RAM operations would be classified as independent. MSS-Tug-RAM operations would be classified as space controlled. However, in all operations involving the MSS ground control is still part of the overall operation. It is not proposed that the MSS maintain surveillance of all operations within its potential sphere of activity. This function is more apropos to a ground control center. Thus, before any maneuvers are commanded by the MSS, the "flight plan" must be checked and verified by a ground control center.

2.2 ELEMENT INTERFACE AND MISSION MODEL MATRICES

An analysis of the operations required of each of the orbital elements of this study identified 51 element-to-element rendezvous interactions in earth orbit as shown in Figure 2-1. The figure also indicates which of the two interfacing elements is normally active or passive during their rendezvous activity. An active rendezvous element is defined as the element that conducts the necessary orbital maneuvers to close with the passive element. Most of the rendezvous interactions occur in interfaces of orbital elements with the shuttle orbiter (EOS) (15 interactions), the ground-based tug (10 interactions), and the space-based tug (13 interactions).

Rendezvous interactions not intuitively obvious are explained below:

1. The EOS to EOS interaction results during a rescue mission as do the interactions between many other identical elements (e.g., ground-based tug to ground-based tug, etc.).

2. It should be noted that in the case of resupply modules (earth orbit or lunar resupply modules), no rendezvous is indicated; this exception was made because it is considered that the rendezvous occurs between the propulsive element that is transporting the resupply module and the passive element that is the destination of the resupply module.

3. The rendezvous interactions shown on Figure 2-1 between an unmanned lunar tug in earth orbit and other elements are of a checkout or simulated nature only. It is assumed that the unmanned lunar tug will be checked out in earth orbit but will not be used for any other operation in earth orbit.

4. The rendezvous interactions shown in the figure for the manned lunar tug include checkout or simulated operations similar to the case for unmanned lunar tugs. In addition, the manned lunar tug rendezvous interactions include those operations associated with the use of this tug as an escape vehicle to transport LSB or OLS crew back to earth in the event of an emergency.

5. The rendezvous between two identical CPS elements occurs either during a rescue mission or as part of the assembly of a tandem CPS configuration.

6. Rendezvous interactions between the EOS orbiter or a space-based tug and the OLS are shown while no interactions with the LSB are indicated. This is because the OLS is assembled, manned (with a test crew), and checked out in earth orbit prior to delivery to lunar orbit. The LSB, however, is not activated or manned until it is assembled on the lunar surface.

		SPACE VEHICLE INVENTORY																								
		EOS	TUG				RAM				SATELLITE			EO RESUP MODS	MSS		CPS			RNS	LUNAR PROGRAM SYSTEMS					OPD
			NON RET	RTN	GRD BASED	SPACE BASED	ATT. EOS	DET. EOS	ATT. MSS	DET. MSS	EOS DELIV	EOS + 3RD ST	RETR, RESUP		LOW EO	GEO SYNCH	OIS	EO SHTL	CLS		OLS	TUG UNMAN	TUG MAN	RESUP MOD	LSB	
	EOS	E	X	E	E	E	X	P	X	P	X	X	P	X	P	X	▨	E	E	E	E	P	E	X	X	P
TUG	NON RET		▨	▨	▨	▨	▨	▨	▨	▨	▨	X	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
	RETURNABLE			▨	▨	▨	▨	▨	▨	▨	▨	X	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
	GRD BASED				E	E	▨	▨	X	X	▨	X	P	X	▨	P	▨	E	P	P	▨	P	E	X	▨	P
	SPACE BASED					E	▨	▨	X	P	▨	X	P	X	P	P	E	E	P	P	E	P	E	X	X	P
RAM	ATT. EOS						▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
	DET. EOS							▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
	ATT. MSS								▨	▨	▨	▨	▨	▨	X	X	▨	X	▨	X	▨	▨	▨	▨	▨	▨
	DET. MSS									▨	▨	▨	▨	▨	P	P	▨	X	▨	X	▨	▨	▨	▨	▨	▨
SATEL	EOS DELIV										▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
	EOS + 3RD ST											▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
	RETR, RESUP												▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
	EO RESUP MODS													X	X	X	▨	X	X	X	▨	X	X	X	▨	X
MSS	LOW EO														X	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
	GEOSYNCH															X	▨	A	▨	A	▨	▨	▨	▨	▨	▨
CPS	OIS																▨	X	X	X	X	▨	▨	▨	▨	X
	EO SHTL																	E	▨	▨	▨	▨	▨	▨	▨	P
	CLS																		E	▨	X	P	P	X	X	P
	RNS																			X	X	P	P	X	X	P
LPS	OLS																				X	X	X	X	▨	▨
	TUG UNMAN																					▨	▨	X	X	X
	TUG MAN																						▨	X	X	X
	RESUP MOD																							X	X	X
	LSB																								X	▨
	OPD																									X

LEGEND	
Potential Interactions	117
Actual Interactions	51
A - Active Element*	2
P - Passive Element*	30
E - Either Element Active	19
X - Not Applicable	66
* - Relative to horizontal scale	

Figure 2-1. Rendezvous Interactions

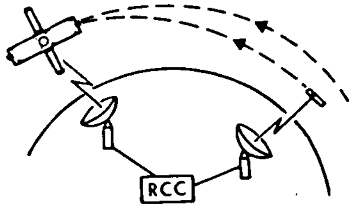
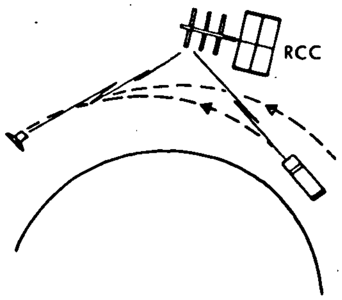
To provide traceability back to the mission models presented in Volume I, Section 2, another interface matrix is shown in Figure 2-2, which lists the mission models that involve a rendezvous interaction between the elements in question. All but two of the mission models are identified on the matrix. They are MM-1, EOS emplacement, and MM-3, EOS sortie. Under the broad definition of rendezvous, which includes rendezvous with a spatial point, even these two missions include rendezvous. These missions are not applicable to an element-to-element interface analysis and are not considered further.

		SPACE VEHICLE INVENTORY																								
		EOS	TUG				RAM				SATELLITE			EO RESUP MODS	MSS		CPS			RNS	LUNAR PROGRAM SYSTEMS					OPD
			NON RET	RTN	GRD BASED	SPACE BASED	ATT. EOS	DET. EOS	ATT. MSS	DET. MSS	EOS DELIV	EOS + 3RD ST	RETR, RESUP		LOW EO	GEO SYNCH	OIS	EO SHTL	CLS		OLS	TUG UNMAN	TUG MAN	RESUP MOD	LSB	
	EOS		X	2	2,7,8	2,4,5	X	2	X	2,4,5	X	X	2	X	2	X	▨	2,10,11	2,10,11	2,11	2	2	2,10,11	X	X	2
TUG	NON RET		▨	▨	▨	▨	▨	▨	▨	▨	▨	X	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
	RETURNABLE			▨	▨	▨	▨	▨	▨	▨	▨	X	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
	GRD BASED				8	5,8	▨	▨	X	X	▨	X	8	X	▨	8	▨	8,10,11	8,10,11	8,11	▨	8	8	X	▨	8
	SPACE BASED					4,5	▨	▨	X	4,5	▨	X	4,5	X	4,5	4,5	5,6,9	4,5,6, 10,11	4,5,6, 10,11	4,5,6,11	4,5	5	4,5, 10,11	X	X	4,5,6
RAM	ATT. EOS						▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
	DET. EOS							▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
	ATT. MSS								▨	▨	▨	▨	▨	▨	X	X	▨	X	▨	X	▨	▨	▨	▨	▨	▨
	DET. MSS									▨	▨	▨	▨	▨	2,5	5,8	▨	X	▨	X	▨	▨	▨	▨	▨	▨
SATEL	EOS DELIV										▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
	EOS + 3RD ST											▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
	RETR, RESUP												▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
	EO. RESUP MODS													X	X	X	▨	X	X	X	▨	X	X	X	▨	X
MSS	LOW EO														X	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
	GEOSYNCH															X	▨	10,11	▨	11	▨	▨	▨	▨	▨	▨
CPS	OIS																▨	X	X	X	X	▨	▨	▨	▨	X
	EO SHTL																	10	▨	▨	▨	▨	▨	▨	▨	10,11
	CLS																		10	▨	X	10,11	10,11	X	X	10,11
	RNS																			X	X	11	11	X	X	11
LPS	OLS																				X	X	X	X	▨	▨
	TUG UNMAN																					▨	▨	X	X	X
	TUG MAN																						▨	X	X	X
	RESUP MOD																							X	X	X
	LSB																								X	▨
	OPD																									X

Figure 2-2. Applicable Mission Models for Rendezvous

2.3 ALTERNATE APPROACHES

Three alternate approaches for the rendezvous activity were developed and are characterized by:

ALTERNATE APPROACHES		
INDEPENDENT	GROUND CONTROL	SPACE CONTROL
		
CONTROLLING ELEMENT MANNED	ELEMENTS MANNED OR UNMANNED	RENDEZVOUS ELEMENTS MANNED OR UNMANNED

INDEPENDENT OPERATION

This approach requires the performance of all rendezvous operations solely by the orbiting elements. It is assumed that either continuous or at least adequate periodic line-of-sight exists between the vehicles. Use of ground relay links between elements is not considered in this approach. Command and control of the operations can be accomplished by either the passive (target) or active (maneuvering) element. The elements could be manned or unmanned.

GROUND CONTROL

In this approach all command and control is accomplished by a ground control center. The orbital elements require certain unique sensors but essentially only execute the commands from the control center. Neither range between elements nor communication gaps are considered a constraint in this approach. Appropriate mission planning is assumed to be feasible to circumvent the contact dropouts. Either the ground network or TDRS are considered as viable control centers for this approach.

SPACE CONTROL

This approach involves three orbital elements, the two elements that are rendezvousing and a third element that functions as the control center. This orbital control center is required to conduct all the operations that the ground control center of the second approach must perform. This approach will have more stringent constraints on both range and line-of-sight to the rendezvousing elements. Continuous line-of-sight is not mandatory, however, the probability of long duration contact drop outs at long ranges is much higher with this approach. Use of ground stations for data relay purposes is not considered in this approach.

The major difference between these approaches is the location of the command and control center. These three distinct approaches were selected for evaluation to assist in a more detailed examination of the design influences of the unique function of each approach. Hybrid combination of the approaches are considered during the design impact assessment associated with the preferred approach selection for each element pair.

2.4 DESIGN CONCEPT MODELS

The design concept for all approaches and ultimately the design impact on the orbital elements are predicated upon the following key functional requirements for accomplishing rendezvous:

1. Attitude Determination
2. State Vector Update
3. Flight Control Computation
4. Relative Range and Velocity
5. Command, Control and Data Transfer Links

Table 2-1 summarizes the hardware complement of rendezvousing elements for the critical functions for the three approaches.

ATTITUDE DETERMINATION

Rendezvous operations are independent of the relative attitude between the elements involved. However, the attitude of any element required to perform delta-V maneuvers must be known to sufficient accuracy to permit efficient thrusting maneuvers. Attitude accuracy is only one factor in the overall error budget for determining propellant consumption rates. Current operational hardware and thrusting maneuvers computations can minimize the affect of attitude inaccuracies. An evaluation of alternate concepts is presented in Appendix A-1. Consideration of this activity and the attitude determination function in conjunction with other activities and related functions such as state vector update resulted in the selection of a star tracker/horizon scanner concept to provide both inertial and local reference attitude information. For the local level earth reference, the horizon scanner provides the reference for the level axes and a yaw reference is derived from star tracker data. For the inertial reference, sequential sightings from a single star tracker or multiple star trackers used simultaneously provide three-axis attitude determination. Accuracies of ± 0.5 degree can be readily obtained. Attitude reference can be maintained by an inertial platform (IMU) or strapdown gyros. Attitude maneuver by either mass expulsion or momentum exchange devices are acceptable. These selections are not dependent upon the functional requirements of rendezvous.

In all these approaches the active or thrusting element must include attitude determination capability.

STATE VECTOR UPDATE

In both the independent and space controlled approaches at least one orbital element must include the capability to perform state vector updates. The sensors required are the same as for attitude determination, namely a star tracker and horizon scanner. On-board computational capability is also required to calculate the ephemerids from the sensor data. Storage capacity and computer complexity for this task is not considered to be a significant design influence.

Table 2-1. Function/Hardware Vs Approach

	INDEPENDENT	SPACE CONTROL	GROUND CONTROL
Attitude Determination Star Tracker/Horizon Scanner and IMU	Both Elements 2K words (32 bit)	All Three Elements Same	Both Elements Same
State Vector Update Star Tracker/ Horizon Scanner	One Element	Control Element Only	None
Computer Deltas	10K words (32 bit)	15K (32 Bit)	
Flight Control Computation Computer Deltas	One Element 2 K words (32 bit)	Control Element Only 2K (32 Bit)	None
Range/Range Rate			
Long Range			
Transmitter (VHF or S-Band)	One Element	Control Element	None
Antenna	Omni-Both Elements	Omni-3 Elements	Omni-Both Elements
Transponder	Both Elements	Both Elements	Both Elements
Computer Deltas	4 K words (32 bit)	6K (32 Bit)	None
Short Range			
Lasar Radar	One Element	Same	Same
Passive Reflector	One Element	Same	Same
Communication Links	VHF or S-Band w/Omni	Same	Same

In addition to determining its own state vector, the orbital element must also determine the state vector of the other element (independent approach). This imposes an additional tracking and ranging requirement, as well as additional storage capacity and complexity on the orbital computer system. If a hybrid approach were used, the initial target state vector could be provided by ground control.

A representative laser radar system was synthesized that is adequate for ranges from 75 nautical miles to essentially zero range. (This system is described in detail in Section 1.0, Communications.) For longer ranges (> 60 n mi) current operational VHF or S-band ranging systems are proposed and are compatible with communication link requirements for other functions.

The ground control approach could use either the ground network or TDRS for state vector updates. Either concept can provide position data to within one nautical mile uncertainty. Only a transceiver would be required on the orbiting elements. However, there are operational limitations to those concepts.

Reliance upon the ground network for state vector update implies that the orbit will be in sight of ground stations and/or a period between propulsive maneuvers for tracking purposes is acceptable. Figure 2-3 presents data for a nominal rendezvous maneuver from a 100 nautical mile circular orbit to a 270 nautical mile circular orbit. Depending upon the operational concept used, terminal uncertainty can vary from less than one nautical mile to greater than 20 nautical miles. If no updates after the initiation of the rendezvous maneuver are planned, targeting of final separation between the "rendezvousing" elements would correspondingly be required to be greater than 20 nautical miles for operational safety reasons. This would be an inefficient operation at best.

Use of TDRS as the method for navigation update purposes will give comparable results. Because of the extended coverage capability possible with the TDRS concept, additional opportunities are available for updates. Also, the optimum times for update can also be selected. This is based upon the assumption that TDRS can be made available (the rendezvous activity will have a high enough priority). In near term orbital operations, the periodic utilization of TDRS for the navigation update function is practical. As the space traffic increases, this concept becomes less practical.

FLIGHT CONTROL COMPUTATION

The computation of the desired maneuver, ignition time, duration, pointing, etc., can be performed effectively by several alternatives. The major prerequisite is the availability of state vector data of the elements involved in the rendezvous. The difference between approaches is simply where the computer is located. Ground control inherently has the computer capability. The space control approach centralizes the on-orbit computational requirements and thus reduces individual element requirements. In order to minimize on-board equipment, complexity, checkout and maintenance, and dedicated usage, the preferred location in general would be ground control.

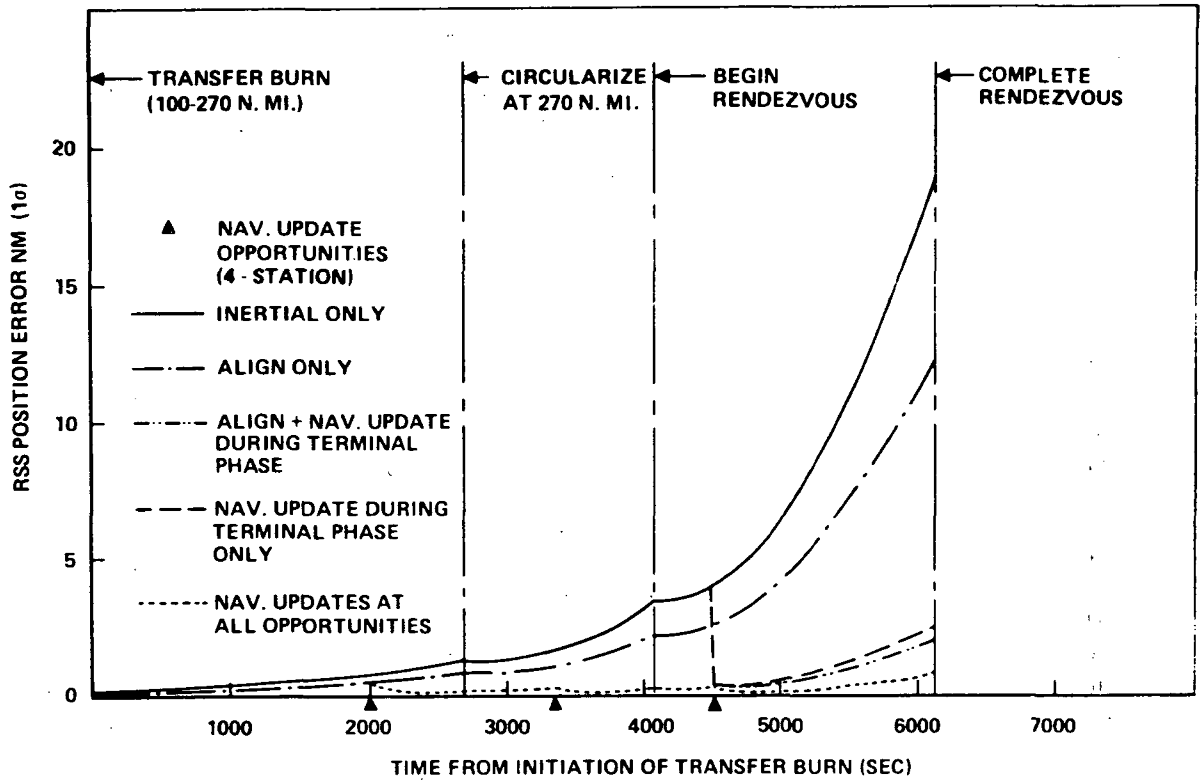


Figure 2-3. Orbital Transfer and Terminal Rendezvous Phase Position Errors Using Minimum MSFN Tracking Stations

RELATIVE RANGE AND VELOCITY

The relative range and range rate between rendezvousing elements varies from thousands of miles and feet per second to only a few miles and less than a foot per second. At the upper end of the spectrum any of the three approaches can adequately perform the task with demonstrated VHF or S-band ranging hardware. Transponders on the target elements are mandatory in order to limit the power and antenna requirements on the tracking centers to reasonable requirements.

The primary differences in the three approaches for long range operations are the potential gaps in the communications. However, gaps are tolerable because tracking and ranging need not be on a continuous basis. If TDRS is used in the ground approach it does afford almost continuous coverage. Use of the ground network will result, in some cases, communication gaps of longer than one orbit and also will require control handover between ground stations. Space control and independent approaches will result in even more sporadic and longer interruptions of tracking. However, with detailed mission planning these shortcomings can be accommodated.

At ranges of a few nautical miles, safety of operations become an overriding factor. Accuracies in both range and range rate become marginal. A scanning laser radar system is proposed for all element pairs involved in rendezvousing. Commonality of design concept is reflected in this recommendation. This same system is used for related functions in stationkeeping and mating. The system is described in detail in Appendix A-1. Typical accuracies for the design concept model are:

Range: 0-75 nautical miles ± .02 percent or ± 4 inches
(whichever is greater)

Range Rate: 0-4000 ft/sec ± 1 percent or ± 0.1 ft/sec
(whichever is greater

These SLR performance characteristics exceed the requirements for close range rendezvous activities.

COMMAND, CONTROL AND DATA TRANSFER LINKS

Communication link calculations are detailed in Section 1.0, Communications. In all three approaches the requirements for rendezvous data transfer is not the determining factor in establishing link requirements for range or data rates. VHF, S-band or K_u-band communication links can accommodate rendezvous communication link requirements.

The one unique aspect of data links associated with rendezvous is the highly desirable real time link between the maneuvering element and the control center during thrusting maneuvers. Note that this is not a mandatory requirement. Both manned (CSM TEI) and unmanned (Apollo spacecraft 011 development flight) thrust maneuvers have been performed while not in contact with the control center.

2.5 OPERATIONAL PROCEDURES

The sequences of events which occur when rendezvous is conducted via the independent, ground control, or space control approach are summarized and compared in this section. One procedure can be utilized for either ground or space control rendezvous by utilizing the rendezvous control center to indicate the command center. The detailed sequence of events for each procedure are contained in Appendix B.

The procedures, while identified with a specific approach, are generic enough in nature that they can be applied to any applicable element pair or flight plan. No unique flight plan or definitive number of thrusting maneuvers were assumed in the procedures. Operations preceding and subsequent to thrust maneuvers are identified. These operations must be repeated for each major burn required to effect rendezvous between orbital elements. Usually three maneuvers are required; transfer orbit injection, target orbit insertion, and terminal phase initiation. The actual number of thrusting maneuvers is dependent upon orbital phasing, orbit transfer required, and plane changes required.

Figure 2-4 summarizes the major events of the procedures in a comparison format. Terms used in this diagram are:

1. Rendezvous Control Center (RCC). The RCC is a manned center which is in command and control of all rendezvous operations. The RCC may be located on the ground or on-board an earth orbiting space element.

2. Controlling Element or Controller. The controlling element or controller is the home of the RCC for the rendezvous approach and procedure in question. The controlling element or controller must always be manned and may be located on:

   a. The ground (ground control approach)
   b. A space element not one of the rendezvous elements (space control approach)
   c. One of the rendezvous elements (independent approach)

3. Active Element. The active element is the rendezvous element which under the direction of the RCC performs the impulse delta-V maneuvers required to effect rendezvous. The active element may be manned or unmanned. The active element if unmanned must be fully automated so that it can be operated independently or by remote commands from the RCC via a communications link.

4. Passive Element. The passive element is the rendezvous element which serves as the target element for the active element. The passive element may be manned or unmanned.

Examination of Figure 2-4 indicates that from a procedures standpoint there is no significant difference between the approaches. The hardware complement on the orbiting elements is, however, the distinguishing characteristic.

In Appendix B the applicability of the procedures to the element pairs is discussed in detail. Considered are whether the elements involved are manned or unmanned, active or passive, target or controlling, etc. In general, all three procedures could be made applicable for any element pair. However, predominant operational modes are identified. For example, rendezvous activities involving the EOS would normally be either independent or ground controlled; unmanned tug rendezvous operations would normally be space controlled or ground controlled, and CPS operations would normally be independent or ground controlled.

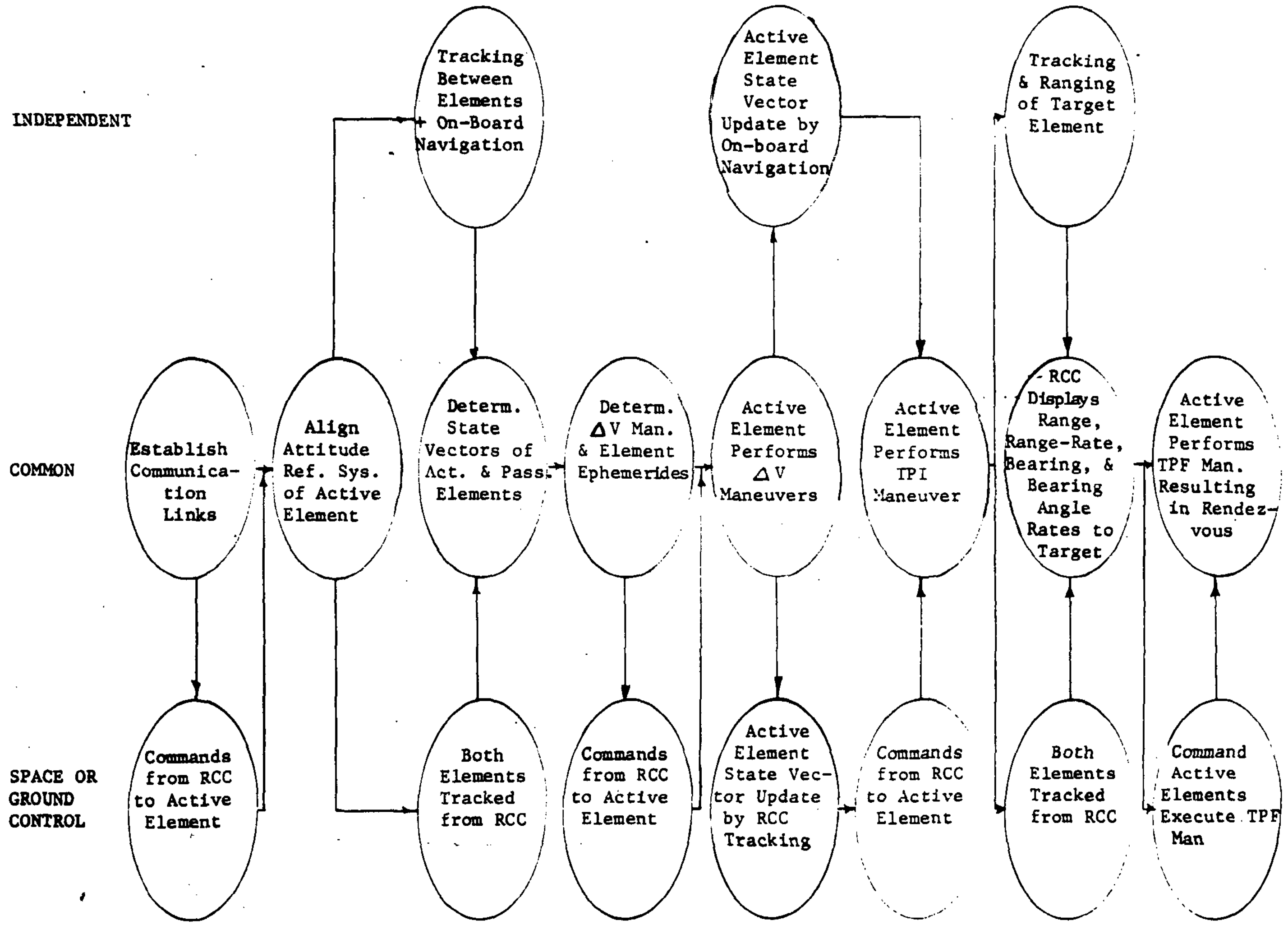


Figure 2-4. Comparison of Rendezvous Procedures

2.6 FUNCTIONAL REQUIREMENTS

The major functional requirements for rendezvous include the need for communications activities of data transfer, command, tracking and ranging, and attitude and state vector measurement and control. When operational control is performed by a space element, it is necessary to provide sufficient computation capability on the element to perform state vector and attitude calculations as well as the maneuver calculations necessary for attitude control and delta-V maneuvers. In the indpendent case, the control element needs this capability including the memory that contains all predicted results. In the space or ground control alternates, the control elements will contain the required capability.

This section first provides basic functional requirements in tabular format defining their application to the alternate approach procedures. These procedures are presented in Appendix B. This is followed by a set of matrices that define in detail, by element pairs, specific characteristics of the communications links. The last portion includes the analyses that were conducted to establish the specific requirements included in these matrices.

FUNCTIONAL REQUIREMENTS TABULAR LIST

The following tabular list delineates the functional requirements and their application to one or both of the alternate approach procedures. It reflects generic requirements by the type of element, active or target.

	Related Procedure		
	Independent Passive In Control	Independent Active In Control	Separate Control
	10-1	10-2	10-3
1. The controlling element must have a computer system capable of computing state-vectors and orbital parameters from range, range-rate data or other data supplied from element on-board sensor systems. It shall also have the capability to compute delta-velocity maneuvers from stored data for the make-up of orbital parameters. At the time of a state-vector update, the one-sigma uncertainty in element position and velocity shall not exceed the limits of the type presented below:	X	X	X

Element Position and Velocity Uncertainty
(Reference DS-572)
Parameter

Component	Position	Velocity
Downrange	± 3 n mile	± 3 ft/sec
Crossrange	± 1 n mile	± 10 ft/sec
Vertical	± 1 n mile	± 20 ft/sec

During initial rendezvous operations when the controlling element is tracking a cooperative target, the one-sigma tracking uncertainties shall not exceed the limits of the type presented below. Terminal rendezvous tracking inaccuracies are covered in Functional Requirement No. 7.

Cooperative Target Tracking Uncertainty

Parameter	Uncertainty At 30 n mi
Range	± 100 feet
Range Rate	± 5.0 ft/sec

	Related Procedure		
	Independent Passive In Control	Independent Active In Control	Separate Control
	10-1	10-2	10-3
2. The control center must have the capability to calculate the relative positional state (position and velocity) of the rendezvous elements and then determine, based on a knowledge of the ephemerides of both elements, the maneuvers (vectorial velocity changes) which the active element must execute to effect rendezvous with the passive element.	X	X	X
3. The active elements must have propulsive systems capable of performing delta-velocity maneuvers in accordance with the computer requirements.	X	X	X
4. Both elements must contain an attitude reference system.	X	X	X

	Related Procedure		
	Independent Passive In Control	Independent Active In Control	Separate Control
	10-1	10-2	10-3
Knowledge of element attitude is necessary for the pointing of on-board sensors, antennas and for orientation to perform delta-V orbital make-up maneuvers.			
For these requirements the attitude reference system shall be capable of measuring attitude to an accuracy of ± 0.5 degree.			
5. The active elements must have attitude control systems enabling implementation of a change in attitude. It shall be capable of holding attitude within 0.5 degree of desired.	X	X	X
6. Communication links must be available between rendezvous elements and between elements and commands and data as follows:	X	X	X
(a) transfer of command data necessary up to 1 Kbps to activate target systems (1) between active and target elements up to LOS (4000 n mi) (2) from ground (either ground station or TDRS) to active element (3) from space control element to active and target elements to LOS (4000 n mi)	X		X
(b) transfer of digital data up to 10 Kbps from (1) target to active element (2) active element to ground (either ground station or TDRS) (3) target or active element to the space control element to indicate element status	X		X
(c) a duplex voice link between manned elements either both rendezvous elements or rendezvous elements and controlling elements.	X	X	X

	Related Procedure		
	Independent Passive In Control	Independent Active In Control	Separate Control
	10-1	10-2	10-3
(d) capability to allow transmission of wake-up commands to either stationkeeping element with omni-directional reception capability to allow reception regardless of element attitude orientation.	X	X	X
(e) the control element transmission system should have sufficient radiated power (EIRP) to provide acceptable signals at the passive element with an antenna whose beamwidth is at least 10 degrees to preclude the necessity for acquisition scan to locate the passive element. An omni-directional antenna is preferred.	X	X	X
7. A measurement system must be available that is capable of determining rendezvous elements relative range, range rate, and bearing angles. These data must be available at the location of the controlling unit. It shall be capable of providing these measurements to the following nominal accuracies:	X	X	X

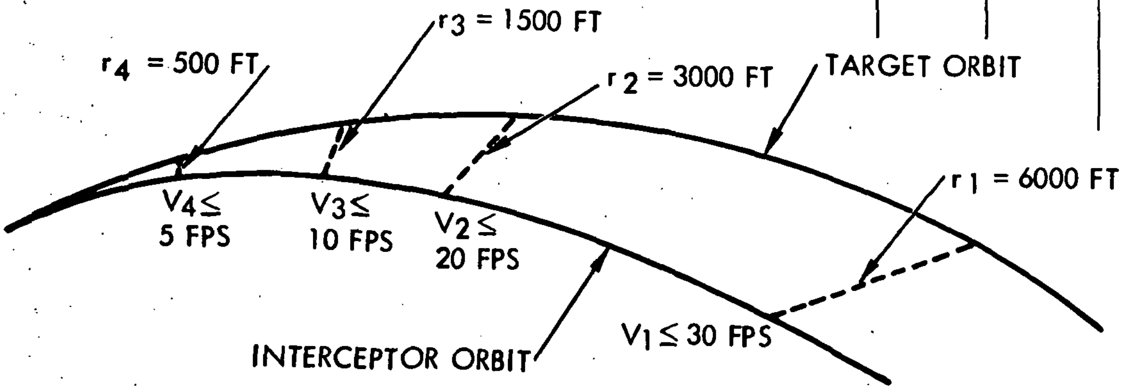
	Accuracy	
Range	Range	Range-Rate
10 to 100 ft	± 6 in.	± 0.1 ft/sec
100 to 1500 ft	± 1 ft	± 0.1 ft/sec
1500 ft to 5 n mi	± 10 ft	± 0.5 ft/sec
5 n mi to 30 n mi	±100 ft	± 0.5 ft/sec
30 n mi to 60 n mi	±500 ft	± 5.0 ft/sec
Over 60 n mi	±1 n mi	± 10 ft/sec

	Bearing Angle
Less than 30 n mi	±0.03 deg.

	10-1	10-2	10-3
8. A monitor and display system shall be available at the controlling (RCC) element that is capable of providing simultaneous real-time display of:	X	X	X

	Related Procedure		
	Independent Passive In Control	Independent Active In Control	Separate Control
	10-1	10-2	10-3
(a) relative rendezvous elements range (b) range-rate between rendezvous elements (c) bearing angles from active to target elements			
9. It must be possible to provide the tracking and ranging data at the same time as the data transfer under requirement #6.	X	X	X
10. If either of the rendezvous elements is manned, a means shall be provided to perform visual tracking of the other element during the terminal phase to separation distances capable of visual tracking capability (approximately 5 n mi).	X	X	X
11. During terminal rendezvous a braking gate criteria similar to that shown below, where the relative velocity (V_r) varies with the relative distance between elements must be satisfied.	X	X	X

<u>Typical Braking Gate Criteria</u>



NOTE: BRAKING GATE ΔV'S APPLIED ALONG LINE OF SIGHT

RENDEZVOUS ELEMENT PAIR REQUIREMENT MATRIX

In order to identify the functional requirements by element pairs for those elements included in this study, a requirements matrix was developed and follows. Since the requirements, when applied to a particular element are the same, the matrix was made by tabulating the requirement against the element utilization. Elements are categorized as either active, passive or control. The elements are then grouped by alternate approach. The requirements are then listed by element and group. At the head of each column is a list of elements that apply to that column.

Rendezvous Element Pairs Requirements Matrix

Item	Elements / Functional Requirements	Active Element In Control		Passive Element In Control		Separate Element In Control		
		Active Element	Passive Element	Active Element	Passive Element	Active Element	Passive Element	Control Element
		EOS Tug CPS RNS	EOS Tug RAM SAT MSS OIS CPS RNS OLS	EOS Tug RAM CPS RNS	EOS Tug MSS CPS RNS OLS	EOS Tug RAM CPS RNS	EOS Tug RAM SAT MSS OIS CPS RNS OLS OPD	EOS MSS
1	TRACKING/ RANGING >60 N MI TO LOS RANGE ± 1 N MI RANGE RATE ± 10 FT/SEC	PRN RANGE TRANSMIT/ RECEIVE, MEASUREMENT SYSTEM PRN RANGE TURNAROUND TRANSPONDER TO GROUND	PRN RANGE TURNAROUND TRANSPONDER ONLY	PRN RANGE TURNAROUND TRANSPONDER ONLY	PRN RANGE TRANSMIT/ RECEIVE, MEASUREMENT SYSTEM PRN RANGE TURNAROUND TRANSPONDER TO GROUND	PRN RANGE TURNAROUND TRANSPONDER ONLY	PRN RANGE TURNAROUND TRANSPONDER ONLY	PRN RANGE TRANSMIT/ RECEIVE, MEASUREMENT SYSTEM IF SPACE-BASED TURNAROUND PRN RANGE TRANSPONDER TO GROUND

Rendezvous Element Pairs Requirements Matrix (Cont.)

		Active Element In Control		Passive Element In Control		Separate Element In Control		
Item	Functional Requirements	Active Element	Passive Element	Active Element	Passive Element	Active Element	Passive Element	Control Element
2	Tracking/ranging < 60 n mi	Active Scanning Laser (SLR) Radar System	Optical Corner Cube Reflectors Only	Active Scanning Laser Radar (SLR) System	Optical Corner Cube Reflectors Only	Active Scanning Laser Radar (SLR) System	Optical Corner Cube Reflectors Only	Not Required
						Accuracy		
				Range 10 to 100 ft 100 to 1500 ft 1500 ft to 5 n mi 5 n mi to 30 n mi 30 n mi to 60 n mi	Range ± 6 in. ± 1 ft ± 10 ft ±100 ft ±500 ft	Range-Rate ±0.1 ft/sec ±0.1 ft/sec ±0.5 ft/sec ±0.5 ft/sec ±5.0 ft/sec		
3	Attitude Reference System Measure within ± 0.5°	Yes	Yes	Yes	Yes	Yes	Yes	If space based

Rendezvous Element Pairs Requirements Matrix (Cont.)

		Active Element In Control		Passive Element In Control		Separate Element In Control		
Item	Functional Requirements	Active Element	Passive Element	Active Element	Passive Element	Active Element	Passive Element	Control Element
4	Attitude Control System Control to ± 0.5°	Yes	NA	Yes	NA	Yes	NA	If space based
5	Delta-V maneuver capability orbital transfer	Yes		Yes		Yes		Orbital makeup only if space based
6	Communications Command data 1 Kbps, 1 X 10^{-6} BER (see Comm, Sec 9 for details)	Transmit	Receive, Decode, Apply Command	Receive, Decode Apply Command	Transmit	Receive, Decode, Apply Command	Receive, Decode, Apply Command	Transmit
7	Communications Data Transfer 10 Kbps, 1 X 10^{-5} BER (see Comm. sec 9 for details)	Receive from passive element	Transmit to active element	Transmit to passive element	Receive from active element	Transmit to control element	Transmit to control element	Receive from both active and passive elements
7A	Communications Voice 4 KHz audio (for manned elements)	Duplex for manned elements to passive and ground	Duplex to active (ground backup)	Duplex with passive (ground backup)	Duplex with active and ground	Duplex with control (ground backup)	Duplex with control (ground backup)	Duplex with active, passive and ground

Rendezvous Element Pairs Requirements Matrix (Cont.)

		Active Element In Control		Passive Element In Control		Separate Element In Control		
Item	Functional Requirements	Active Element	Passive Element	Active Element	Passive Element	Active Element	Passive Element	Control Element
8	Computation Requirements	Attitude determination, attitude control, tracking and ranging position determination, delta-V maneuver	Attitude determination, attitude control	Attitude determination, attitude control, tracking and ranging	Attitude determination, attitude control, position determination delta-V maneuver	Attitude determination, attitude control, tracking and ranging	Attitude determination, attitude control	Attitude determination, attitude control if space based Tracking and ranging position determination both active and passive elements, delta-V maneuvers

QUANTITATIVE REQUIREMENTS ANALYSIS

Rendezvous missions cover separation ranges from LOS between elements (up to 4000 n miles, to the termination point that could be as close as 50 feet). The latter is the point from which a docking maneuver could begin. Another type of rendezvous could be positioning to a point in space for an experiment mission. A RAM experiment mission falls in this category where a MSS would control the RAM to positions up to 450 n miles away. Each type and portion of the activity impacts the requirements in a different manner. The quantitative requirements stipulated in the requirements matrix define the rendezvous performance necessary at different phases, by range separation. Experiment type missions have not been considered. These pointing and stability accuracies are assumed to be part of the particular element and experiment module design.

Accuracy of position, especially relative element position, varies with separation distance. As indicated under functional requirement 11, the relative element velocity is typically in the range of 20 feet per second when their separation is approximately 6000 feet. As the elements close, this relative velocity must reduce until it approaches a maximum of ± 0.1 foot per second. At distances greater than 6000 feet, when the active element is in a chasing mode, the relative velocities would be progressively higher with range. This means at close ranges, up to 50 feet, the measurement accuracy for range rate should be a maximum of ± 0.1 ft per second. At the same time, range should be measured to within 6 inches. As the range increases, the accuracies of measurement need not be as precise. Table 2-2 below and function requirement 7 delineate these requirements.

Close in accuracies are established for safety purposes. At ranges greater than 30 nautical miles, the accuracies are established to effect efficient fuel use during rendezvous maneuvers. Bearing angle measurements are necessary at ranges of approximately 60 n miles. Bearing angle accuracy at distances less than 60 n miles should be within 0.03 degree (DS-572). These accuracies were selected to minimize delta-V fuel consumption consistent with performance of rendezvous sensors.

In the same manner and for the same reason - minimizing fuel consumption - the navigation accuracies were established. Nominal values for navigation errors prior to the period when target relative navigation begins (30 to 75 n miles) are as follows.

Table 2-2. Relative Range/Range Rate Accuracies

Separation Range	Range Accuracy	Range Rate Accuracy
RELATIVE ELEMENT PARAMETERS		
10 to 100 feet	± 6 inches	± 0.1 ft/sec
100 to 1500 feet	± 1 foot	± 0.1 ft/sec
1500 ft to 5 n mi	± 10 feet	± 0.5 ft/sec
5 n mi to 30 n mi	± 100 feet	± 0.5 ft/sec
30 n mi to 60 n mi	± 500 feet	± 5.0 ft/sec
Over 60 n mi	± 1 n mi	± 10 ft/sec
ELEMENT POSITION AND VELOCITY UNCERTAINTY		
	Position Error (1σ)	Velocity Error (1σ)
Downrange	± 3 n mi	± 3 ft/sec
Cross range	± 1 n mi	± 10 ft/sec
Vertical	± 1 n mi	± 20 ft/sec

The value of ± 1 degree attitude orientation is a nominal value established for element pointing for delta-V maneuvers when considering minimization of fuel consumption. The attitude reference system can be within ± 0.5 degree and the attitude control will operate to hold that attitude with ± 0.5 degree.

Communication data rates are nominal. Further discussion of command data transfer and telemetry digital transfer is included in the Communications section 1.0. The rates needed for rendezvous operations are minimum and are not driving factors on communication systems.

2.7 DESIGN INFLUENCES AND PREFERRED APPROACH SELECTION

A generalized evaluation of the three rendezvous approaches is presented in Table 2-3. The primary factors that influence the preferred approach selection are:

1. Operational ranges between elements

2. Complement/complexity of equipment on orbital elements

3. Safety of operations

OPERATIONAL RANGES

The rendezvous activity encompasses a large dispersion of ranges between elements. Rendezvous between an orbiting element and one just previously launched could involve ranges of many thousands of miles at the initiation of the rendezvous maneuver down to a few thousand feet at the terminal phase. Rendezvous between two long-term orbiting elements (MSS-RAM) may never involve ranges over 400 miles. Therefore, the preferred approach is dependent not only upon the instantaneous range between elements but the maximum dispersion throughout the rendezvous operation.

A major consideration in evaluating the range implications is the operational mode of the rendezvous mission. Rendezvous between two elements nominally stationed in orbit has different implications than rendezvous between a "just launched" element and an on-orbit element. The ephemerides of two on-orbit elements are established and usually long ranges are not involved especially beyond line-of-sight operations. Rendezvous in the later case frequently involves beyond line-of-sight operations and very long ranges. Ephemerides of the just launched element must be established prior to initiation of the rendezvous maneuvers.

Rendezvous from relatively short ranges by on-orbit vehicles is more adaptable to independent or space controlled operations. Rendezvous between an ascending and on-orbit vehicle is more adaptable to ground control operations or a hybrid approach using ground information for initial target element state vectors.

COMPLEMENT/COMPLEXITY OF ON-BOARD EQUIPMENT

None of the equipment required to accomplish rendezvous with either of the three approaches is a technology issue. All approaches require the active or maneuvering vehicle(s) to have attitude determination capability. Adequate accuracies can be obtained with a star tracker/horizon sensor combination for inertial and earth reference purposes. Various combinations of equipment were evaluated to select not only an adequate attitude determination concept but also to accomplish other related functions such as navigation updates. This evaluation is presented in Appendix A-1.

For the independent approach at least one element must be capable of determining its own state vector, tracking and ranging on the second element, computing the necessary delta velocity maneuvers of the elements involved, and command control and monitoring the operations. For operations within a relatively short range the complexity of equipment is reasonable. However, at long ranges the communications equipment will increase in complexity. In addition, the added potential problems of other orbiting elements being within the expanded sphere of operations may require computations that consider the ephemerides of these non-involved elements. (In the near term this is not envisioned as a problem.)

The generic equipment complement required for the space and ground control approaches is essentially the same. Each approach requires the tracking and ranging of the rendezvousing elements, navigation computations, trajectory calculations, and execution of commands, control and monitoring of the operation. The ground control approach is preferred when long ranges are involved. The current models of the ground network or TDRS can adequately accomplish the rendezvous operations. A significant degree of complexity and sophistication of equipment would be required to be incorporated in a space element. Long range tracking, updating of other element ephemerides, and multi vehicle-multi maneuver computations with respect to the controlling orbital element would be required. In addition, provisions for checkout and monitoring the performance of the two rendezvousing elements would also be required on the third orbital element. The independent approach is preferred for short ranges ($<$ 60 n mi). This can be adequately supported by utilization of SLR for range and range-rate.

SAFETY OF OPERATIONS

Safety of operations is dependent upon the ranges involved as well as the traffic model or elements within the sphere of rendezvous operations. At relatively short ranges the manning status of the elements influences the preferred approach. Corrective action or evasive maneuvers can be more readily accomplished at short ranges in the independent mode because of the capability for continuous real time observation. Space control normally can also do these functions but only by remote control. Rendezvous operations will occur in orbits and inclinations that will result in long duration communication gaps with the ground network. Although TDRS all but eliminates the communication gaps, this mode would require dedication of a TDRS channel to the rendezvous operation. In the near term this may be feasible. But as the orbital traffic increases the dedication of a TDRS link may be objectionable.

Accuracies for the alternate approaches are comparable. All three can accomplish rendezvous maneuvers to within a one nautical mile uncertainty. The primary consideration then is the desired resultant separation distance upon completion of the rendezvous maneuvers, and also the relative terminal velocity of the final delta maneuvers. Again if one of the elements is manned, more flexibility is available in the independent mode. But, additional safety precautions should be incorporated.

A laser scanning radar system is proposed to be incorporated in all rendezvous elements to provide the highly desirable margin of safety. This system also has multiple uses. It greatly enhances stationkeeping detached element operations, mating, and separation activities also. In the manned independent mode the data could be directly displayed as well as factored into the computations. For all other modes the data would be telemetered to the controlling center.

PREFERRED APPROACH SELECTION

The predominant mode of rendezvous envisioned in both near term and long term orbital operations is the operations between an ascending logistics element (EOS) and an on-orbit element. By definition the EOS is always manned. Also, there will be operational altitudes and inclinations when long duration communication gaps will occur. For this mode of operation a semi-independent mode of operation is preferred.

Prelaunch flight operations planning will determine the desired maneuvers for the entire mission taking into consideration all other elments operating in the projected sphere of rendezvous activities. Normally, ground control could be utilized to accomplish state vector updates; however, some proposed missions will require quick reaction times that will not be compatible with required parking orbit stay times for ground tracking purposes. Therefore, the manned ascending vehicle, the EOS, should have independent state vector update capability and computational capability to modify the preplanned orbital maneuvers to effect rendezvous with the target vehicle. Tracking and ranging of the target vehicle is not required until the range is less than 75 nautical miles,which is the nominal capability of the laser scanning radar model used in this study.

Rendezvous between orbital stationed elements involve both manned and unmanned elements with operations over a wide range dispersion. Except in one case, ground control is preferred for all of these operations with the provision that at close ranges when a manned element is involved an override capability is incorporated in the manned element. The one exception is the control of rendezvous operations of elements related to or in support of space station operations. The nature of detached element operation involving the station requires maintenance of surveillance and control of the elements within the sphere of influence. The additional station equipment complexity to also control rendezvous operations of these elements is considered to be more acceptable than the operational complexity of transfer of command and control back and forth between ground control and the station. A similar concept is preferred for stationkeeping also.

The preferred approach selections for rendezvous are summarized in Table 2-4. These selections were based upon the currently proposed traffic models through 1990. However, as the specific orbits of various program elements become firm, ground control may be required to assume an even more predominant role. At this juncture of the space program traffic is comparable to air traffic of 20 to 30 years ago. Traffic in "preferred" orbits may require extensive "space traffic" control provisions which would place excessive computational, memory, and tracking requirements on all orbital elements.

All facets of the preferences for rendezvous are compatible with similar aspects of stationkeeping and detached element operations. The design concepts are inaccord and utilize the same equipment proposed for communications, mating, and separation for the same or similar functions.

Table 2-3. Rendezvous Approach Evaluation

Consideration	Independent	Ground Control	Space Control	Remarks
Operating Range	✓	✓	✓	
Line-of-Sight				
Beyond LOS	NA	Necessary	Limited*	
Attitude Determination	Necessary	NA	NA	Orbital Element must determine own attitude
Navigation Update				
Accuracy	Same	Same	Same	
Onboard Complex.	Nominal	Minimum	Maximum	
Technology	SOA	SOA	SOA	
Operational Safety				
Close Proximity	Better	Good	Adequate	Based upon Reasonable equip.
C/O & Maintenance	Nominal	Minimum	Maximum	Elem Equip. Only
Relative Cost				
Development	Nominal	Minimum	Maximum	Elem Equip. Only
Operations	Minimum	Nominal	Maximum	Total Operation
Operations Impact				
Near Term	None	None	None	
Long Range	None	Could be major	Minor	Requires priority scheduling of activity
Communication Requirements	1-10 KBPS	1-10 KBS	1-10 KBS	Available comm links adequate

*Note: Unique case where control element is within LOS of other two elements but rendezvousing elements are not within LOS of each other.

Table 2-4. Rendezvous Preferred Approach Selection

Element Pair	Preferred Approach	Rationale
EOS TUG, RAM, Satellite, MSS, CPS, RNS, CPD, OLS	Independent	Preplanned operation, ground network, communication GAPS, close proximity terminal range, manned element
MSS TUG and RAM TUG or RAM	 Space Controlled Independent	 Nature of operations, Nature of operations, close proximity terminal range manned element
TUG* OPD, CPS, RNS, Satellite, RAM	Ground Control	Wide range dispersion, minimize on-board equipment, frequent operations beyond line-of-sight
CPS/RNS* (Manned/Unmanned) OPD	Ground Control	Wide range dispersion, minimize on-board equipment, frequent operations beyond line-of-sight

*Direct measurement of range/range rate between elements required at close range (SLR preferred); manual override capability required when one element is manned.

DESIGN INFLUENCE

Based upon the preferred approach selection the resulting design influences on elements involved in rendezvous operations are summarized in Table 2-5. The EOS and the MSS require the full complement of equipment to conduct all the potential rendezvous operations that they will be involved in. The primary driver on the EOS is its requirement for quick response time and thus independent operation. The MSS, by definition, is an independent space facility and thus must accommodate all the potential operations.

The tug normally is commanded by ground control in its rendezvous operations. However, one class of missions will require the total complement of equipment except for command links to the target. This class consists of a quick response operation in conjunction with the EOS for retrieval of a satellite. It is not recommended that all ground based tugs incorporate this equipment complement.

The CPS or RNS are limited in their rendezvous operations in earth orbit. (Lunar operations may impose different requirements.) Ground control will perform all ranging, state vector determination, and thrust vector determine functions for both TLI and EOI operations. This is based upon the assumption that these two elements are non-piloted. If piloted independent capability would be included.

Detached RAM's, especially in conjunction with the station, will be required to make rendezvous maneuvers. Therefore, their equipment complement reflects the associated functions when commanded from another element.

Satellites are considered to be non maneuvering (excluding attitude control) elements. Therefore, their equipment complement is indicative of a passive but cooperative target.

The OPD is also considered a passive-cooperative target in rendezvous operation. The SLR is included in the OPD list for rendezvous with cislunar shuttles.

Table 2-5. Rendezvous Design Influences

	EOS	Tug	CPS/ RNS	DRAM	MSS	Sate-llite	OPD
Star Tracker	✓	✓	✓	✓	✓		
Horizon Scanner	✓	(1)			✓		
Attitude Reference System	✓	✓	✓	✓	✓		
Scanning Laser Radar	✓	✓			✓		✓
Passive Reflector	✓	✓	✓	✓	✓	✓	✓
S-band Omni	✓	✓	✓	✓	✓	✓	✓
S-band Transponder	✓	✓	✓	✓	✓	✓	✓
S-band Ranging	✓	(1)			✓		
State Vector Computation	✓	(1)			✓		
LSR Tracking and Ranging	✓	✓			✓		
S-band Trackings and Ranging	✓	(1)			✓		
ΔV Computations	✓	(1)			✓		
ΔV Capability	✓	✓	✓	✓	✓		
Command Link	✓				✓		

NOTES: (1) It is envisioned that some ground based tug missions will require reaction times that will not permit parking orbits stay time for ground track navigation and thrust vector updates. On these selected tugs independent capability, similar to the EOS, will be required.

✓: Indicates necessary for operation.

3.0 STATIONKEEPING

The stationkeeping interfacing activity includes those operations required to maintain a prescribed orbital relationship between two elements. This relationship can include varying range, range rate and/or attitude between the elements.

The operating ranges between stationkeeping elements can vary from a few feet (inspection of one element by another) to thousands of miles (quiescent orbital storage of elements such as the CPS and OPD). However, the predominant modes of stationkeeping are concerned with post rendezvous/pre-mating operations and detached element operations. A final inspection/checkout of the elements to be mated would be conducted prior to initiation of the mating maneuvers. A RAM could be deployed from either an EOS or MSS to eliminate the environmental effects of the base element but maintain a prescribed relationship with that base for control/monitor purposes of the operations of the RAM.

3.1 SUMMARY

Evaluation of the total 117 element pair interactions indicated that 49 of these would involve stationkeeping operations. The EOS and the tug are involved in 40 of these interactions. Nine of the 11 representative mission models synthesized in Volume 1 include stationkeeping as a major mission event.

Three alternate approaches to accomplish the stationkeeping activity were evaluated:

1. Autonomous

   The two elements involved perform the necessary functions independent of all other elements and ground control.

2. Ground Control

   Although on-board sensors and communications links are required, ground control monitor and commands the operations of the stationkeeping elements.

3. Space Control

   The approach is similar to ground control except the monitor and command functions are performed by a third orbital element rather than by ground control.

These approaches were analyzed to establish gross functional requirements. Included in these requirements were, orbit determination/navigation updates, attitude determination, maneuver computations, command/control data links, tracking and ranging, and visual/video inspection provisions.

Design concepts were synthesized to perform these stationkeeping functions and analyzed for potential impact on the elements involved as well as the potential multi usage of the equipment for other interfacing activity functions such as those associated with communications, rendezvous, detached element operations, and mating. The design concept models selected were as follows:

Orbit Determination/Navigation Update

Autonomous/Space Control--star tracker/horizon scanner

Ground Control--S-band tracking and ranging by the ground network

Attitude Determination

Star tracker/horizon scanner/IMU (or equivalent) on each element

Maneuver Computations

Autonomous--computation on controlling element only

Space Control--computation on third element only

Ground Control--computation by ground network only

Command/Control Data Links

Element-to-Element--VHF or S-band

Ground-to-Element--S-band only

Tracking and Ranging

Short Range--scanning laser radar

Long Range--element-to-element; VHF or S-band

ground-to-element; S-band only

Visual/Video Inspection

Low resolution television

Operational procedures were developed for the three approaches based upon the synthesized design concept models. Evaluation of the procedures indicated that other than the location of key hardware items there was no significant procedural difference between the ground control and space control approaches. Therefore, a procedure was generated that encompassed both the space and ground control approaches.

Although the autonomous approach procedure was significantly different from the space/ground approach it was primarily due to the hardware complement required on the orbital vehicle and the resulting sequence of operations.

The two procedures would be made applicable to all stationkeeping element pairs. However, the autonomous procedure is preferred for all stationkeeping operations involving the EOS or MSS. A manned element is always involved and either the range between elements is small or the nature of the operation is based upon direct control of the EOS or MSS.

The functional requirements for each approach were analyzed to determine limiting factors and potential design impacts on the elements or required technology advancements. Current existing hardware concepts could adequately meet all stationkeeping performance requirements. Because of the potential duration of close proximity stationkeeping operations between manned and unmanned elements it is recommended that range-range rate determination be automated and accuracy requirements be performed to a high degree of precision. Scanning laser radar concepts can provide both of these functions. Accuracies of ±6 inches and 0.1 foot/second are typical for a laser system.

The primary factors that influenced the preferred approach selection for stationkeeping were the manning status of the elements involved and the range between elements. Normally, if a manned element is involved in stationkeeping, relatively short ranges are involved and control/monitor operations are required (e.g., MSS-RAM). In this case the autonomous approach is preferred. If only unmanned elements are involved in stationkeeping the ground control approach is preferred at separation distances greater than 75 nautical miles (reflects SLR design concept model capability). At shorter ranges at least one of the elements must be equipped with an SLR. The unmanned elements should operate in an autonomous mode at short ranges. Even though the selection for close proximity stationkeeping between unmanned elements is the autonomous approach, it is recommended that, when feasible, the operations are scheduled/conducted during periods of available ground control coverage.

3.2 ELEMENT INTERFACE AND MISSION MODEL MATRICES

Operations analyses of the earth orbit activities of the orbital elements considered in this study indicate a need for 49 different element-to-element stationkeeping interactions. The orbital elements involved in these interactions are identified in the stationkeeping interaction matrix shown in Figure 3-1. Most of the stationkeeping interactions involve as one of the participating elements the EOS orbiter (15 interactions), the ground-based tug (9 interactions), and the space-based tug (12 interactions).

Interactions shown in Figure 3-1 that warrant specific explanation are discussed below:

1. An EOS orbiter might be required to stationkeep with another EOS orbiter during a rescue mission or following an accident or malfunction of an orbiter in flight.
2. Neither an EOS orbiter nor a ground or space-based tug would stationkeep with earth orbit resupply modules, unmanned lunar tugs, lunar resupply modules, or LSB modules, because all of these are nonfree-flyers in earth orbit. However, the orbiter might stationkeep with the propulsive element to which any one of these elements is mated while in earth orbit.
3. A manned lunar tug may be required to stationkeep with one or more of the orbital logistics vehicles (as shown in Figure 3-1) subsequent to its arrival in earth orbit following its employment as a lunar escape vehicle.
4. None of the tugs are considered to perform stationkeeping with a satellite upon initial deployment. By definition, the satellites are controlled and monitored from ground. However, both the ground-based and space-based tugs will perform stationkeeping with satellites during retrieval, inspection, and resupply operations.

To provide traceability to the mission models presented in Section 2.0 of Volume I identifying the stationkeeping interactions, a second element-to-element matrix is presented in Figure 3-2. The applicable mission models for each interaction are indicated.

SPACE VEHICLE INVENTORY

		EOS	TUG				RAM				SATELLITE			EO RESUP MODS	MSS		CPS			RNS	LUNAR PROGRAM SYSTEMS					OPD
			NON RET	RTN	GRD BASED	SPACE BASED	ATT. EOS	DET. EOS	ATT. MSS	DET. MSS	EOS DELIV	EOS + 3RD ST	RETR, RESUP		LOW EO	GEO SYNCH	OIS	EO SHTL	CLS		OLS	TUG UNMAN	TUG MAN	RESUP MOD	LSB	
	EOS	S	S	S	S	S	X	S	X	S	S	S	S	X	S	X	▨	S	S	S	S	X	S*	X	X	S
TUG	NON RET		▨	▨	▨	▨	▨	▨	▨	▨	▨	X	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
	RETURNABLE			▨	▨	▨	▨	▨	▨	▨	▨	X	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
	GRD BASED				S	S	▨	▨	X	S	▨	X	S	X	▨	S	▨	S	S	S	▨	X	S*	X	▨	X
	SPACE BASED					S	▨	▨	X	S	▨	X	S	X	S	S	S	S	S	S	S	X	S*	X	X	S
RAM	ATT. EOS						▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
	DET. EOS							▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
	ATT. MSS								▨	▨	▨	▨	▨	▨	X	X	▨	X	▨	X	▨	▨	▨	▨	▨	▨
	DET. MSS									▨	▨	▨	▨	▨	S	S	▨	X	▨	X	▨	▨	▨	▨	▨	▨
SATEL	EOS DELIV										▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
	EOS + 3RD ST											▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
	RETR, RESUP												▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
	EO RESUP MODS													X	X	X	▨	X	X	X	▨	X	X	X	▨	X
MSS	LOW EO														X	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
	GEOSYNCH															X	▨	S	▨	S	▨	▨	▨	▨	▨	▨
CPS	OIS																▨	X	X	X	X	▨	▨	▨	▨	X
	EO SHTL																	S	▨	▨	▨	▨	▨	▨	▨	S
	CLS																		S	▨	X	X	S*	X	X	S
	RNS																			X	X	X	S*	X	X	S
LPS	OLS																				X	X	X	X	▨	▨
	TUG UNMAN																					▨	▨	X	X	X
	TUG MAN																						▨	X	X	X
	RESUP MOD																							X	X	X
	LSB																								X	▨
	OPD																									X

LEGEND

Potential Interactions	117
Actual Interactions	49
S - Stationkeep	49
X - Not Applicable	68
* - Following Lunar Escape	

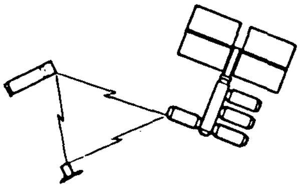
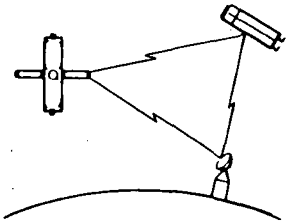
Figure 3-1. Stationkeeping Interactions

		SPACE VEHICLE INVENTORY																								
		EOS	TUG				RAM				SATELLITE			EO RESUP MODS	MSS		CPS			RNS	LUNAR PROGRAM SYSTEMS					OPD
			NON RET	RTN	GRD BASED	SPACE BASED	ATT. EOS	DET. EOS	ATT. MSS	DET. MSS	EOS DELIV	EOS + 3RD ST	RETR, RESUP		LOW EO	GEO SYNCH	OIS	EO SHTL	CLS		OLS	TUG UNMAN	TUG MAN	RESUP MOD	LSB	
	EOS	2	1	2	2,7,8	1,2,4	☒	1,2	☒	1,2	1	1	2	☒	1,2	☒	▩	1,2, 10,11	1,2, 10,11	1,2,11	1,2	☒	2,10,11	☒	☒	1,2
TUG	NON RET		▩	▩	▩	▩	▩	▩	▩	▩	▩	☒	▩	▩	▩	▩	▩	▩	▩	▩	▩	▩	▩	▩	▩	▩
	RETURNABLE			▩	▩	▩	▩	▩	▩	▩	▩	☒	▩	▩	▩	▩	▩	▩	▩	▩	▩	▩	▩	▩	▩	▩
	GRD BASED				8	8	▩	▩	☒	7,8	▩	☒	8	☒	▩	7,8	▩	8,10,11	8,10,11	8,11	▩	☒	8	☒	▩	☒
	SPACE BASED					4,5	▩	▩	☒	4,5	▩	☒	4,5	☒	4,5	4,5	5,9	4,5, 10,11	4,5, 10,11	4,5,11	4,5	☒	4,5, 10,11	☒	☒	4,5
RAM	ATT. EOS						▩	▩	▩	▩	▩	▩	▩	▩	▩	▩	▩	▩	▩	▩	▩	▩	▩	▩	▩	▩
	DET. EOS							▩	▩	▩	▩	▩	▩	▩	▩	▩	▩	▩	▩	▩	▩	▩	▩	▩	▩	▩
	ATT. MSS								▩	▩	▩	▩	▩	▩	☒	☒	▩	☒	▩	☒	▩	▩	▩	▩	▩	▩
	DET. MSS									▩	▩	▩	▩	▩	1,2,5	4,5,8	▩	☒	▩	☒	▩	▩	▩	▩	▩	▩
SATEL	EOS DELIV										▩	▩	▩	▩	▩	▩	▩	▩	▩	▩	▩	▩	▩	▩	▩	▩
	EOS + 3RD ST											▩	▩	▩	▩	▩	▩	▩	▩	▩	▩	▩	▩	▩	▩	▩
	RETR, RESUP												▩	▩	▩	▩	▩	▩	▩	▩	▩	▩	▩	▩	▩	▩
	EO. RESUP MODS													☒	☒	☒	▩	☒	☒	☒	▩	☒	☒	☒	▩	☒
MSS	LOW EO														☒	▩	▩	▩	▩	▩	▩	▩	▩	▩	▩	▩
	GEOSYNCH															☒	▩	10,11	▩	11	▩	▩	▩	▩	▩	▩
CPS	OIS																▩	☒	☒	☒	☒	▩	▩	▩	▩	☒
	EO SHTL																	10	▩	▩	▩	▩	▩	▩	▩	10,11
	CLS																		10	▩	☒	☒	10,11	☒	☒	10,11
	RNS																			☒	☒	☒	11	☒	☒	11
LPS	OLS																				☒	☒	☒	☒	▩	▩
	TUG UNMAN																					▩	▩	☒	☒	☒
	TUG MAN																						▩	☒	☒	☒
	RESUP MOD																							☒	☒	☒
	LSB																								☒	▩
	OPD																									☒

Figure 3-2. Applicable Mission Models for Stationkeeping

3.3 ALTERNATE APPROACHES

The stationkeeping operation can be controlled using any of the following general approaches:

ALTERNATE APPROACHES		
AUTONOMOUS	SPACE CONTROL	GROUND CONTROL
		
(1) BOTH ELEMENTS UNMANNED (2) ACTIVE ELEMENT MANNED	STATIONKEEPING ELEMENTS UNMANNED	STATIONKEEPING ELEMENTS UNMANNED

1. Autonomous--Both Elements Unmanned

   Autonomous stationkeeping operations are conducted without support from external bases either space or ground. One element is in command of all the operations of both stationkeeping elements. It is equipped with automated systems that perform preprogrammed timing for all operations. Both elements have the capability to perform both attitude and orbital makeup maneuvers to maintain orbital parameters.

2. Autonomous--One Element Manned

   When one of the autonomous stationkeeping elements is manned, it assumes command and control of all stationkeeping operations. Man takes over command and controls all operations in the same procedural sequence as in the unmanned autonomous approach. Both elements have the ability to perform both attitude and orbital makeup maneuvers.

3. Ground--Controlled

   This approach employs complete ground control of all stationkeeping operations. Relative position information can be obtained by ground-tracking both vehicles or having one vehicle track the other and transmit the data to the ground. The ground computes the necessary correction manevuers and transmits attitude and translation commands to the active vehicle which executes the maneuver. The communication links are either direct from ground stations or via TDRS. The ground-controlled concept is particularly suitable for a stationkeeping operation involving two unmanned vehicles or a single synchronous unmanned orbital vehicle.

4. Space--Controlled--Remote

   This approach is characterised by being independent of the ground. Intelligence and control of the vehicle are included in a third nonactive or nonmaneuvering vehicle. This approach is comparable to the ground control approach but imposes additional functional requirements on the orbital elements. For example, the MSS could control a Space Tug stationkeeping with a detached RAM for the purposes of inspection.

   The station computes and controls the operation; at least one of the detached elements must be cooperative and able to execute commands.

Although an unmanned, autonomous approach has been developed in procedural form and is technologically possible, it should be monitored and subject to override from another control element--either space based or ground based. Such a recommendation evolves from the desire to enhance the absolute safety of such an operation.

Some alternate stationkeeping flight modes that could be utilized with any of the stationkeeping approaches previously mentioned are illustrated in Figure 3-3. These modes are described as follows:

1. In the football-drift mode, one orbital element E_1 is in a circular earth orbit, while element E_2 is in a coplanar elliptical orbit such that the resultant relative motion between the two is as shown in Figure 3-3. This mode could be applicable for MSS and detached RAM operations.

2. In the big-D flight mode, element E_1 is in a circular earth orbit, and element E_2 is initially in a coplanar, slightly larger, circular orbit. If E_1 has either less drag than E_2 or E_1 employs orbit makeup and E_2 does not, then the relative motion between the two will appear as shown in Figure 3-3. After E_2 has "fallen" into a lower orbit beneath and ahead of E_1, a propulsive maneuver is conduced to reposition E_2 to its initial orbit. This mode could also be applicable for MSS and detached RAM operations.

3. In the follow-the-leader flight mode, both elements E_1 and E_2 are in the same size circular earth orbit. Orbit makeup and other corrections are utilized by either or both elements to maintain their relative positions within desired limits. Inspection operations could be oncducted with this mode.

4. In the side-by-side flight mode, orbital elements E_1 and E_2 are in the same size circular orbits but the orbits in question have slightly different inclinations and one vehicle has a greater true anomaly than the other. Orbit makeup and other corrections are used by either or both elements to maintain separation distance within desired limits at those points where the two orbits intersect. A potential application of this mode would be the quiescent storage of a cislunar shuttle while maintaining a safe fixed relationship with an orbital propellant depot.

5. In the tethered flight mode, the two elements are physically connected by a tether. Element E_2 may assume the relative position with respect to E_1 shown in Figure 3-3 because of the gravity gradient effects. Other factors such as aerodynamic forces and torques may influence the realtive motion or trim position.

6. In the tethered-and-spun flight mode, the two elements are physically connected by a tether and then spun up using positive expulsion devices.

These various flight modes were investigated to determine their influence on the functional requirements of stationkeeping. The two tethered flight modes introduce significant increases in complexity and functional requirements, all of which are almost totally dependent upon the configuration and design concept of the elements involved. Therefore, this class of flight mode is more apropros as an analysis task for an individual element study. Tethered modes will not be considered further in this study.

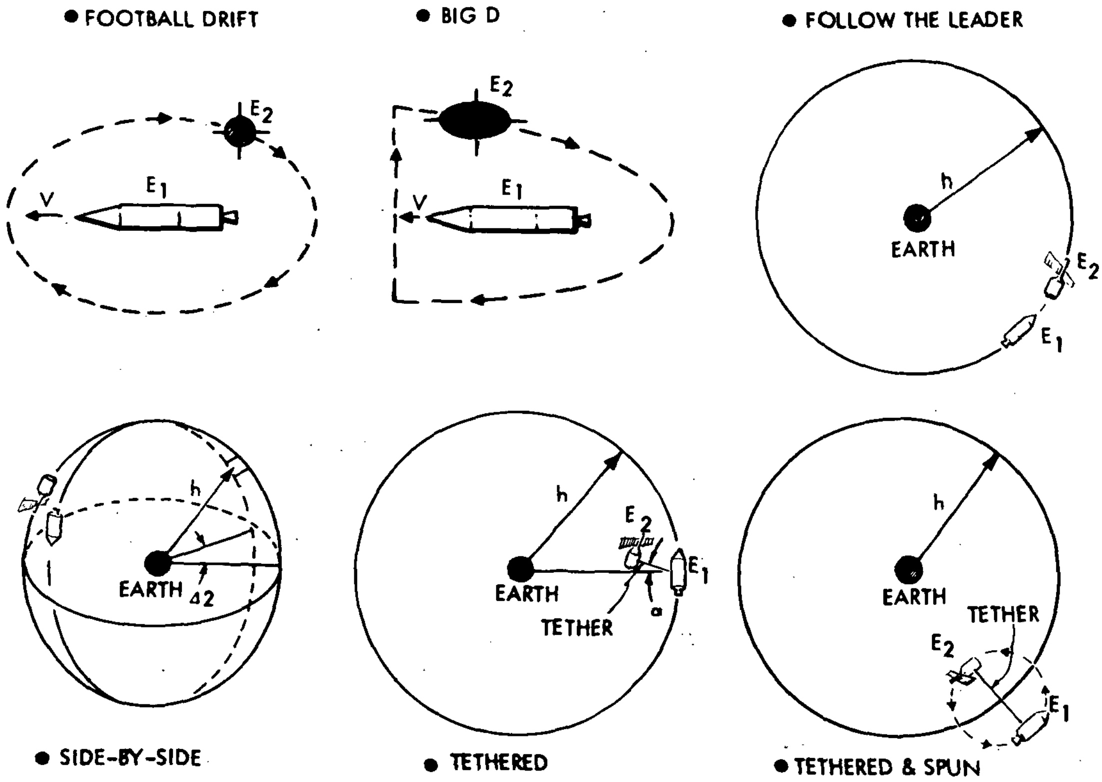


Figure 3-3. Alternate Stationkeeping Flight Modes

3.4 DESIGN CONCEPT MODELS

The design concept models in all approaches are predicated on the methods used to provide (1) attitude reference and control, (2) state-vector determination, (3) relative element position and velocity, (4) navigation and flight control computation, and (5) communications and remote command and control. Table 3-1 summarizes the design concepts for each major function and approach.

ATTITUDE REFERENCE AND CONTROL

Both stationkeeping elements must maintain specific attitudes to fulfill either mission requirements and/or to ensure the orientation for delta-V or attitude maneuvers. A guidance and control analysis (contained in Appendix A, Trade Study A-1) was conducted to establish an integrated concept for all related functions of the various activities. A common usage system consisting of an Inertial Measurement Unit (IMU), star tracker and horizon scanner can provide sufficient attitude reference for all stationkeeping operations. The horizon scanner will facilitate earth coordinate relationship determination. The star tracker is used for yaw axis (local vertical axis) attitude determination. This equipment also provides the measurements necessary for autonomous state vector determination. Control authority could be implemented by either a positive expulsion concept or a momentum exchange concept. The selection would be based upon performance requirements other than those related to stationkeeping.

STATE VECTOR DETERMINATION

For the autonomous approach, state vector determination can be implemented by the IMU/star tracker/horizon scanner set of equipment to accuracies of one nautical mile position uncertainty. In the case of the separate control center approaches--space or ground--state vectors and orbital parameters are determined by measuring range and range rate data on each of the stationkeeping elements and computing the ephemerids based upon the known position of the control center. This imposes the requirement on the space control center to be capable of determining its own state vector.

Use of the ground network S-band system in conjunction with transponders on the stationkeeping elements will result in position uncertainties of approximately one nautical mile. Similar results can be obtained with an S-band system on the space controlling element. VHF ranging similar to the Apollo-LEM concept could also be used.

RELATIVE ELEMENT POSITION AND VELOCITY

In all three approaches S-band will adequately provide relative position and velocity data at long range. However, when the two stationkeeping elements are within five nautical miles of each other, ambiguties in the space and ground control approaches commence. In close proximity operations such as inspection or premating operations, the S-band or VHF (between elements) techniques are no longer adequate regardless of the approach. In the case of manned elements visual techniques could be utilized. Video could be used for

Table 3-1. Design Concept Summary

Operational Function	Design Concept	Approach		
		Autonomous	Space Controlled	Ground Controlled
Local Level Attitude Determination	IMU/Star Tracker/ Horizon Scanner (2)	✓	✓	✓
State Vector Determination	IMU/Star Tracker/ Horizon Scanner (2)			
	One Element	✓		
	Control Element		✓	
	Tracking and Ranging			
	One Element	✓		
	Control Element		✓	
	None			✓
Relative Position	VHF (3)	✓	✓	
	S-Band	✓	✓	✓
	Laser (SLR) (1)	✓	(✓)*	(✓)*
Flight Control Computation	One Element	✓		
	Control Element		✓	
	Ground Element			✓
Communication Links	VHF (3)	✓	✓	
	S-Band	✓	✓	✓
*Laser system is on stationkeeping elements				

(1) SLR is necessary for close-in stationkeeping (≲ 75 n. miles) to provide required accuracy.

(2) Design concepts reflect commonality of required hardware for multiple functions and not necessarily optimization for a configuration.

(3) S-band is the primary mode; VHF is the recommended alternate or redundant mode.

the separate control center approaches. However, both of these design concepts require almost continuous monitoring. The preferred design concept is to incorporate laser scanning radars regardless of the approach.

In all three approaches the monitoring of the critical range/range rate parameters can be automated and thus alleviate a tedius and judgment task. In the separate control approach the data is telemetered to the control center. In the autonomous case direct readouts and alarms can be incorporated for the manned element option. Unmanned operations can be automated in the same manner as in the separate control centers.

An evaluation was conducted to establish the practicality of a laser radar system for the stationkeeping functions and is contained in Vol. II, Part 2, Sec. 1.0, Mating. A system within the state-of-the-art was defined that can provide accuracies of ±6 inches (0.02 percent of range) and 0.1 foot/second (1 percent of range rate) up to 75 nautical miles. Therefore, the recommended design concept for determining relative range and range rate between stationkeeping elements at ranges ≤75 nautical miles is the scanning laser radar. Such accuracies (±6", ±0.1 FPS) are necessary at ranges approaching 50 to 100 feet. At greater distances, the precision of measurement accuracy can decrease. Since this precision is available within the state-of-art and commonality of usage of equipment is a goal. This choice can be used for mating, docking, rendezvous and stationkeeping.

NAVIGATION AND FLIGHT CONTROL COMPUTATIONS

The computational concepts are essentially the same for all three approaches. There are no unique computer requirements. Numerous hardware designs can provide the necessary storage and processing functions. The significant impact is the additional equipment that is required on the space elements for both the autonomous and space controlled approaches. Flight control computational capability is required independent of stationkeeping requirements, but navigation computation requirements are a delta and could impose additional storage or memory capacity requirements.

COMMUNICATIONS AND REMOTE COMMAND AND CONTROL

Although all three approaches require data links that have numerous options, the selections are based upon the integrated communication link trades developed in the Communications activity. Stationkeeping data transfer requirements are not the governing factor in the preferred approach selections of communications. Element-to-element communication (autonomous and space controlled approach) requirements can be accommodated on VHF or S-band omni antenna links. Ground control links can be accomplished by utilizing the ground network S-band system with only omni antennas on the orbital elements.

Low resolution video (TV) is considered adequate for inspection purposes. The corresponding data rates can also be accommodated on the S-band link with an omni antenna on the stationkeeping elements.

3.5 OPERATIONAL PROCEDURES

Evaluation of the functions to be performed for stationkeeping operations indicated that two procedures could adequately describe the sequence of events that would occur. The events associated with either the ground or space control approach are the same; only the location of the activity are unique. The worst case approach was assumed for the autonomous approach, namely unmanned vehicles.

The detailed procedures are presented in Appendix B. Figure 3-4 summarizes the major functional events of the two procedures in a comparison format. Regardless of the approach, the elements involved must be capable of determining their own attitude. The significant differences between the approaches are related to the orbit determination and maneuver determination functions. If the orbital element determines the orbital parameters this imposes unique computational and ranging and tracking requirements. Similarly, additional on board computer complexity is required if all maneuvers are to be determined by the orbital element. Imposing these functional requirements on a third or controlling space element is considered as a viable option at this point in the analyses because of the potential multiple use of such an element.

Accomplishment of the orbit determination and maneuver computation requirements is well within the capabilities of the proposed ground network. However, on-board sensors will be required for generation of pertinent range data for close proximity operations to insure mission safety.

The applicability of the two procedures is also presented in Appendix B. Two elements in the study inventory, the EOS and tug, are involved in the majority of the stationkeeping interfaces. Although the two procedures could be considered applicable to EOS stationkeeping interfaces only the autonomous one is considered a viable option because the EOS is always manned. Also stationkeeping operations involving the EOS are of a temporary nature and usually at short ranges. In the case of the tug both long duration and long range operations will be frequently involved and therefore both procedures are applicable.

The other stationkeeping interfaces include the MSS-RAM, OPD-CPS, and OPD-RNS combinations. The nature of the MSS-RAM interface inherently dictates the applicability of the autonomous procedure. The primary purpose of the MSS-RAM operation is for remote control of the RAM by the MSS. In the cases involving the OPD both procedures are applicable because of potential long duration and long range operations.

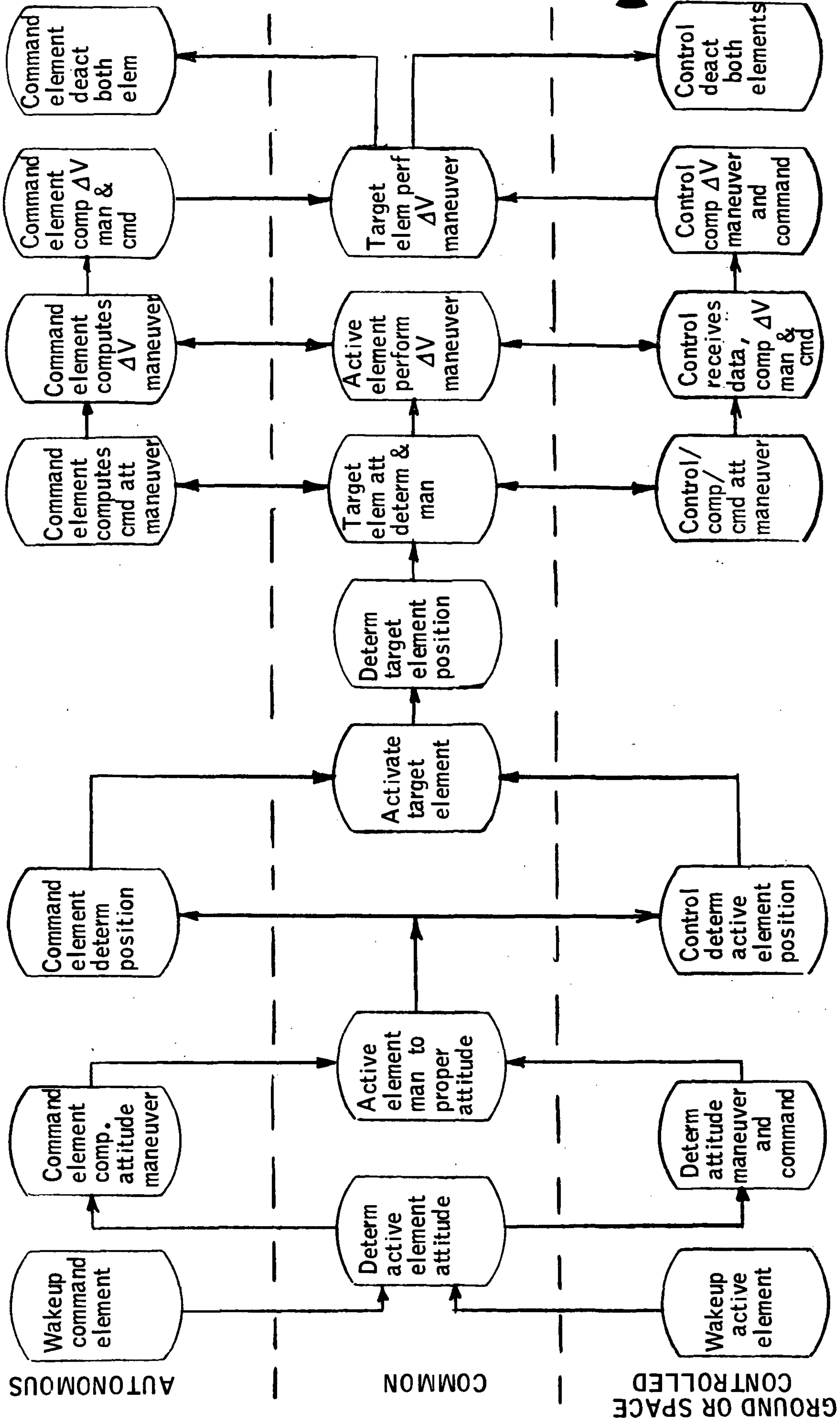


Figure 3-4. Stationkeeping Procedural Comparison

3.6 FUNCTIONAL REQUIREMENTS

The major functional requirements for stationkeeping include the need for communications activities of data transfer, command, tracking and ranging, and attitude and state vector measurement and control. When operational control is performed by a space element, it is necessary to provide sufficient computation capability on the element to perform state vector and attitude orientations calculations as well as the maneuver calculations necessary for attitude control and maneuvers for stationkeeping position maintenance. In the autonomous case, one of the stationkeeping elements needs this capability including the memory that contains predicted results. In the space or ground control alternates, the control centers will contain the required capability.

A functional requirement that should be noted in the ground control approach is the potential use of the active element communications system as a relay for the target element communications with ground. This evolves from the need to simplify and maintain continuous communications with both stationkeeping elements when their separation distance is greater than the ground system antenna field of view. A further discussion of this requirement is included under functional requirement 11 of the subsequent listing.

This section first provides basic functional requirements in tabular format defining their application to the alternate approach procedures. These procedures are presented in Appendix B. This is followed by a set of matrices that define in detail, by element pairs, specific characteristics of the design concepts. The last portion includes the analyses that were conducted to establish the specific requirements included in these matrices.

FUNCTIONAL REQUIREMENTS TABULAR LIST

The following tabular list delineates the functional requirements and their application to one or both of the alternate approach procedures. It reflects generic requirements by the type of element, active or target. The active element is defined as the element that performs the required maneuvers to maintain the stationkeeping relationship. Also identified are the requirements imposed on the control center or "element" for each approach.

	Applicable Procedure	
	Autonomous	Ground or Space Control
	11-1	11-2
1. The active element must have a sequence timer or computer scheduled timing activation system that can automatically activate or wake up specified subsystems utilized in stationkeeping of two unmanned near-earth orbital elements. This is either automatically programmed at the end of the last previous operation or is set up in a ground contact to the active element.	X	
2. Both the active and target elements must contain an attitude reference system capable of determining the element position in relation to the element coordinates and orbital or earth coordinates. Knowledge of element position is necessary for the pointing of on-board sensors, antennas and for orientation to perform delta-V orbital makeup maneuvers.	X	X
3. The active element must have a computer memory capable of storing attitude reference data and predicted attitudes for all stationkeeping operations. The computer must be programmed and a look-up routine available that can perform a computation to determine the difference between actual and predicted attitudes and to calculate the attitude control maneuvers to correct the attitude within prescribed limits.	X	
4. The active element must have a cooperative transponder to operate with either ground network stations or TDRS tracking and ranging to enable determination of its state vectors and orbital parameters. Accuracy and visibility time will determine which--ground station or TDRS.		X

	Applicable Procedure	
	Autonomous	Ground or Space Control
	11-1	11-2
5. Both elements must have attitude control systems enabling implementation of a change in attitude.	X	X
6. Communication links must be available between elements and between elements and ground (either direct or TDRS) to allow transfer of commands and data as follows:		
a. Transfer of command data up to 1 kbps	X	X
(1) Between active and target element up to LOS (4000 nautical miles)		
(2) From ground (either ground network station or TDRS) to active element		
(3) From space control element to active and target elements to LOS (4000 nautical miles)		
b. Transfer of digital data up to 10 kbps from	X	X
(1) Target to active element		
(2) Active element to ground (either ground network station or TDRS)		
(3) Target or active element to the space control element		
c. Capability to allow transmission of wakeup commands (≤1 kpbs) to either stationkeeping element with omni-directional reception capability to allow reception regardless of element attitude orientation.	X	X

	Applicable Procedure	
	Autonomous	Ground or Space Control
	11-1	11-2
d. The active element transmission system should have sufficient radiated power (EIRP) to provide acceptable signals at the target element with an antenna of a wide beamwidth (≥10 degrees) that precludes the necessity for acquisition scan to locate the target element.	X	X
7. The active vehicle must have a PRN ranging system capable of operating with a cooperative element. It shall have the capability to process the transmitted and turned-around PRN signals to determine range and range rate of the target element relative to the active element. Its antenna system should be relatively broad beamwdith to avoid acquisition-scan. If a narrow beam is required and scanning necessary, it should be a preprogrammed scan. See the Communications subsection for required link characteristics.	X	X
8. The target element must have a coherent transponder compatible with the active element interrogating transmitter and receiver that is capable of coherently retransmitting the received PRN signal from active element back to the active element at a sufficeent signal level to maintain the specified signal-to-noise ratio. See the Communications subsection for details. The target element transponder must be capable of receiving and retransmitting the PRN ranging signals over an omni-directional antenna system that is not inhibited by element attitude.	X	X
9. The active element must have a computer system capable of computing state vectors and orbital parameters from the range, range rate data and its own state vectors. It shall also have the capability to compute necessary delta-velocity maneuvers from stored data of orbital makeup parameters.	X	

Requirement	Applicable Procedure	
	Auton-omous	Ground or Space Control
	11-1	11-2
10. Both elements must have propulsive systems capable of performing delta-velocity maneuvers in accordance with the computer requirements for orbital makeup to ensure orbital maintenance during the lifetime of the element.	X	X
11. The active element communications system must have the capability to receive commands and retransmit these commands to the target element. The active element must have the capability to provide the same relay function for target element data in the reverse direction; i.e., target element to active element to control element. This requirement imposes the capability of switching from internal to external communications for relay operation on the active element communication system. Switching would be activated by the controlling element. (See Note 1 at the end of this listing for a detailed description of the reasons for this type operation and when the relay operation should be applied.)		X
12. The active element must contain the means to measure range and range rate angle and angle rates with a passively cooperative target element at ranges from 50 miles to 50 feet within the following accuracies:	X	X

	Accuracy	
Range	Range	Range-Rate
0-100 ft	±6 inches	±0.1 ft/sec
100-1500 ft	±1 ft	±0.1 ft/sec
1500 ft - 5 n mi	±10 ft	±0.5 ft/sec
5 n mi - 30 n mi	±100 ft	±0.5 ft/sec
30 n mi - 60 n mi	±500 ft	±5.0 ft/sec

These capabilities are necessary to perform visual inspection of target elements at close ranges.

	Applicable Procedures	
	Autonomous	Ground or Space Control
	11-1	11-2
13. The control element must have an onboard autonomous navigation system capable of determining its own state vectors and orbital parameters.	X	

NOTE 1: Active Element Relay Operation (Application to Functional Requirement No. 11)

In order to preclude acquisition switching from active to target element by ground or TDRS, all operational commands and data transfer are performed through the control element acting as a relay. With narrow beamwidth ground antennas, this switching would be complex and time consuming because of the necessity to slew the large antennas back and forth between elements. This would be further complicated when it becomes necessary to hand over from one ground station to another. Each orbital element could be in view of different ground stations for a short time. It is much simpler to utilize the control element for all contacts with both elements. If TDRS is used, switch-over becomes simpler since the field of view of narrow-beam antennas from a distance of 23,000 nautical miles is a factor of approximately 50 times that at low earth orbits from ground. There would be many cases where the TDRS Ku-band antenna field of view would cover both elements. If stationkeeping is performed within the field of view a single frequency could illuminate both elements. For command operations, this could be further simplified by using VHF and taking advantage of the semi-directional antenna from the TDRS. VHF is, however, limited to low data rate commands (1 kbps) and 10 kbps down-link telemetry data. Most stationkeeping modes could be covered by a single TDRS illumination of both elements. This assumes that the separation distance is less than approximately 400 nautical miles. If control is from ground direct, stationkeeping by illumination from a single ground station frequency (within a singular antenna beam) could be accomplished with element spacings as displayed in Figure 3-5. This spacing constraint is defined to reflect the distance between the 3 dB (or one-half power) point on the antenna pattern. It is possible that greater spacing can be accommodated due to the ground antenna size and the associated peak antenna gains available.

Stationkeeping Element Pair Requirements Matrix

In order to identify the functional requirements by element pairs for those elements included in this study, a requirements matrix was developed and follows. Since the requirements, when applied to a particular element are the same, the matrix was made by tabulating the requirement against the utilization of the element. Elements are categorized either as active, target or control. This division holds regardless of which alternate approach is used. An element can, of course, be a combination; i.e., active and control or target and control. When this occurs, the requirements for both divisions apply to the element. At the head of each column is a list of the elements that apply. For convenience, the possible combinations of each element are listed below.

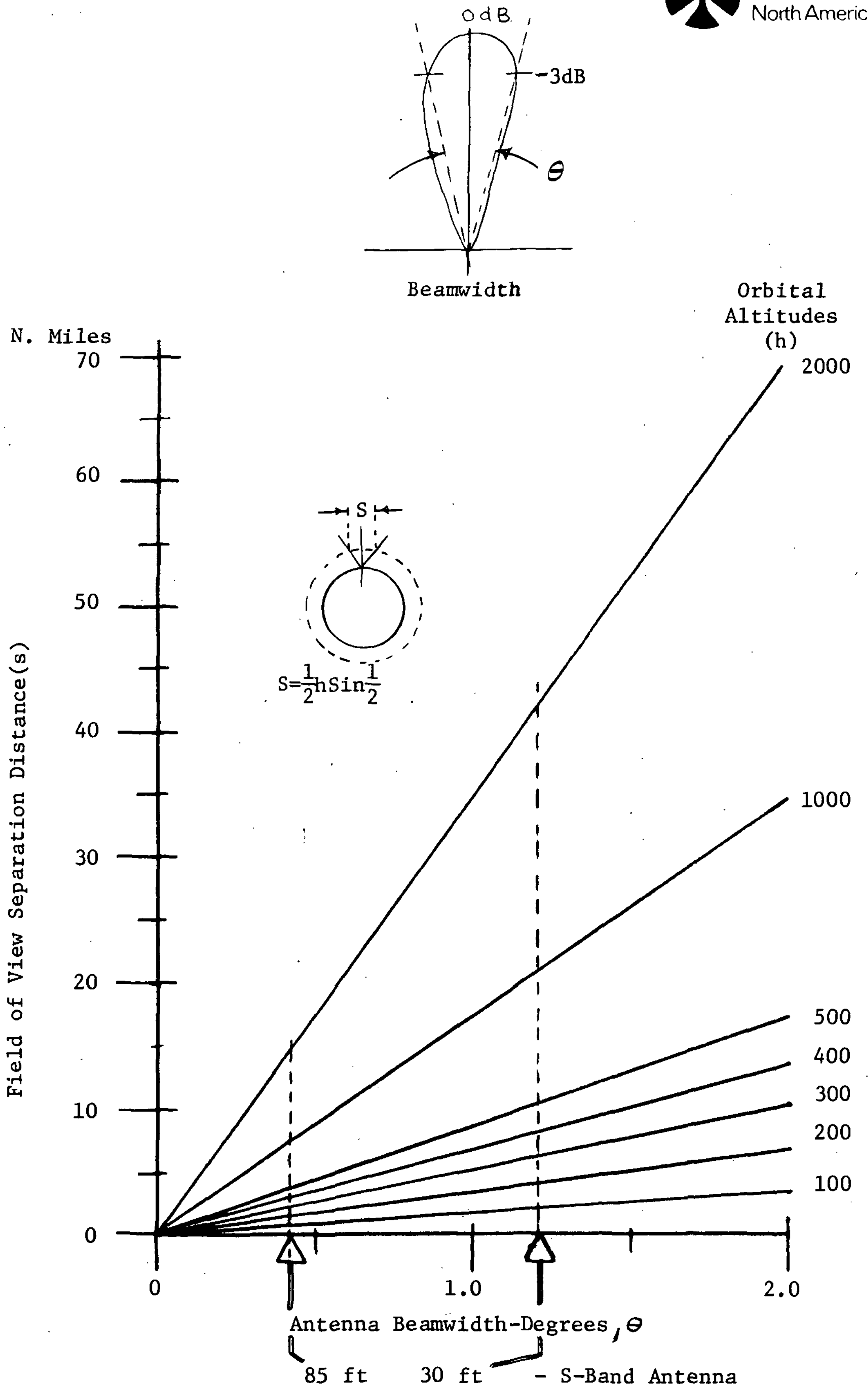


Figure 3-5. Field of View at Various Orbits Vs. Antenna Beamwidth

Active and In Control

EOS, TUG, OIS, CPS, RNS, OLS

Target and In Control

MSS

Active But Not in Control

RAM

MSS and RAM define the only pair where the target vehicle is in control. Any manned element can operate as a separate space control element. The matrix columns identify all elements.

Quantitative Requirements Analyses

Stationkeeping requires knowledge and control of attitude and position to perform whatever missions are associated with stationkeeping operations. Some missions can be a long range separation parking orbit while awaiting a rendezvous with another element. Another mission could require very short ranges -- for inspection purposes. This could be as close as 50 feet. Another could be stationkeeping with a point-in-space to position an experiment platform, but controlled from either a ground or a space element. This could be accomplished with medium range separation (up to 450 nautical miles) of the element pair. Each of these impacts the requirements for element control of attitude and position in a different manner. The quantitative requirements stipulated in the matrix of requirements are intended to define those associated with the interfacing activity of providing stationkeeping for normal operations. If, for instance, the RAM needs to provide a pointing accuracy of 1 arc-second and less than 0.01 arc-second stability for a particular experiment that accuracy is not considered part of this interfacing activity. This is, incidentally, a requirement stipulated for some experiments--such as astronomy. Implementation to support this would be part of the design task of that particular element and operation. The accuracies used in the table are those numbers associated with holding position and attitude to satisfy stationkeeping activities in preparation for rendezvous or docking maneuvers. Vehicle configuration, location of attitude reference system relative to the experiment sensor and the type of control system all effect the precision of pointing accuracy and pointing stability. Maximum precision would be obtained by integrating the precision attitude reference system with the experiment sensor module. This avoids the problem of vehicle structural integrity influence on the stability and precision of the reference between the experiment module and attitude sensing system. The analyses and the requirements for such operations are not covered in this study.

Table 3-2. Stationkeeping Element Pair Requirements

		Active	Target	Control
	ELEMENTS	EOS - TUG OIS - CPS RNS - OLS RAM -	EOS - TUG RAM - SAT MSS - CPS OIS - RNS OLS - OPD	EOS - TUG OIS - CPS RNS - OLS MSS
1.	Tracking/Ranging >75 nm Range: ±1 nm Range Rate: ±10 ft/sec	PRN range transmit, receive measurement system PRN Range turn-around transponder to ground	PRN range turn-around transponder only	PRN range transmit, receive measurement system If space-based PRN range turn-around transponder to ground
2.	Tracking/Ranging <75 nm Range: 30 to 75 nm ±100 ft; 50 ft to 30 nm ±5 ft Range Rate: 30 to 75 nm ±0.5 ft/sec; 50 ft to 30 nm ±0.1 ft/sec	Active Scanning Laser Radar (SLR) system	Optical corner cube reflectors only	Not required
3.	Attitude Reference System ±0.5 deg for normal activities (see analyses section)	Yes	Yes	If Space Based
4.	Attitude Control System ±0.5 degree stability for all normal activities (see analyses section)	Yes	Yes	If Space Based

Table 3-2. Stationkeeping Element Pair Requirements (continued)

		Active	Target	Control
5.	Delta-V Maneuver Capability "Orbital Transfer"	Yes	Orbital Make-up Only	Yes
6.	Communications Command Data 1 Kbps, 1 x 10^{-6} BER (see communications section 2.9 for details)	Receive, decode, apply command	Receive, decode, apply command	Transmit to both active and target
7.	Communications Status Telemetry Data Transfer 10 Kbps, 1 x 10^{-6} BER (see communications section 2.9 for details)	Transmit to control	Transmit to control	Receive, decode, monitor data
7a.	Communications Voice 4 KHz Audio (for manned elements) (see communications section 2.9 for details)	Duplex to target and control	Duplex to active and control	Duplex to target and active
8.	Communications Wake-up Receiver (see communications section 2.9 for details)	Omni-direct VHF or S-Band	Omni-direct VHF or S-Band	Transmit wake-up command on VHF or S-Band
9.	Sequence Timer	Not required	Not required	Space based unmanned element
10.	Relay Switching Capability Receive/Transmit 1 Kbps Commands Receive/Transmit 10 Kbps Data Receive/Transmit Voice	When being controlled by separate element	Not required	Not required

Table 3-2. Stationkeeping Element Pair Requirements (continued)

		Active	Target	Control
11.	Computation Capability	Attitude determination, Attitude control, Tracking and ranging for <75 nm	Attitude determination, Attitude control	Attitude determination, Attitude control if space based Tracking and ranging >75 nm position determination of all elements, delta V maneuvers of all elements

Relative position accuracy requirements are dependent upon the stationkeeping mode that is desired. Close range operations that are characteristic of inspection missions or pre-mating functions require accuracies that are determined by safety considerations. In these cases only relative range and range rate control are significant. Appendages on the elements involved (e.g., solar arrays, antennas, etc.) must also be considered in establishing the accuracy requirements. The listed accuracy requirements reflect an integration of required accuracy and capability of a scanning laser radar system. It should be noted that attitude control requirements can be quite loose during this class of stationkeeping operations. Tight control is not required until a mating operation is initiated. (Assumes inspection can be accomplished either visually or with optical aids without reducing the distance between elements to within potential collision range if one element should rotate.)

Long range stationkeeping operations are usually more dependent upon absolute position knowledge and element inertial attitude. Attitude constraints are based upon subsequent rendezvous or orbit maintenance pointing requirements. Pointing accuracies are only one facet of the total error analysis associated with the development of delta V maneuvers/propellant utilization requirements. Although the requirements must be determined separately by individual element studies accuracies of ± 0.5 degrees for attitude reference and attitude control are typical for pre-thrusting operations associated with stationkeeping.

Similarly, knowledge of absolute position and the data required to provide maintenance of position are needed to sufficient accuracy to determine efficient thrusting maneuvers. The data listed in the functional requirements is based upon nominal mission requirements utilizing current hardware. Typical position accuracies that can be achieved by the proposed ground network based upon measurements from four ground stations in 1-1 1/2 orbits are:

Position	Accuracy (1σ)
Down Range	370 ft.
Cross Range	360 ft.
Altitude	320 ft.

Figure 3-6 illustrates the position uncertainty that can be achieved utilizing TDRS as the tracking station. Both single and dual TDRS capabilities are presented.

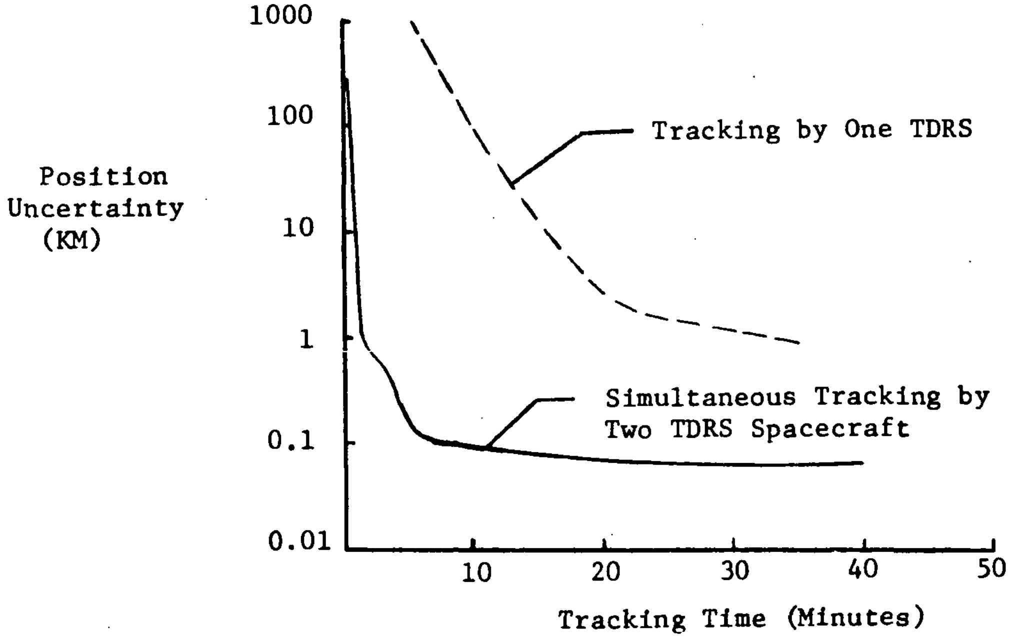


Figure 3-6. Nominal Position Accuracy Via TDRS

3.7 DESIGN INFLUENCES AND PREFERRED APPROACH SELECTION

The primary factors that influence the selection of a preferred stationkeeping approach are:

(1) Type of stationkeeping mode

(2) Range between elements

(3) Design implications of the approach

(4) Relative costs

(5) Manning status of the elements

Table 3-3 presents an evaluation of the three approaches with these factors.

APPROACH EVALUATION

The autonomous approach is applicable for operational, inspection, and pre-mating modes of stationkeeping if either of the elements are manned. Only pre-mating operations between unmanned elements are considered practical for use with the autonomous approach. Ground control is recommended for all other stationkeeping operations between unmanned elements. In fact, if possible, even pre-mating operations between unmanned elements should be scheduled/conducted during periods of available ground contact.

The applicability of the autonomous approach to manned elements is a function of the range between the elements. At close ranges this approach is preferred for safety reasons. The accuracies obtainable with the other two approaches are not considered to be adequate for close proximity manned operations. However, at long range the accuracies that would be realizable with reasonable on board equipment, although adequate, are less than what can be readily obtained by ground control. Also, at long ranges there is no need for frequent communication contacts/tracking of the elements involved. The primary justification for an autonomous approach is the requirement for frequent or continuous determination of the relative position of the elements involved. Autonomous operations is not applicable for beyond line-of-sight because by definition it requires a ground link.

The design influences associated with autonomous operations are directly related to the element separation range. At close ranges either a video or laser technique is adequate. The laser concept is preferred because of the increased accuracies and direct readout capability, which can reduce the tasks of the crew. At long ranges more complex scan and trade systems are required for autonomous operations.

Table 3-3. Stationkeeping Approach Evaluation Criteria

	Modes								Operating Range			Design Impacts/Complexity							Relative Cost			
	Detached Operations		Inspection		Premate		Quiescent Storage		Close Proximity	Long	Beyond LOS	Close Proximity	Long	Beyond LOS	State Vector Update	Computer Capacity	C/O & Maintenance	Technology	Development		Operational	
	M	U	M	U	M	U	NA	U											M	U	M	U
Autonomous	✓		✓		✓				Best	Fair	--	Low	High	--	High	--	Med	SOA	Med	--	Low	--
Ground ** Control	✓	✓		✓		✓		✓	Good	Best	Best	Med	Low	Low	Low	Low	Low	SOA	Low	Low	Med	Med
Space Control	✓	✓		✓		✓			Fair	Good*	Limited*	Med*	Med*	Med*	Low*	Low*	Low*	SOA	Hi	Hi	Hi	Hi

*Requires complexity on control element **Assumes operation is conducted within contact of ground control (TDRS)

State vector determination by a manned element is a well proven and demonstrated technique. Utilizing the attitude determination sensors for this function minimizes the impact on the space element; however, additional on-board computer complexity is required.

Additional equipment is obviously needed to implement the autonomous approach. Although the equipment required is considered to be state-of-the art (including the laser radar), there is a definite delta requirement of checkout and maintenance.

The primary factor influencing the development cost is the laser radar. It would be difficult to justify a laser system solely for stationkeeping operations. However, the versatility of the system permits improved performance and safety in rendezvous and mating. Provisions for manual override must also be included. Thus, pilot simulation and training activities with visual aids must be considered in the development cost evaluation. Although manual control is available, the preferred nominal mode of operation would be an automatic laser system. Thus, operational costs are considered to be low because the astronauts on-orbit time is not required to do the routine stationkeeping tasks.

Ground control of the stationkeeping activity is applicable for all modes of operation. However, at close ranges when manned elements are involved, the inherent increased accuracy requirements, real-time decision flexibility, and safety considerations tend to eliminate ground control as a practical option. At long range ground control is preferred because of the characteristics of the ground network. Accuracy and communication contact requirements are not stringent. Ground network capabilities are well within the required limits. On-board equipment to interface with the ground network is relatively simple and has been demonstrated on previous space programs.

Ground control does not relieve the need for element-to-element range and range rate determination by the elements involved for close proximity operations (less than 10 nautical miles). Ground station measurement accuracies would not be sufficient to ensure mission safety, thus necessitating element-to-element range and range rate data transfer to ground control over the communication links. This data would be processed through ground computers and necessary commands transmitted to the on-orbit elements. Thus, except for the computer concept, the orbital element equipment requirements are basically the same for the autonomous and the ground control approach. The complexity of operations results from the inherent gaps in communications, the problem of remote control, and the intricacies of control handover between ground stations.

Utilizing standard tracking and ranging techniques between the ground network and transponder equipped stationkeeping elements, state vector determination can be readily derived by the ground network. On-board computer complexity is minimized. Thus across the entire spectrum of stationkeeping ranges the ground control approach impacts the checkout and maintenance requirements of the orbital elements the least. No advanced technology is required.

Development costs associated with the orbital elements are lower than the autonomous case primarily because of the decrease in computer and software complexity. Operational costs are considered to be slightly higher because of the continuing requirement for ground support for the duration of the mission.

The space control approach in essence requires the incorporation of the ground control capabilities in an orbital element. This includes transmitters, antennas, video monitoring, and computer programs. Although the stationkeeping elements could be comparable for the ground or space control approach, the impact on the space control element is severe. Quite possibly directional antennas would be required on the space control element, especially if the two stationkeeping elements are not within line-of-sight of each other but are within LOS of the controlling element.

The space control approach, although state-of-the-art, imposes the severest penalties in all areas of design requirements, complexity, checkout and maintenance, and costs for orbital elements.

PREFERRED APPROACH SELECTION

Based upon the above considerations each element pair that will conduct stationkeeping operations was analyzed to identify a preferred approach. Table 3-4 summaries these analyses.

Examination of the element pairs and the potential stationkeeping operations that may occur between elements indicated that the predominant mode was either inspection or premating (close proximity). For all element pairs involving manned elements operating in close proximity the autonomous mode was selected. If two unmanned elements were involved, regardless of range, the ground control approach, supplemented by active element range and range rate measurements, was preferred.

There were a few cases where space control was considered. For example, an EOS controlling a tug/RAM or tug/satellite combination was considered but the design impact on the shuttle was not warranted. The stationkeeping operation would be either an inspection or post rendezvous/premating operation. In either case it was determined that ground control was the most efficient-least complex approach.

One unique long range stationkeeping operation was identified. Detached RAM's associated with the MSS could operate at considerable range from the MSS. Normally the approach would be for ground control to direct the operation. However, the mission concept is based upon the MSS directing the activities of the RAM. (Otherise, the RAM should be considered an EOS delivered/serviced/retrieved element controlled by ground.) Therefore, the autonomous approach was selected for this element pair also. This imposes the requirement on the MSS to range, track, and determine the state vector of the RAM. In all other autonomous stationkeeping operations only the relative position of the elements involved were required to be determined.

Table 3-4. Stationkeeping Preferred Approach Selection

Element Pair	Preferred Approach	Rationale
EOS-- EOS, Tug, RAM, MSS, Satellite, CPS, RNS, OPD, OLS	Autonomous	Manned elements and close range stationkeeping provides the desired flexibility, safety and "quick reactions" provided by the manned operators.
Tug (Manned)-- Man/Unman Tug, MSS, RAM, Satellite, OPD, CPS, RNS, OLS	Autonomous	Same rationale as above.
Tug (Unmanned)-- RAM, Satellite, CPS, RNS, OPD, Unman Tug	Ground Controlled	For safety reasons, close range operations can be enhanced by ground control supplemented by on-board element range/range-rate data.
MSS-- Tug, EOS, RAM	Autonomous	Same as EOS autonomous rationale.
OPD-- CPS, RNS (Man) CPS, RNS (Unman)	Autonomous Ground Controlled	Same rationale Same as Tug Ground Controlled approach.

DESIGN INFLUENCES

Based upon the preferred approach selections for stationkeeping the design influences on the potential elements involved are summarized in Table 3-5. Note that they reflect stationkeeping requirements only. For example, independent state vector determination is not listed for the EOS. It was a requirement for rendezvous.

Laser scanning radar is recommended for all active elements for mission safety reasons during close proximity operations except the RAM. The MSS includes the laser for operation in conjunction with detached RAM's. Thus all elements that stationkeep with the RAM have a laser.

Video (TV) was identified as a requirement for stationkeeping solely for inspection purposes. It could be made a kit but basic provisions should be incorporated because of the high frequency of "inspection" operations prior to mating.

Both command and data transfer requirements can be accommodated by S-band omni equipment on the elements. All elements involved in stationkeeping include this type of equipment. In addition all elements that are either controlled or are the target require S-band transponders.

Table 3-5. Stationkeeping Design Influences

Primary Element	Preferred Approach/Design Influence
EOS	Autonomous Stationkeeping Operations Video (TV) inspection capability, S-Band omni data links Passive laser reflectors Laser scanning radar
Tug (Manned)	Autonomous Stationkeeping Operations Video (TV) inspection capability, S-Band omni data links Passive laser reflectors Laser scanning radar
Tug (Unmanned)	Ground Control Stationkeeping Operations Video (TV) inspection capability, S-Band omni data links Passive laser reflectors Laser scanning radar
MSS	Autonomous Stationkeeping Operations Independent state vector determination Target vehicle state vector determination capability Video (TV) inspection capability, S-Band omni data links Detached element control capability Passive laser reflectors Laser scanning radar
CPS/RNS	Autonomous Stationkeeping Operations Video (TV) inspection capability, S-Band omni data links Passive laser reflectors Laser scanning radar
All Other Elements (including RAM)	Autonomous and Ground Control Stationkeeping Target Operations Passive laser reflector, S-Band omni data links

4.0 DETACHED ELEMENTS OPERATIONS

Detached element operations encompass all element-to-element interfacing support necessary to operate a spatial element that is separated from its control center. Either an orbital element or a ground station can be employed as the operational control center.

There is a significant interrelationship between this activity and communications, rendezvous, and stationkeeping. Communications treated the link geometry and hardware concepts for transferring of data. Rendezvous and stationkeeping were concerned with the generation and use of specific types of data. Detached element operations are concerned with the required data transfer rates for space experiment/application operations as well as rendezvous and stationkeeping operations. Communication link constraints superimposed upon the potential data transfer options are important considerations in evaluating the feasibility of detached element operations.

4.1 SUMMARY

Evaluation of the mission models and element pair interactions presented in Volume 1 of this report indicated that there were a total of 54 detached element operation interactions. The EOS and tug are involved in 17 and 28 of these interactions, respectively. Exclusive of these, the MSS is involved in 4 and cislunar shuttle in the remaining 5. In most of the cases the principal interface is low data rates associated with rendezvous and/or stationkeeping operations. High data rates involve detached RAM's and satellites. Only the EOS sortie mission does not involve some type of detached element operations.

Two general approaches are evaluated: (1) ground operations and control and (2) space operations and control. The ground control approach was further subdivided into three options: (1) direct from element to ground, (2) via another orbiting element to ground, and (3) via TDRS to ground. Procedures for each of these approaches were developed to assist in identifying detailed function requirements. The significant differences between the approaches were all associated with the required orbital element equipment complements.

The data transfer requirements ranged from 1 kbps to 10 Mbps. Very high frequency links are adequate to 10 kbps, S-band links to 1 Mbps, and Ku-band links (with directional antennas) to 10 Mbps. Continuous data communication was impractical in almost all cases. Data storage concepts were evaluated to establish the feasibility of delayed data dumps. Current magnetic tape concepts are adequate. Laser systems that are currently being developed will provide margin and growth potential.

The evaluation of the approaches and the preferred concept for each element pair were primarily dependent upon the required data transfer rates, contact duration, the extent of real-time support requirements, and manning status of the elements. Low data rates (10 kbps) associated with rendezvous and stationkeeping can be adequately handled by the direct-to-ground approach for EOS, tug, CPS, and RNS operations at long ranges. At short range (<75 n mi), unmanned element operations would utilize one of the elements as a relay to ground control. For manned operations at short ranges, space control by one of the elements is preferred.

High data rates were identified for satellite and RAM operations. In the case of the EOS-RAM interface, only the capability of the EOS links to ground, established for other activities (S-band, 1 Mbps), is proposed for RAM data transfer purposes. Any additional requirements should be met either integrally in the RAM or in kit form on the EOS and considered to be part of the RAM. Imposing the requirement for a Ku-band (with directional antenna) or complex and bulky data storage equipment in the baseline EOS for a comparatively rare interface operation is not warranted.

Accommodation of high data transfer rates between the MSS and RAM are warranted. If the RAM is operating in conjunction with the MSS the basic concept is that the MSS will process the RAM-generated data. Also, the MSS-RAM complex is expected to consist of more than just one RAM. The multiple free-flying RAMs in conjunction with both the integral and attached RAM operations will impose the requirement for an MSS-TDRS link. Therefore, the unique impact is only on the high data rate producing RAM. S-band (omni antenna) would be used for data transfer between a RAM and MSS provided the data rates are $\leq$ 1 Mbps.

Depending upon the data transfer rates that a satellite requires, either direct to ground (S-band omni) or via TDRS (Ku-band directional) is recommended. No operational interface - except rendezvous and stationkeeping - was recommended between satellites and other orbiting elements.

The paramount conclusion from the analysis of detached operations is the very strong requirement for data compression. Past space programs have been able to operate in conjunction with ground control with respect to data transfer in a dedicated mode. The proliferation of unrelated orbital elements and operations within the next 15 to 20 years will saturate any reasonable ground network. Limitations on measurements and sample rates must become more stringent. Incorporation of techniques that will limit data transfer to only significant deltas from previous readings are highly recommended. Temporary data storage of these increments for future high rate playback (data dump) will become more imperative as space traffic increases. Communication gaps and limited data channels will impose data compression, storage, and high rate playback requirements on almost all orbit stationed elements.

4.2 ELEMENT INTERFACE AND MISSION MODEL MATRICES

Detached element operations interactions between the orbital elements under consideration in this study are indicated in the matrix shown in Figure 4-1. Fifty-four element-to-element interactions are identified. Most of these occur as interfaces with the EOS orbiter (17), the ground-based tug (10), and the space-based tug (13). Potential interactions warranting specific explorations are enumerated below.

1. There are no interactions between the orbiter, ground-based or space-based tugs and resupply modules or the lunar surface base (LSB). Neither the resupply modules nor the LSB are manned, activated, or checked out in a detached mode.

2. None of the tugs have a detached operation interaction with satellites during initial delivery or deployment. By definition, the satellite is activated, monitored, and controlled by ground. However, both the ground-based tug and the space-based tug will conduct detached operations with satellites during retrieval, inspection, and resupply operations.

3. The only detached element operations involving an orbital insertion stage (OIS) occur between the OIS and a space-based tug. These interactions can occur either during (1) a tug logistics mission (Mission Model 5) when the tug rendezvous with the OIS, and after inspecting it, mates with the payload the OIS has boosted to earth orbit and continues the mission, or during (2) a disposal mission (Mission Model 6) wherein the tug rendezvous with the OIS, inspects it before mating, and then conducts a retrograde burn to deorbit the OIS.

4. Detached element operations interactions between two identical CPS vehicles occur either during a rescue mission or when the two stages are being mated for the purpose of forming a two-stage CPS vehicle for the purpose of transporting large payloads to geosynchronous or lunar orbits.

5. Detached element operations interactions between unmanned lunar tugs and other orbital elements occur during its mating to and assembly of a cislunar shuttle.

6. Detached element operations interactions between manned lunar tugs and other orbital elements can occur either during delivery sequence or during a rescue mission, where the tug in question has been employed as a lunar escape vehicle.

To provide traceability back to the mission model data, a matrix that identifies the mission models associated with each of the 54 detached element operations interactions is presented in Figure 4-2. Detached element operations interactions occur in all mission models except MM-3, EOS sortie mission. In this mission there are no detached elements.

		SPACE VEHICLE INVENTORY																								
		EOS	TUG				RAM				SATELLITE			EO RESUP MODS	MSS		CPS			RNS	LUNAR PROGRAM SYSTEMS					OPD
			NON RET	RTN	GRD BASED	SPACE BASED	ATT. EOS	DET. EOS	ATT. MSS	DET. MSS	EOS DELIV	EOS + 3RD ST	RETR, RESUP		LOW EO	GEO SYNCH	OIS	EO SHTL	CLS		OLS	TUG UNMAN	TUG MAN	RESUP MOD	LSB	
	EOS	D	D	D	D	D	X	D	X	D	D	D	D	X		X	▨	D	D	D	D	D	D	X	X	D
TUG	NON RET		▨	▨	▨	▨	▨	▨	▨	▨	▨	X	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
	RETURNABLE			▨	▨	▨	▨	▨	▨	▨	▨	X	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
	GRD BASED				D	D	▨	▨	X	D	▨	X	D	X	▨	D	▨	D	D	D	▨	D	D	X	▨	X
	SPACE BASED					D	▨	▨	X	D	▨	X	D	X	D	D	D	D	D	D	D	D	D	X	X	D
RAM	ATT. EOS						▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
	DET. EOS							▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
	ATT. MSS								▨	▨	▨	▨	▨	▨	X	X	▨	X	▨	X	▨	▨	▨	▨	▨	▨
	DET. MSS									▨	▨	▨	▨	▨	D	D	▨	X	▨	X	▨	▨	▨	▨	▨	▨
SATEL	EOS DELIV										▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
	EOS + 3RD ST											▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
	RETR, RESUP												▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
	EO RESUP MODS													X	X	X	▨	X	X	X	▨	X	X	X	▨	X
MSS	LOW EO														X	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
	GEOSYNCH															X	▨	D	▨	D	▨	▨	▨	▨	▨	▨
CPS	OIS																▨	X	X	X	X	▨	▨	▨	▨	X
	EO SHTL																	D	▨	▨	▨	▨	▨	▨	▨	D
	CLS																		D	▨	X	D	D	X	X	D
	RNS																			X	X	D	D	X	X	D
LPS	OLS																				X	X	D	X	▨	▨
	TUG UNMAN																					▨	▨	X	X	X
	TUG MAN																						▨	X	X	X
	RESUP MOD																							X	X	X
	LSB																								X	▨
	OPD																									X

LEGEND

Potential Interactions	117
Actual Interactions	54
D - Detached Support	54
X - Not Applicable	63

Figure 4-1. Detached Element Operations Interactions

		SPACE VEHICLE INVENTORY																								
		EOS	TUG				RAM				SATELLITE			EO RESUP MODS	MSS		CPS			RNS	LUNAR PROGRAM SYSTEMS					OPD
			NON RET	RTN	GRD BASED	SPACE BASED	ATT. EOS	DET. EOS	ATT. MSS	DET. MSS	EOS DELIV	EOS + 3RD ST	RETR, RESUP		LOW EO	GEO SYNCH	OIS	EO SHTL	CLS		OLS	TUG UNMAN	TUG MAN	RESUP MOD	LSB	
	EOS	2	1	2	2,7,8	1,2,4,5	☒	1,2	☒	1,2	1	1	2	☒	1,2	☒	▨	1,2, 10,11	1,2, 10,11	1,2,11	1,2	2	2	☒	☒	1,2
TUG	NON RET		▨	▨	▨	▨	▨	▨	▨	▨	▨	☒	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
	RETURNABLE			▨	▨	▨	▨	▨	▨	▨	▨	☒	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
	GRD BASED				8	5,8	▨	▨	☒	7,8	▨	☒	8	☒	▨	7,8	▨	8,10,11	8,10,11	8,11	▨	8	8	☒	▨	☒
	SPACE BASED					4,5	▨	▨	☒	4,5	▨	☒	4,5	☒	4,5	4,5	5,6,9	4,5,6 10,11	4,5,6 10,11	4,5, 6,11	4,5	5	4,5	☒	☒	4,5,6
RAM	ATT. EOS						▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
	DET. EOS							▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
	ATT. MSS								▨	▨	▨	▨	▨	▨	☒	☒	▨	☒	▨	☒	▨	▨	▨	▨	▨	▨
	DET. MSS									▨	▨	▨	▨	▨	1,2,5	4,5,7,8	▨	☒	▨	☒	▨	▨	▨	▨	▨	▨
SATEL	EOS DELIV										▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
	EOS + 3RD ST											▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
	RETR, RESUP												▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
	EO. RESUP MODS													☒	☒	☒	▨	☒	☒	☒	▨	☒	☒	☒	▨	☒
MSS	LOW EO														☒	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
	GEOSYNCH															☒	▨	10,11	▨	11	▨	▨	▨	▨	▨	▨
CPS	OIS																▨	☒	☒	☒	☒	▨	▨	▨	▨	☒
	EO SHTL																	10	▨	▨	▨	▨	▨	▨	▨	10,11
	CLS																		10	▨	☒	10,11	10,11	☒	☒	10,11
	RNS																			☒	☒	11	11	☒	☒	11
LPS	OLS																				☒	☒	☒	☒	▨	▨
	TUG UNMAN																					▨	▨	☒	☒	☒
	TUG MAN																						▨	☒	☒	☒
	RESUP MOD																							☒	☒	☒
	LSB																								☒	▨
	OPD																									☒

Figure 4-2. Applicable Mission Models for Detached Element Operations

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4.3 ALTERNATE APPROACHES

Alternate approaches for detached element operations may be grouped into two major categories: (1) ground operations and control, and (2) space operations and control.

Ground operations and control directs detached element operations from the ground system either by direct contact or by a communication relay link. Space operations and control provides operational support directly via communications space links from one space element to the detached element. Details of these alternates are discussed in the following paragraphs.

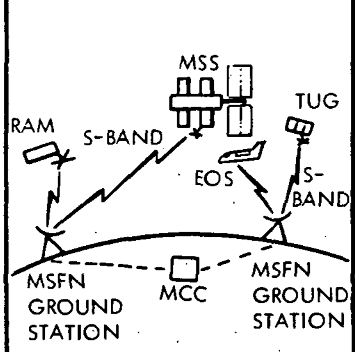
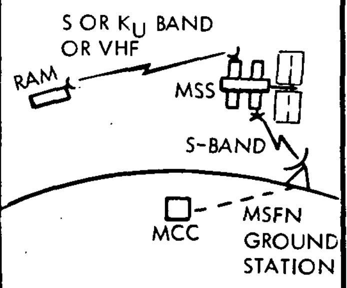
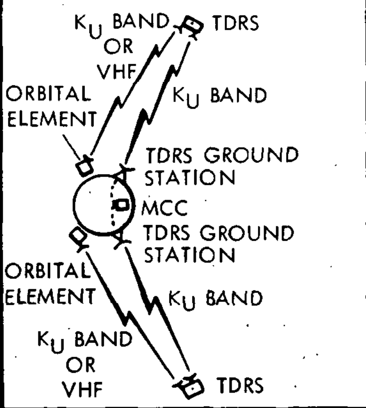
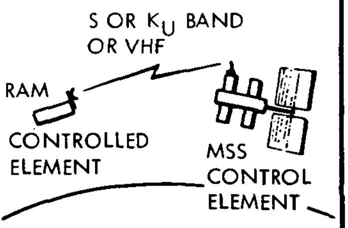
	GROUND OPERATIONS AND CONTROL			SPACE OPERATIONS AND CONTROL
	I TYPICAL EXAMPLE 	II TYPICAL EXAMPLE 	III 	IV TYPICAL EXAMPLE 
	DIRECT FROM GROUND	GROUND TO ELEMENT VIA A RELAY ELEMENT	GROUND TO ELEMENT VIA TDRS	ELEMENT TO ELEMENT
CONSIDERATIONS	LIMITED VIEWING TIME MOST ACCURATE TRACKING/ RANGING LIMITED DATA DUMP CAPABILITY	CONTINUOUS VIEWING TIME REDUCED TRACKING/ RANGING ACCURACY AT LONGER DISTANCES ADDED RELAY MECHANIZATION REQUIREMENT ADDITIONAL FREQUENCY POSSIBLE RECORD AND DUMP CAPABILITY POSSIBLE INCREASED DATA TRANSMISSION CAPABILITY IN RELAY ELEMENT	ALMOST CONTINUOUS VIEWING TRACKING/RANGING DEGRADED FROM DIRECT BUT PROBABLY SATISFACTORY FOR MOST USES. ADDITIONAL FREQUENCY PROVIDES HIGH DATA RATE CAPABILITY MAXIMUM DATA DUMP CAPABILITY	CONTINUOUS VIEWING REDUCED TRACKING/ RANGING ACCURACY AT LONGER RANGES NEED MONITOR OF OPERATIONS AND UPDATE OF TRACKING/ RANGING FROM GROUND CONTROL ELEMENT MUST BE MANNED FOR FULL OPERATIONAL CAPABILITY NEED RECORD AND DUMP CAPABILITY NEED ON BOARD DATA PROCESSING

Figure 4-3. Operations and Control Alternatives

GROUND OPERATIONS AND CONTROL

Figure 4-3 illustrates the three communications links that may be used for ground operations and control of the detached elements. Each of the communication link alternates presents certain limitations to full operational support. A combination of links will be required to provide full support. The combination of direct from ground (Link I) and ground to detached element via the TDRS (Link III) can support the operation efficiently. Direct ground to detached element contact is necessary on a regular basis to establish accurate ephemerides of the detached element when a requirement for periodic transfer of large quantities of data exists; the use of the TDRS as a relay element appears attractive to provide a near-continuous communication link. A combination of these links can provide the necessary control and operations of the detached element. Utilization of another orbital space element as a relay imposes additional functional requirements on that element. Such operation is considered necessary for some interfacing activities such as rendezvous or stationkeeping. In these cases, all communications with the element pair flows from ground through one of the elements.

SPACE OPERATIONS AND CONTROL

Space operations and control is implemented by a direct communications space link from one space element to the detached element. Figure 4-3, Link IV, illustrates a typical detached element operation, MSS-to-RAM. All operations support to the RAM is provided by the MSS. In this example, the controlling element requires a manned element to provide full operational capability. Man is necessary to implement the control and operations at the proper time to provide interpretation of received data, to monitor data, and to perform checkout functions. The MSS remains in continuous line of sight with the detached element and thus can easily provide for direct control, reception of data, ranging and tracking, monitoring and checkout of detached element systems, and visual or video inspection. Such support necessitates on-board data processing and displays. One of the considerations is the accuracy of ranging and tracking data in providing accurate ephemerides. The accuracy of the position of the controlling element (MSS, in this example) enters into the detached element position accuracy. For most applications, sufficient tracking/ranging accuracy can be directly provided by the controlling element. Even in this type operation, it is considered advisable to provide backup and monitoring of operations from ground.

4.4 DESIGN CONCEPT MODELS

Hardware concepts for detached element operations involve the implementation of the communications interface function, the requirement to store, process and transfer large quantities of data to ground and the visual inspection function. Communications design concepts are covered in detail in Section 1, Communications. Element-to-element communications are provided by element receiver/transmitter terminals operating in either VHF, S and/or Ku frequency bands. Compatibility with ground operations was the major influence in these choices. S-band is a direct-to-ground network requirement. Very high frequency and Ku-band is necessary when operation with TDRS is required. These frequencies are consistent with the NASA/MSC ground network and synchronous relay satellite model (see DS-504). Use of TDRS must be considered when continuous or near-continuous communications are necessary. TDRS is also necessary when data transfer rates to ground exceeding 1 to 5 Mbps are required, either in real time or in delayed data dump mode. The ground network is limited presently to a 1 Mbps data rate. It may have the future capability for 5 Mbps. TDRS will be capable of handling 50 Mbps in one of its two Ku-band channels. Continuity of communications by voice or low data rates (1 to 10 kbps) can be implemented on VHF with the TDRS. Table 4-1 indicates some typical data dump and communications continuity available from ground network direct, or TDRS when high data rates are necessary. Data dump for ground direct is further inhibited for data transfer to the switching center by the limitation of 72 kbps lines from remote stations.

It is apparent that TDRS provides an order of magnitude capability improvement over the ground network. RAM and MSS must use TDRS to provide data transfer imposed by experiments. Other elements must be analyzed to ensure whether such a need, either for continuity or data rate is required.

Although TDRS or ground direct may be able to support most missions, an alternate concept is recommended as supplement to provide data transfer of large quantities. Use of a recorder system with physical recovery of stored data as well as communications data dump can relieve the time usage of the communications links. Both ground and TDRS must be time-shared among many elements. Provisions should be made for a data recorder with removable stored increments of data on board the space element. These increments can then be transported to ground on regular logistics flights. Recorded data would be that data that does not need real-time transfer to ground. Many experiments fall in this category. In many cases, partial data can be transmitted real time and the remainder stored for either later dump or transport.

Table 4-1. TDRS/Ground Network Coverage Comparison

Parameter	Ground Network (1)		TDRS Network (2)
	Orbits		Orbits
	90°/100 n mi	55°/240 n mi	90°/100 n mi or 55°/240 n mi
Percent of orbit coverage	3.2 percent	10.3 percent	$>$ 90 percent
Maximum gap between contacts	6 hr, 30 min.	7 hr, 15 min.	
Average contact	3.2 min.	6.0 min.	
Data sink capacity/orbit	5.0×10^{8} bits	1.7×10^{9} bits	$\hat{=} 2.5 \times 10^{11}$ bits
Line capacity to switching center			
Real time	1.3×10^{7} bits/day	4.2×10^{7} bits/day	4.0×10^{12}
Post pass (3)	1.5×10^{9}	1.6×10^{9}	Not applicable

(1) Goldstone, Madrid, Honeysuckle Creek, Rosman and Fairbanks ground stations per NASA model

(2) Two TDRS satellites, equatorial orbit at 15° and 145°W. Ground station located next to switching center

(3) Assumes recording and dump at ground stations

Two systems were analyzed for data storage, magnetic tape recorders and laser-type recorders. Magnetic tape recorders are available presently that can store 54 x 10^9 bits on a 9200-foot reel of 1-inch wide magnetic tape. Data can be recorded and dumped at 30 Mbps rate. These recorders use 21 tracks per inch of width and record at a track density of 24 kilobits per track inch. Recorders are in development that will increase the track density to 50 kilobits per inch. Use of magnetic tape recorders with reasonable size reels will provide sufficient capacity in feasible volume and weight to be logistically handled. This technique is recommended for data storage. Figure 4-4 illustrates the quantity of reels needed for different amounts of data. This assumes 10-inch, 1200-foot, 1-inch wide tape reels in cassette form, environment protected for easy handling.

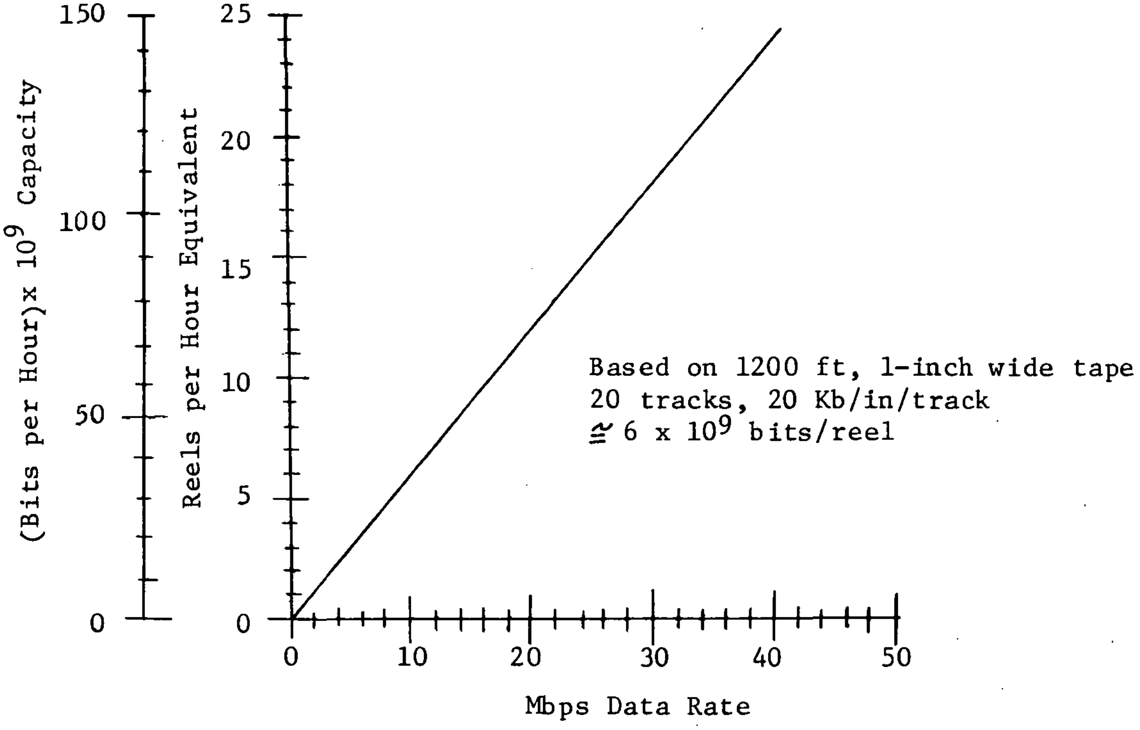


Figure 4-4. Equivalent Magnetic Tape Use versus Data Rate

This figure may be used to translate quantities of data to number of reels using columns A and B. It provides a quick idea of how many reels are filled per hour by the collection data rate of abcissa "C" or how many reels of data can be dumped per hour at various data rates. These calculations were used to determine RAM and MSS data storage and dump requirements found in the requirements section arranged by element pairs.

Visual inspection was assumed to be performed using television cameras appropriately placed on the inspecting vehicle. This could be either on a boom or at a docking port with remote control of pointing and focus available to the operator. The inspection operation is supported by the stationkeeping interfacing activity and communication links for remote control and remote viewing when the inspecting element is unmanned.

TRADE STUDY

As mentioned previously, a trade was performed to define the data storage medium. Two candidates, magnetic tape and laser recording on metallic-coated mylar film,were analyzed for use. It was determined that magnetic tape recorders with sufficient capacity will be available for orbital operation missions. Present recorders can provide densities of approximately 0.5×10^6 bits per square inch of tape. In the near future (presently in laboratory development), 1×10^6 bits per square inch will be available. These recorders are simple to operate, can provide the necessary life, and will be economically practical.

Laser recorders, using a laser beam to vaporize a rhodium coating on a mylar film, are being developed. This system projects equipment that uses 16 mm coated film that needs no photographic processing. The data are contained in the presence or absence of a hole (3×10^{-6} meters diameter) burned in the metallic coating. The hole presence represents a "1" digital bit, absence a "0". Very high densities can be obtained and the result is a permanent recording impervious to some of the environmental conditions (radiation, magnetic fields) that the magnetic tape must be protected from. Information densities of 13×10^6 bits per square inch are possible with lasers. This compares to the 1×10^6 bits per square inch projected for magnetic tape recordings. It appears that a laser system such as described above would provide significant advantages over the magnetic recorder. The problem foreseen is the development cost and the low probability that this system would be developed for space use in the time frame for these operations (1975-1980). It should seriously be considered for ground data storage where huge quantities of data will need to be stored when many of the projected orbital satellites are in operation.

4.5 OPERATIONAL PROCEDURES

Detached element operations involve those operational support activities provided by a controlling and/or supporting element (ground or space element) to a separated or detached element in space. In all cases, a communication link provides the interface between the elements. Alternate concepts revolve around the nature of the supporting element, which may be grouped into two major categories, ground operations and control, and space operations and control. Existing space networks involve entirely direct links and interfaces between a detached space element and the ground network system. Other ground-controlled situations may involve a relay space element. Thus, detached element operations directed from the ground system through another space element acting only as a relay involve links and interfaces between the two space elements and between the relay element and the ground. When the relay element is a TDRS, similar procedures are involved, but the TDRS is given an important role in the operational functions supporting the detached element, and a new design TDRS ground station is included. The concept of space operation and control involves a direct link for space element to detached element operations. The operational procedures for the four operations, (1) direct with ground, (2) ground via a space element, (3) ground via TDRS, and (4) element-to-element, are defined in detail in Appendix B.

Element pair applicability is discussed in further detail in Appendix B, and the Element Pair Applicability Matrix is also included therein. Of the 17 element listed, at least 5 are potential controlling elements and 15 are controlled elements. Most of the interactions involve the EOS orbiter (15) and the space-based tug (11). A total of 29 interfaces are projected. These numbers (or the matrix) does not include interface with ground or TDRS. Only space orbital elements were considered. The matrix will therefore only show Procedure 13-4 for space operations and control. Other pairs that include operating with ground are included in rendezvous and stationkeeping.

Figure 4-5 presents a summarized flow diagram of the procedures for conducting detached element operations using the direct-to-ground approach. Each of those functions must also be performed in the approaches. By substituting "control center" for "GND" in the blocks, the operations are applicable for all the approaches. The design implications on the orbital elements vary considerably with the approach. These implications are examined in more detail in subsequent parts of this section as well as in Section 1 - Communications, Section 2 - Rendezvous, and Section 3 - Stationkeeping.

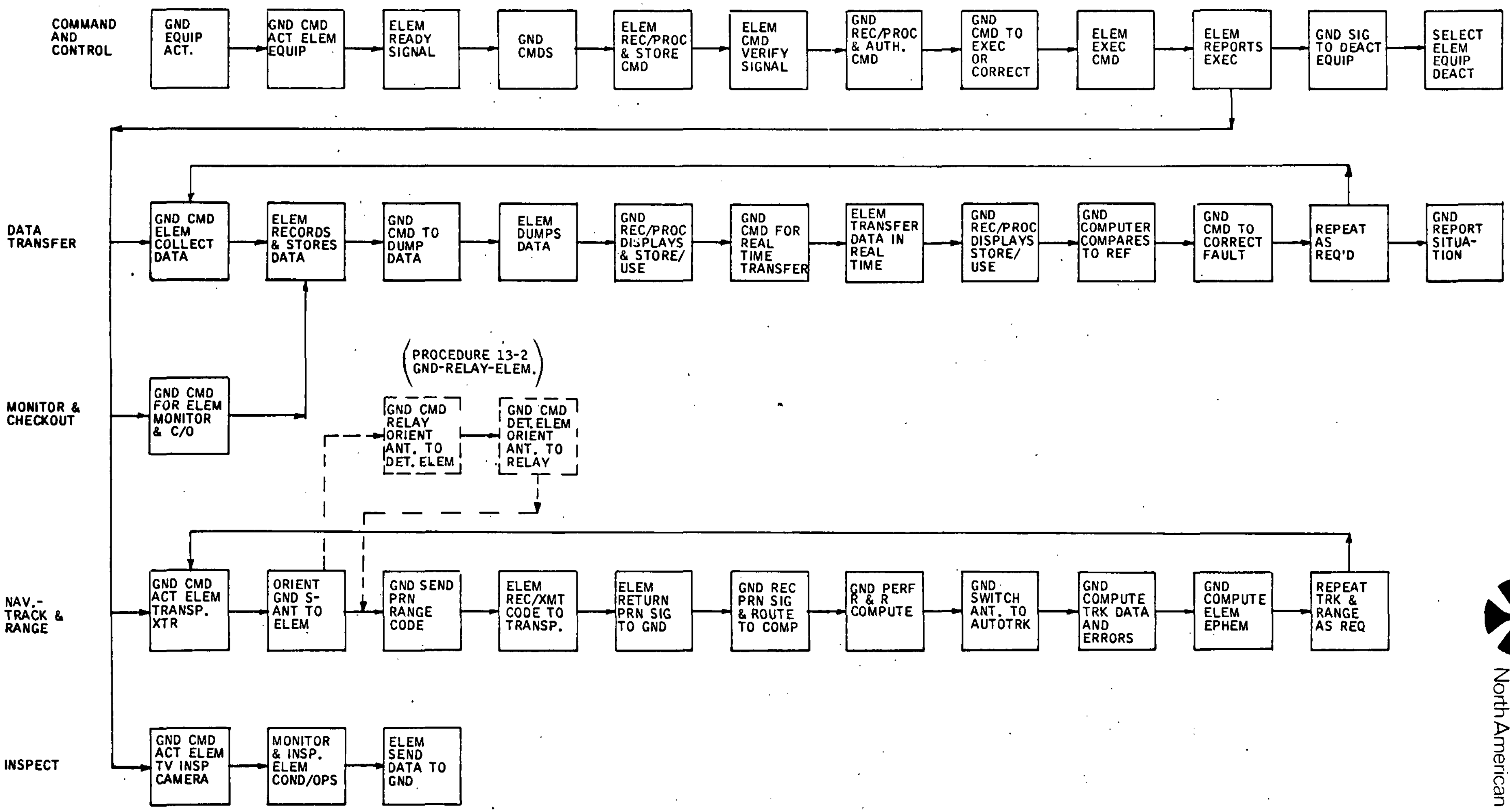


Figure 4-5. Operational Procedure Logic

4.6 FUNCTIONAL REQUIREMENTS

General functional requirements, requirements by element pairs and quantitative data analyses are presented in this section. Functional requirements include:

1. Command and control data
2. Collection, processing, recording, and/or dump of data
3. Monitoring and checkout data and display requirements
4. Establishment of orbital parameters and ephemerides
5. Visual or TV inspection of the detached element

These are essentially the same for either ground or space operations and control alternate approaches. The first subsection herein defines the general requirements and their application to the four procedures. The second subsection groups these requirements into closely related requirements that are defined for application to individual element pair combinations. These tables include quantitative data developed for application to other interfacing activities (communications) and from other activities (rendezvous, stationkeeping). The final subsection briefly states the analyses performed to arrive at the quantitative data presented.

Table 4-2, Functional Requirements Definition, defines each of the major detached element operations in terms of element system requirements, requirement's representative characteristics, and typical applications. This table can serve as a basic reminder of the requirements to be accommodated in detached element operations.

Table 4-2. Functional Requirements Definition

Functional Requirements		System Requirements	Representative Characteristics	Typical Application
Command and Control	Element command	Transmission of low data rate command data	Up to 10 Kbps digital data	Solar array pointing, element attitude control, element equipment control, element activation, antenna pointing, deorbit commands, element positioning
	Experiment control	Transmission of low data rate command data	Up to 10 Kbps digital data	Sensor attitude control sensor equipment control and operation
Performance Monitoring and Checkout	Systems monitoring (element and experiment)	Reception of medium rate telemetry data processing and display of data	Up to 50 Kbps digital data	Subsystem equipment monitoring, subsystem status, processing as necessary to display parameters
	Systems checkout (element and experiment)	Reception of medium rate instrumentation data-processing, comparison, display of data	Up to 50 Kbps digital data	Complete checkout of subsystem to determine health or to isolate faults—requires on-board computer for data reference plus element-to-element computer compatibility
Data Collection Data Transfer	Data record and dump	On-board data recording of experiment data and dump to ground or other element	High data rate data 50 Mbps and large quantities of data >7.2 x 10^9 Bits per day	Data from various experiment sensors and/or combinations thereof
	Voice communication	Aural data transfer	Up to three channels; 300-4000 Hz analog voice	Voice communications between element and ground, element-to-element--provisions for conference, duplex operation

Table 4-2. Functional Requirements Definition (Continued)

Functional Requirements		System Requirements	Representative Characteristics	Typical Application
Data Collection Data Transfer	Real-time data transfer	Transmission of real-time experiment data	Possibly >5 Mbps digital data	Experiment sensor data for real-time activities, needs either ground or space element collection point with capability to process and interpret data
	Video data transfer (experiments)	Transmission of black and white or color television	Analog signals 2.9 MHz baseband or 4.5 MHz baseband	Multispectral camera experiment data, picture transmission, docking, remote pictures
Navigation Data	Element tracking	Capability to acquire and track another element	Determine angular position of element from reference-	Requires either narrow beam antenna with tracking capability or some interferometer technique
	Element ranging	Capability to perform ranging function and provide turn around ranging	Range accuracy at $\leq$ 30 ft RMS Range rate measurement $\leq$ 0.2 FPS RMS at 4000 n mi	Determination of orbital parameters and ephemerides of element
Visual/Video Inspection	Video data transfer	Transmission of black and white television	$\cong$ 2.9 MHz baseband analog signals	Pictures of element from inspecting element camera

FUNCTIONAL REQUIREMENTS TABULAR LIST

This subsection defines by generic functional requirement the definition of the requirement qualitatively and/or quantitatively that supports detached element operations. Each requirement identifies its application to the procedures developed for each approach. It should be noted that out of the 16 requirements only two do not apply to all approaches or procedures. These both are specific to particular approaches. Item 13 defines the necessity for the space control element to determine its own orbital position and ephemerides. It applies only to the space operations and control alternate. Item 16 defines the requirement for a handover system when TDRS and the ground network are being used in the ground operations and control alternates.

	RELATED PROCEDURE			
	DIRECT WITH GROUND	WITH GROUND VIA RELAY ELEMENT	WITH GROUND VIA TDRS	CONTROL BY SPACE ELEMENT
	13-1	13-2	13-3	13-4
1. The system shall incorporate a means of commanding and controlling the detached element via communication link. Commands vary from 1 kbps for most unmanned spacecraft and manned spacecraft.	X	X	X	X
2. A means shall be provided in the detached element for processing and storing operations commands and for transmitting verification signals for authentication and execution authority and operation-executed signals/data. Operations commands will be transmitted to the user element from the controlling element for execution. Such received signals must be processed before it can be used for operations. A digital data storage device will be needed on the controlled element to hold the command data while the verification process is proceeding. Verification may consist of an echo of the received signal after demodulation to ensure correctness. Only critical type commands that jeopardize element safety need undergo this verification. After ground verification, an execute signal will be transmitted releasing the commands from storage.	X	X	X	X
3. A means must be provided in the controlling element to convert commands into digital format compatible with the controlled element receiving and translation equipment. A standard command data format and data rate should be established for all orbital elements operations.	X	X	X	X

	RELATED PROCEDURE			
	DIRECT WITH GROUND	WITH GROUND VIA RELAY ELEMENT	WITH GROUND VIA TDRS	CONTROL BY SPACE ELEMENT
	13-1	13-2	13-3	13-4
4. A means shall be provided in the controlling element (ground or space) to command and control the collection, storage, and transfer of dumped or real-time data from the detached element. This operation consists of commands to the detached element communication equipment for operation of the onboard (controlled element) tape recorder, the experiment equipment, and the associated communication equipment.	X	X	X	X
5. Data processing, storage, and display provisions shall be available in the controlling element (ground or space) for handling dumped or real-time data transferred from the detached element and/or for evaluation and utilization of such data. Manned controlling elements will need digital and/or analog storage devices to accept large quantities of data from controlled elements. In some cases, the data will be processed and displayed either in real time or in delayed playback mode for element evaluation. In other cases, it will be recorded and played back at lower data rates over accessible communications links to the user. See the Design Concept Model discussion and elements pair matrix for further definition.	X	X	X	X
6. A means shall be provided in the detached element for on-board collection, recording, and storage of data, and for dumping or real time transfer.	X	X	X	X

	RELATED PROCEDURE			
	DIRECT WITH GROUND	WITH GROUND VIA RELAY ELEMENT	WITH GROUND VIA TDRS	CONTROL BY SPACE ELEMENT
	13-1	13-2	13-3	13-4
In the same manner as the controlled element in requirement #6, the detached element must have storage capability to record data quantities that are impossible to transmit feasibly in real time.				
7. Monitoring and checkout by the controlling element of detached element condition, operations, and equipments by continuous or periodic interrogation shall be provided for determining element status, isolating faults, processing and displaying such data for evaluation and possible correction.	X	X	X	X
Controlling element storage shall be provided that contains controlled element equipment and system data for purpose of checkout comparison. This must be computer controlled and correlated with data telemetered from controlled element systems to determine status of the element systems. Displays shall be incorporated to provide data viewing.				
8. A means shall be provided to enable the controlling element to track and range the detached element and to determine the detached element orbital parameters.	X	X	X	X
Orbital parameters shall be computed from these data within accuracies that fulfill mission requirements included in rendezvous and stationkeeping.				
9. A means shall be provided to determine the controlling space element orbital parameters and position data.	X	X	X	X
Orbital parameters shall be computed from these data within accuracies that fulfill mission requirements included in rendezvous and stationkeeping.				

10. A means shall be provided for inspection of the detached element by direct visual observation or by a television system.

This may be accomplished by means of a black and white television camera system. This can be used for both self-inspection and inspection of other elements. The TV system will transmit approximately 2.9 MHz baseband analog signals for direct or relayed pictures of the detached element to the ground or space controlling element.

RELATED PROCEDURE			
DIRECT WITH GROUND	WITH GROUND VIA RELAY ELEMENT	WITH GROUND VIA TDRS	CONTROL BY SPACE ELEMENT
13-1	13-2	13-3	13-4
X	X	X	X

ELEMENT PAIR REQUIREMENTS MATRIX

Each element pair was examined for relationship to the functional requirements. Tables were set up for each element, including ground, to identify the element with which it interfaces, and the requirements dictated on the element by the element with which it interfaces. Thus, ground to each of the interfacing elements defines in tabular form the requirement that ground must support to provide detached element operations with that element. These tables can be used to establish element requirements by examination of the table for the maximum requirement imposed by the interfacing elements. Note that the element pair requirements presented in the following tables are indicative of the ramifications of the various approach options. They are not intended to indicate the preferred approach. The preferred approach, by element pair, is presented in Table 4-7.

EOS Element Pair Requirements Matrix

	EOS (Controlling)	EOS	TUG	RAM	SAT	MSS	CPS	RNS	OPD	GROUND
1	Command Data Transmission to									
	Digital BER 1 x 10^{-6}	2 kbps	→	→	→	→	→	2 kbps	2kbps	NA
	Voice (4 kHz)	Yes	Yes	NA	NA	Yes	Yes	Yes	1	
2	Command Verification Digital from BER 1 x 10^{-6}	2 kbps	→	→	→	→	→	→	2 kbps	NA
	Receive/verify	Yes	→	→	→	→	→	→	Yes	
3	Data Storage									
	Digital storage per day	NA	→	→	→	→	→	→	→	NA
	Later dump per day	NA	→	→	→	→	→	→	→	NA
	Film or tape delivery	NA	NA	15 reels per day trans-port (max)	NA	1 reel of mag tape in 2 days	NA	NA	NA	NA
4	Digital Data Transfer Receive from	10 kbps	4 kbps	5 kbps	27.5 kbps	51.2 kbps	10 kbps	8.5 kbps	10 kbps	2 kbps
	Transmit to	See cmds	→	→	→	→	→	→	See cmds	51.2 kbps
5	Analog Data Transfer Voice (4 kHz) Channels	1	1	NA	NA	1	1	1	1	2
	Television	NA	→	→	→	→	→	→	→	NA
	Facsimile	NA	→	→	→	→	→	→	→	NA
	Other	NA	→	→	→	→	→	→	→	NA
6	Tracking/Ranging PRN range capability ±1000 ft/range ±1 ft/sec range rate	Meas.	→	→	→	→	→	→	Meas.	Respond
		Resp.	→	→	→	Resp.				
7	Computer capability to determine ephemerides	Yes	→	→	→	→	→	→	Yes	NA
8	Visual Inspection	Yes, TV	→	→	→	→	→	→	→	Yes, TV
9	Analog Data Transmission to Voice (4 kHz) Channels	1	1	NA	NA	1	1	1	1	1
	Television	NA	→	→	→	→	→	→	→	NA
	Others	NA	→	→	→	→	→	→	→	NA

Space Tug Element Pair Requirements Matrix

	Tug (Controlling)	EOS	TUG	RAM	SAT	MSS	CPS	RNS	OPD	GROUND
1	Command Data Transmission to									
	Digital, BER 1×10^{-6}	4 kbps	→	→	→	→	→	4 kbps	10 kbps	NA
	Voice (4 kHz)	Yes	Yes	NA	NA	Yes	Yes	Yes	Yes	
2	Command Verification									
	Digital from BER 1×10^{-6}	4 kbps	→	→	→	→	→	4 kbps	10 kbps	NA
	Receive/verify	Yes	→	→	→	→	→	→	Yes	NA
3	Data Storage	NA								NA
4	Digital Data Transfer									
	Receive from	2 kbps	10 kbps	4 kbps	27.5 kbps	10 kbps	10 kbps	8.5 kbps	10 kbps	2 kbps
	Transmit to	4 kbps	→	→	→	→	→	→	4 kbps	50 kbps
5	Analog Data Transfer									
	Voice (4 kHz) Channels	1	1	NA	NA	1	1	1	1	1
	Television	NA	→	→	→	→	→	→	→	NA
	Facsimile	NA	→	→	→	→	→	→	→	NA
	Other	NA	→	→	→	→	→	→	→	NA
6	Tracking/Ranging PRN range capability ±1000 ft/range ±1 ft/sec range rate	Respond	Meas.	→	→	→	→	→	Meas.	Respond
7	Computer Capability to Determine Ephemerides	No	Yes	→	→	→	→	→	Yes	NA
8	Visual Inspection	Yes, TV	→	→	→	→	→	→	Yes, TV	NA
9	Analog Data Transmission to									
	Voice (4 kHz) Channels	1	1	NA	NA	1	1	1	1	1
	Television	NA	→	→	→	→	→	→	NA	B&W, 2.9 MHz
	Other	NA	→	→	→	→	→	→	→	NA

Ground Network Element Pair Requirements Matrix

	Ground (Controlling)	EOS	TUG	MSS	CPS	RNS	OPD	SAT	RAM
1	Command Data Transmission to:								
	Digital, BER 1×10^{-6}	2 kbps	2 kbps	10 kbps	30 kbps	2 kbps	1 kbps	1 kbps	10 kbps
	Voice (4 kHz)	Yes					Yes	NA	NA
2	Command Verification								
	Digital from BER 1×10^{-6}	2 kbps	2 kbps	10 kbps	30 kbps	2 kbps	1 kbps	1 kbps	10 kbps
	Receive/verify	Yes →	→	→	→	→	→	→	→ Yes
3	Data Storage								
	Digital storage per day	NA →	→	→	→	→	→	→	→ NA
	Later dump per day	NA →	→	→	→	→	→	→	→ NA
	Film or tape delivery	NA →	→	→	→	→	→	→	→ NA
4	Digital Data Transfer								
	Receive from	51.2 kbps	50 kbps	2.0 Mbps	1 Mbps	8.5 kbps	50 kbps	1.6 Mbps	35 Mbps
	Transmit to	See cmds	See cmds	500 kbps	See cmds	See cmds	See cmds	See cmds	See cmds
5	Analog Data Transfer								
	Voice (4 kHz) Channels	2	1	3	1	1	1	NA	NA
	Television	NA	B&W 2.9 MHz	Color 4.5 MHz	B&W 2.9 MHz	B&W 2.9 MHz	Color 4.5 MHz	B&W 2.9 MHz	B&W 2.9 MHz
	Facsimile	NA	NA	0.5 MHz	NA →	→	→	→	→ NA
	Other	NA →	→	→	→	→	→	→ NA	7 MHz
6	Tracking/Ranging PRN range capability ±1000 ft/range ±1 ft/sec range rate	Meas. →	→	→	→	→	→	→	→ Meas.
7	Computer Capability to Determine Ephemerides Compute from range, range rate and tracking	Yes →	→	→	→	→	→	→	→ Yes
8	Visual Inspection	NA →	→	→	→	→	→	→	→ NA
9	Analog Data Transmission to								
	Voice (4 kHz) Channels	2	1	3	1	1	1	NA	NA
	Television	NA →	→	→	→	→	→	→	→ NA
	Other	NA	NA	0.03 - 10 kHz audio hi-fi	NA →	→	→	→	→ NA

RAM Element Pair Requirements Matrix

	RAM	EOS	MSS	TUG	GROUND
1	Command Data Transmission to				
	Digital, BER 1 x 10^{-6} Voice (4 kHz)	NA →	→	→	NA
2	Command Verification				
	Digital from BER 1 x 10^{-6} Receive/verify	NA →	→	→	NA
3	Data Storage				
	Digital storage per day	NA →	→	NA	94 x 10^9
	Later dump per day	NA →	→	NA	30 Mbps/for 1 hour
	Film or tape delivery	NA		NA	15 reels/day
4	Digital Data Transfer				
	Receive from	2 kbps	10 kbps	4 kbps	10 kbps
	Transmit to	5 kbps	50 kbps	4 kbps	35 Mbps
5	Analog Data Transfer				
	Receive from				
	Voice (4 kHz) Channels	NA →	→	→	NA
	Television	NA →	→	→	NA
	Facsimile	NA →	→	→	NA
	Other	NA →	→	→	NA
6	Analog Data Transmission to				
	Voice (4 kHz)	NA →	→	→	NA
	Television	NA	B&W, 2.9 MHz	NA	B&W, 2.9 MHz
	Other	NA →	→	NA	7 MHz
7	Tracking/Ranging				
	PRN range capability	respond	measure respond	respond	respond
	±1000 ft/range				
	±1 ft/sec range rate				
8	Computer Capability to Determine Ephemerides	NA →	→	→	NA
9	Visual Inspection	NA →	→	→	NA

Modular Space Station Element Pair Requirements Matrix

	MSS	EOS	TUG	RAM	GROUND
1	Command Data Transmission to				
	Digital, BER 1 x 10^{-6}	10 kbps	10 kbps	10 kbps	NA
	Voice	Yes	Yes	NA	NA
2	Command Verification				
	Digital from BER 1 x 10^{-6}	10 kbps	10 kbps	10 kbps	NA
	Receive/verify	Yes	Yes	Yes	NA
3	Data Storage				
	Digital storage per day	NA	NA	94×10^{9} (max)	NA
	Later dump per day	NA	NA	30 Mbps for 1 hour	NA
	Film or tape delivery	NA	NA	15 reels per day (to grnd)	NA
4	Digital Data Transfer				
	Receive from	2 kbps	4 kbps	50 kbps	500 kbps
	Transmit to	51.2 kbps	10 kbps	10 kbps	2.0 Mbps
5	Analog Data Transfer				
	Voice (4 kHz) Channels	1	1	NA	3
	Television	NA	NA	B&W, 2.9 MHz	NA
	Facsimile	NA	NA	NA	0.03 to 10 kHz audio hi-fi
6	Tracking/Ranging				
	PRN range capability ±1000 ft/range ±1 ft/sec range rate	measure respond	measure respond	measure --	-- respond
7	Computer Capability to Determine Ephemerides	Yes	Yes	Yes	NA
8	Visual Inspection	Yes, TV	Yes, TV	Yes, TV	NA
9	Analog Data Transmission to				
	Voice (4 kHz) Channels	1	1	NA	3
	Television	NA	NA	NA	4.5 MHz color
	Other	NA	NA	NA	Facsimile 500 kHz

Satellite Element Pair Requirements Matrix

	SAT	EOS	TUG	GROUND
1	Command Data Transmission to			
	Digital, BER 1 x 10^{-6}	NA	NA	NA
2	Command Verification			
	Digital from BER 1 x 10^{-6}	NA	NA	NA
3	Data Storage			
	Digital storage per day	NA	NA	NA
	Later dump per day	NA	NA	NA
	Film or tape delivery	NA	NA	NA
4	Digital Data Transfer			
	Receive from	2 kbps	4 kbps	1 kbps
	Transmit to	27.5 kbps	27.5 kbps	1.6 Mbps
5	Analog Data Transfer			
	Receive from			
	Voice (4 kHz)			
	Channels	NA	NA	NA
	Television	NA	NA	NA
	Facsimile	NA	NA	NA
	Other			
6	Analog Data Transmission to			
	Voice (4 kHz)	NA	NA	NA
	Television	NA	NA	B&W, 2.9 MHz
	Other	NA	NA	NA
7	Tracking/Ranging			
	PRN range capability	respond	respond	respond
	±1000 ft/range			
	±1 ft/sec range rate			
8	Computer Capability to Determine Ephemerides	NA	NA	NA
9	Visual Inspection	NA	NA	NA

Chemical Propulsion Stage Element Pair Requirements Matrix

CPS		CPS	EOS	TUG	OPD	RNS	GROUND
1	Command and Data Transmission to						
	Digital, BER 1 x 10^{-6}	10 kbps	NA	NA	10 kbps	NA	NA
	Voice (4 kHz)	1			1		
2	Command Verification						
	Digital from BER 1 x 10^{-6}	10 kbps	NA	NA	10 kbps	NA	NA
	Receive/verify	Yes			Yes		
3	Data Storage						
	Digital storage per day	NA	→	→	→	→	NA
	Later dump per day						
	Film or tape delivery						
4	Digital Data Transfer						
	Receive from	2 kbps	2 kbps	4 kbps	10 kbps	8.5 kbps	30 kbps
	Transmit to	10 kbps	10 kbps	10 kbps	10 kbps	2 kbps	1 Mbps
5	Analog Data Transfer						
	Voice (4 kHz)						
	Channels	1	1	1	1	1	1
	Television	NA	→	→	→	→	NA
	Facsimile	NA	→	→	→	→	NA
	Other	NA	→	→	→	→	NA
6	Tracking/Ranging						
	PRN range capability	measure respond	respond	respond	measure respond	measure respond	respond
	±1000 ft/range						
	±1 ft/sec range rate						
7	Computer Capability to Determine Ephemerides	Yes	NA	NA	Yes	Yes	NA
8	Visual Inspection	Yes, TV	→	→	→	Yes, TV	NA
9	Analog Data Transmission to						
	Voice (4 kHz)						
	Channels	1	1	1	1	1	1
	Television	NA	→	→	→	NA	B&W 2.9 MHz
	Other	NA	→	→	→	→	NA

Orbital Propellant Depot Element Requirements Matrix

	OPD	EOS	TUG	CPS	RNS	GROUND
1	Command Data Transmission to Digital, BER 1 x 10^{-6} Voice (4 kHz)	NA →	→	→	→	NA
2	Command Verification Digital from BER 1 x 10^{-6} Receive/verify	NA →	→	→	→	NA
3	Data Storage Digital storage per day Later dump per day Film or tape delivery	NA →	→	→	→	NA
4	Digital Data Transfer					
	Receive from	2 kbps	4 kbps	10 kbps	8.5 kbps	10 kbps
	Transmit to	10 kbps	10 kbps	10 kbps	10 kbps	50 kbps
5	Analog Data Transfer Receive from Voice (4 kHz) Channels	1	1	1	1	1
	Television	NA →	→	→	→	NA
	Facsimile	NA →	→	→	→	NA
	Other	NA →	→	→	→	NA
6	Analog Data Transmission to					
	Voice (4 kHz)	1	1	1	1	1
	Television	NA →	→	→	NA	Color 4.5 MHz
	Other	NA →	→	→	NA	Apollo-type TV 500 kHz
7	Tracking/Ranging PRN range capability ±1000 ft/range ±1 ft/sec range rate	respond	respond →	→	→	respond
8	Computer Capability to Determine Ephemerides	NA →	→	→	→	NA
9	Visual Inspection	Yes, TV	Yes, TV	Yes, TV	Yes, TV	NA

QUANTITATIVE REQUIREMENTS ANALYSES

The major quantitative requirements involved the transmission of data between elements. Commands in one direction and telemetry, scientific experiment data, voice and television are required in the other direction. These data for each of the element pairs was derived from contractual reports and analysis of the requirements defined therein. Tables 4-3 and 4-4 are typical of individual element requirements used for data rates. Table 4-5 is a compilation of typical satellite data rates established for proposed experiments and other purposes.

Tracking and ranging requirements were derived from the stationkeeping and rendezvous interfacing activities. The need for precision attitude and position control for specific experiments was considered to be part of the individual experiment requirement and not a general element requirement.

The data storage and data dump numbers were derived from maximum expected data rates (including experiments) and the analyses discussed under design concept models. Only three elements were involved in this requirement; RAM and MSS for storage and dump and EOS for transport. It is possible that an earth resources satellite - if accomplished by other than RAM - will require on-board storage and dump systems. If so, the tables in the design concept model paragraph can be used to derive the quantity of storage and the data dump capability.

Table 4-3. Space Station Requirements

		RF Channel	Voice	Telev.	System TLM	Comp. Data	Expmt. Data	Text/ Graphics	Command Data	EVA TLM	Facsim.	Ranging	
												Measure	Respond
FROM SPACE STATION TO	Detached RAM	S-band	(1) 300 to 4000 Hz						10 kbps			0.5 Mbps	
	Shuttle Orbiter	S-band	(1) 300 to 4000 Hz		50 kbps							0.5 Mbps	0.5 Mbps
	MSFN Ground Terminal Direct	S-band	(3) 300 to 4000 Hz	4.5 MHz	500 kbps	500 kbps	2.0 Mbps	1.0 kbps		200 bps			0.5 Mbps
	Ground Terminal via TDRS	VHF	(1) 300 to 4000 Hz		10 kbps								
	Gnd Term via TDRS	K-band	(3) 300 to 4000 Hz	4.5 MHz	500 kbps	500 kbps	2.0 Mbps	1.0 kbps		200 bps	0.5 MHz		0.5 Mbps
TO SPACE STATION FROM	Detached RAM	S-band	(1) 300 to 4000 Hz	2.9 MHz	50 kbps	500 kbps	Part of system TLM						0.5 Mbps
	Shuttle Orbiter	S-band	(1) 300 to 4000 Hz						1.0 kbps			0.5 Mbps	0.5 Mbps
	MSFN Gnd Term Direct	S-band	(4)* 300 to 4000 Hz			500 kbps		1.0 kbps	1.0 kbps			0.5 Mbps	
	Gnd Term via TDRS	VHF	(1) 300 to 4000 Hz						1.0 kbps				
	Gnd Term via TDRS	K-band	(4)* 300 to 4000 Hz			500 kbps		1.0 kbps	1.0 kbps				

* One of the four voice channels - Ground to MSS - is a high fidelity channel

Table 4-4. Shuttle Link Requirements

Signal	Q	Mode	Data Rate	Modulation	SCO	Quality	Deviation	Carrier (MHz)
A. Uplink Voice	1	FDX	300 to 3000 Hz	FM-FM	30 kHz ±7.5 kHz	46db-Hz	$\beta = 1$	148-150
	1	FDX	300 to 3000 Hz	FM-PM	30 kHz ±7.5 kHz	46db-Hz	1.34 rad	2106.5
Data	1	SPX	2 kb/s	FM-FM	70 kHz ±5 kHz	BeR = 10^{-5}	$\beta = 1$	148-150
	1	SPX	2 kb/s	FM-PM	70 kHz ±5 kHz	BeR = 10^{-5}	1.85 rad	2106.5
Range, range rate	1	Turnaround	100 kHz (tones)	VHF-FM	-	BeR = 10^{-5}	TBD	148-150
	1	Turnaround	0.5 Mb/s	PM	-	BeR = 10^{-5}	1.2 rad.	2106.5
B. Downlink Voice	1	FDX	300 to 3000 Hz	FM-FM	30 kHz ±7.5 kHz	46db-Hz	$\beta = 1$	136-138
	1	FDX	300 to 3000 Hz	FM-PM	1.25 MHz ±7.5 kHz	46db-Hz	0.7 rad.	2287.5
Data	1	SPX	2 kb/s	FM-FM	70 kHz ±5kHz	Ber = 10^{-5}	$\beta = 1$	136-138
	1	SPX	51.2 kb/s	PSK-PM	1.024MHz	Ber = 10^{-5}	1.2 rad.	2287.5
Range, range rate	1	Turnaround	0.5 Mb/s	FM		Ber = 10^{-5}	TBD	136-138
	1	Turnaround	0.5 Mb/s	PM		Ber = 10^{-5}	1.2 rad.	2287.5
Special data	1	SPX	51.2 kb/s	PSK-PM	1.024 MHz	Ber = 10^{-5}	600 kHz	2272.5

SPX = Simplex FDX = Duplex

Table 4-5. Satellite Requirements

User S/C	Purpose	Orbit	Command Requirements	Telemetry Requirements	
AE	Explore lower thermosphere	150 x 4000 km to 600 km circ. i=63°,T=130min.	128 b/s, VHF or S, at least once/orbit, up to 4 min/contact	16 kb/s, VHF or S, once/ orbit, up to 20 min/orbit	131 kb/s, S 1 orbit to 1/3 orbits, up to 30 min/contact total 1 hr/day
EOS	Oceanography, earth research, meteorology	1000 km circ. i=100°,T=100 min.	128 b/s, VHF, at least once/ orbit, 2.5 min/contact	12 kb/s,VHF twice/orbit 10 min/contact	1.6 Mb/s, S once/orbit 5 min/contact Some 100 to 200 Mb/s
HEAO	Map celestial sphere and galactic plane for HE sources	320-400 km circ. i=28°,T=90 min.	128-1024 b/s, S, once/orbit, 3.5min/contact	27.5 kb/s and 500 kb/s, S once/orbit 6-18 min/contact	
NIMBUS F	Meteorology	1000 km circ. i=90°,T=100min.	128 b/s, VHF once/orbit 2.5 min/contact	4 kb/s and 128 kb/s, VHF 1.5 MHz BW analog, S once/orbit, 3-15 min/contact	
OSO	Solar radiation measurements	500 km circ. i=33°,T=95 min.	800 b/s, VHF once/orbit; up to 10 min/contact	6.4 kb/s, VHF once/orbit 10 min/contact	128 kb/s, S once/orbit 5 min/contact
SAS	X-ray, astronomy	550 km circ; i=33°,T=96 min.	64 b/s, VHF once/orbit 14 sec/contact	8 kb/s & 30 kb/s, VHF or S once/orbit; up to 13 min/contact	
SATS	Application experiments	500 km circ. i=0°-90°, T=100 min.	64 b/s; once/2 orbits 4 min/contact	400 b/s - 20 kbs, VHF and 128 kb/s, S; once/2 orbits 6 min/contact	
TIROS N	Meteorology	1700 km circ. i=76°,T=120 min.	100 b/s, VHF once/orbit; 2 to 5 min/contact	833 kb/s,S continuous Up to 17 min/contact	1.4 Mb/s, S once/orbit

4.7 DESIGN INFLUENCES AND PREFERRED APPROACH SELECTION

The operational considerations for each approach are summarized in Table 4-6. The two major considerations are the data rates involved and the required contact time with the data processing center.

APPROACH EVALUATION

Some of the proposed orbital elements will generate > 10 Mbps data rates. Currently there are only two concepts that can handle data rates of this magnitude, TDRS relay and hard storage (magnetic tape or laser). The TDRS relay link imposes the requirement for a Ku band communications link with a directional antenna. The storage concept results in major logistics problems as well as imposing stringent design requirements for interchange of packages on unmanned elements.

Storage requirements are also imposed because of the communication gaps with the data processing or control center. Use of the TDRS link minimizes this problem with the least amount of element hardware. As the orbital traffic model increases time sharing the two TDRS high data rate links may become a limitation.

Record and delayed data dump concepts are currently operational at relatively low data rates. The technology exists for high data rate processing but the contact duration with ground network stations in many orbits is short. Thus either the relay element or the space control element will also require hard storage capability for high data rates.

The operating frequencies are predetermined by the links to ground, S-band to the ground network and VHF and/or Ku band to TDRS. The VHF link to TDRS is a low data rate link. It can accommodate 20 channels simultaneously.

One additional capability is assumed in the space control option. If an orbiting element is performing as a control center then at least initial processing/editing/compressing of the data from detached elements is conducted on this control element. The resulting maintenance - both software and hardware - of this orbital control center could be comparable to the maintenance of a Ku band transmission system on an element.

As orbital traffic increases use of the relay or space controlled approaches becomes less adaptable unless the orbital equipment complement is correspondingly increased. The direct ground approach can accommodate additional uses because of the sequential nature of orbital element contacts. TDRS gives maximum coverage and can time share its data channels with many orbiting elements.

Table 4-6. Alternate Approach Evaluation

Approaches / Considerations	Ground Control: Direct to Ground Control	Ground Control: Via Space Element	Ground Control: Via TDRS	Space Control	Remarks
Data Handling Capability	1 Mbps	1 Mbps	50 Mbps (a)	1 Mbps	(a) Maximum Ku, 10 Kbps VHF
Communication Contacts	≈10%	100% (b)	≈90%	100% (b)	(b) Assumes LOS between elements
Operating Frequency	S-Band	S-Band (c)	VHF, Ku	VHF, S-Band or Ku-Band	(c) Could use VHF or Ku-band between elements
Operational Complexity	Requires preplanned dump schedule or temporary storage	Data dump flexibility via temporary storage	Time share with other elements	On-orbit data reduction or hard storage	
Technology Status	Operational	Operational	Phase B	Phase B	
Orbital Element Design Impact	S-Band omni data storage	S-Band omni data storage	Ku-Band directional	S-Band omni data processing	
C/O & Maintenance	Low	Nominal	Medium (d)	Medium (d)	(d) Ku-band system may require EVA maintenance but computer processing equipment requires more frequent maintenance/revision
Traffic Model Accommodation	Medium	Low (e)	High	Low (e)	(e) Restricts operational Orbits

One obvious conclusion that can be drawn from this evaluation is that a major effort is required to reduce the quantity of data required to be transmitted. This must be accomplished at the source of data generation. There are several techniques of data compression that can be implemented. Perhaps the simplest is a "skimmer" concept that was implemented to reduce the quantity of CSM checkout data that required evaluation. Analyses were conducted to determine the allowable range of values that may occur for a given measurement. Data readouts or transmittals occurred only when these limits were exceeded.

Measurement sample rates must be thoroughly analyzed and justified. Early in the Apollo program requested sample rates on some measurements bordered on the ludicrous. After extensive analysis the measurement list and sample rates for the Apollo were reduced to a manageable level that was both adequate and within the capability of the data transfer system. A clear distinction between scientific/engineering edification and scientific/engineering evaluation must be made.

PREFERRED APPROACH SELECTION

There are three major orbital activities that are related to the interfacing activity of detached element operations, rendezvous, stationkeeping, and space operations investigation/applications. Rendezvous and stationkeeping approaches and implications are discussed in detail in sections 2.0 and 3.0. The requirements for space operations are delineated in a previous part of this section. All three orbital activities rely upon communication links. Alternate concepts and implications of communication links are presented in detail in section 1.0.

An integrated preferred approach is summarized in Table 4-7. The distinction for rendezvous and stationkeeping operations between the alternate approaches is based upon the range between elements and the manning status of the elements involved (see sections 2.0 and 3.0). The space element relay concept is applicable to unmanned elements operating at close ranges.

The preferred approach for space operations of detached elements is dependent upon the quantity of data generated and the necessity of real time data transfer. The currently identified elements that will generate large quantities of data are MSS, RAM and satellites.

By definition the MSS is a data generating, collecting, and processing orbital facility. Integrally generated data would normally be pre-processed on-board. Selected and summarized data could be transferred to ground based users either directly or via regular logistics flights in the form of hard storage.

Table 4-7. Preferred Approach Selection

	Ground Operations and Control				Space Operations and Control	
For Interfacing Activity	I Direct with Ground	II Via a Space Element		III Via TDRS	IV Direct By Space Element	
		Relay	Controlled Element		Control	Controlled Element
Rendezvous and Stationkeeping	EOS, TUG, MSS, CPS, RNS, OLS, OPD, SAT, RAM	TUG	TUG, CPS, RNS, OLS, RAM, SAT, CPS, RNS, OPD	NA	MSS	RAM, TUG
		CPS	OPD		EOS	RAM, TUG, RNS, OLS, OPD, SAT, CPS
		RNS	OPD			
Detached Elements Operations	EOS, TUG, MSS, CPS, RNS, OLS, OPD, SAT, RAM	MSS	Detached RAM	MSS, SAT, RAM	MSS - RAM	
		EOS	Attached/ Detached RAM			
Communication Links (1)	S-Band/Omni			Ku-Band/ Directional (Selected SATs & RAMs)	S-Band/Omni Ku-Band/Directional (Selected RAMs)	

(1) VHF/Omni low data rate to TDRS recommended as backup link for all elements

The term RAM encompasses dedicated modular assemblages of experiments/sensors that may operate in conjuction with an EOS, MSS or tug. It includes "pallets" that remain in the cargo bay of the EOS, free flyers, and modules deployed on the EOS or attached to the MSS. Maximum commonality could be achieved by imposing that all RAMs incorporate a TDRS link because a selected few will require real time transfer of large quantities (10 Mbps) of data. This would be unrealistic and impose undue complexity and cost in both operations and hardware of RAM's. Because of the broad range of data transfer requirements over the spectrum of proposed RAM's (1 Kbps to 10 Mbps) all four concepts are applicable.

There are two distinct recommendations concerning the elements that RAM's interface with. All RAMs associated with the MSS should rely upon the MSS for data transfer/data processing. This imposes the requirement on the MSS to include Ku band capability. Some station related RAM's will generate data rates as high as 10 Mbps. Also as the MSS-RAM complex increases it will become necessary to utilize TDRS for data dumps to earth.

The amount of data generated by RAMs associated with the EOS will vary over a wide spectrum. At this juncture in the RAM definition it is extremely doubtful if a realistic RAM data transfer requirement can be identified and imposed on the EOS. In addition EOS operations involve numerour other elements and activities that do not require the data transfer capacity associated with RAM's. Therefore it is recommended that the EOS accommodation of RAM data transfer requirements, for both attached and detached versions, be limited to providing access to its basic S-band capability. All RAM data transfer requirements in excess of the basic EOS capability (1 Mbps) should either be provided as part of the RAM (independent) or be a kit installation on the EOS and considered as part of the RAM payload.

Satellites are characterized by orbital operations spanning years of unattended service. The data generated by these elements could be voluminous and repetitive. Data compression and storage for periodic dumps is mandatory if the TDRS link is used. Dedication of a TDRS link for the operational life of a satellite is impractical. Operational data compression can be achieved by only activating or "sampling" the satellite data system periodically. If feasible a preferred technique would be selective sampling and skimming of the data from the satellite sensors, storing it, and periodically dumping it to the ground users via TDRS.

The same data compression/selection constraints are imposed upon the satellite in the direct to ground control approach. Communication gaps are longer and more frequent. Handovers from one station to another adds complexity to the data transfer function. As the orbital traffic model increases the problems associated with scheduling of data transfer will become quite complex. The current ground network model is capable of handling data rates to 1 Mbps. That is maximum for any one ground station.

All potential users of either the ground network or TDRS must realize and recognize that the data handling capabilities of these concepts will not be dedicated to support of their operation. Of the three alternatives - data compression, autonomous operation, or hard storage/resupply - data compression is the preferred design concept. Autonomous data processing and evaluation is only practical on a facility such as the MSS. (Even in the case of the MSS periodic data dumps are required for ground utilization.) Hard storage/resupply is feasible in most cases during the experimental phase of orbital operations but would be impractical in almost all cases in the applications phase of orbital operations.

When possible data should be "compressed" to within the 1 Mbps capability of the ground network. This compression must taken into account the fact that, on the average, only 3 to 6 minues per orbit are available for data dump to the ground network. Time sharing TDRS links with other elements will not be as restrictive because of almost continuous line-of-sight operations; but if the TDRS link is used Ku-band equipment is required.

DESIGN INFLUENCES

Detached element operations is the prime driver on establishing the communication link design concepts for all elements. In order to comply with the ground network and TDRS models used in this study only VHF, S and Ku band transmission frequencies are applicable. Based upon the preferred approaches, by element pair, for this activity as well as rendezvous and stationkeeping and the attendant data transfer requirements the recommended data handling characteristics of the various elements are summarized in Table 4-8.

S-band omni communication links are recommended for all elements. Up to 1 Mbps data rates can be accommodated on this link. Selected RAM's and satellites as well as the MSS should incorporate TDRS links. VHF is required to request the use (order wire) of the Ku or high data rate TDRS channel.

Only the MSS is required to include data processing equipment because, by definition, one of the primary functions of the MSS is to provide an orbital data evolution facility.

RAM access to both the EOS and MSS communication links is recommended. In the case of the EOS the basic capability is recommended. The MSS is driven to the Ku band link by the proposed RAM data transfer requirement.

The EOS and MSS both should contain autonomous state vector update, thrust vector maneuver computation, and tracking and ranging capability. Nominally the tug should relay upon either ground control on the MSS for three functions. However, some tug missions will require autonomous operations because of quick response requirements that precluded waiting for ground contacts.

Table 4-8. Detached Element Ops Design Influences

Element	Communication Link*	Data Handling Characteristics
EOS	S-band omni Laser	1 Mbps data transfer (TV) 10 kbps (commands) Autonomous state vector update Thrust vector determination Tracking and ranging; S-band and laser RAM access to comm. link Transponder
Tug	S-band omni Laser	1 Mbps data transfer (TV) 10 kbps (commands) Tracking and ranging; laser Transponder
RAM	Nominal: S-band omni Selective: VHF and Ku directional	Up to 10 Mbps + TV (Ku-band) 1 kbps order wire (VHF) Up to 1 Mbps data transfer (S-band) Data compression in all cases Data storage up to 15 reels/day Access to comm. links - EOS and MSS Transponder; S and Ku
MSS	S-band omni VHF and Ku band directional Laser	Up to 10 Mbps (Ku band) 1 kbps order wire (VHF) 10 kbps commands (S-band) Up to 1 Mbps + TV (S-band) Autonomous state vector update Tracking and ranging, S-band and laser RAM access to communication links Data processing, reduction, storage, real time display Transponder
Satellite	Nominal: S-band omni Selective: VHF and Ku band directional	Up to 10 Mbps (Ku band) 1 kbps order wire (VHF) Up to 1 Mbps (S-band) Data compression in all cases Transponder; S and Ku
CPS/RNS	S-band omni Laser	1 Mbps (TV) Tracking and ranging; laser 10 kbps commands 10 kbps data transfer Transponder
OPD	S-band omni Laser	1 Mbps (TV) Tracking and ranging; laser 50 kbps data transfer 10 kbps commands Transponder

*S-band is recommended as the basic concept for data transfer for all elements; VHF is recommended as the alternate/redundant concept for all elements

INFLUENCES OF INTEGRATED MISSIONS

The primary emphasis in the study of detached element operations was the same as that of the other interfacing activities, space element to element interactions. In addition to the element pair recommendations of the Orbital Operations study, the analyses and conclusions associated with detached element operations also indicated that a subsequent study of integrated missions should be accomplished.

The data management group of interfacing activities developed operational limitations, constraints, hardware recommendations, and nominal operating characteristics of element pair relationships. Only one space element--the MSS-- was required to operate with more than one other terminal in the same time frame. MSS could be called upon to communicate with two RAM's, an EOS and/or ground control during the same time period. Frequency multiplex or time multiplex could be used to accommodate this type operation. Other element-to-element data transfer could readily be accommodated with the design concepts proposed.

Although the MSS operation appears complex, examination of the potential multiple links that ground control will be required to accommodate indicates an increase in complexity of at least an order of magnitude. No longer will dedicated link operation be possible. By the 1980's, large numbers of earth orbital satellites--up to 100 by 1990--will be operating simultaneously. In order to ensure effective mission performance for each of these "data producers" a detailed integrated missions analysis needs to be performed. Not only will the "data production" explosion need to be examined, but the logistics for delivery, resupply, and possibly retrieval missions will need careful investigation. Orbital parameters, sensor performance, data contact times, geographical sensor data collection, element compatibility, and other factors must be considered.

An evaluation of the total earth orbital traffic model, considering the factors mentioned above, must be coordinated with an attempt to maximize EOS payload utilization. For example, placement of a maximum number of elements in the same orbit would result in optimum use of the EOS payload capability both for delivery and resupply missions. The definition of the maximum number of elements that could be supported must consider not only the EOS payload capability but also the system capability in terms of the number that can be flown economically, the turn around time, and launch support capabilities. These considerations are all of a physical nature.

A singularly complex operation will be that of the ground collection, processing and distribution of large quantities of data from the multitude of "data producers" in earth orbit. Much of this data will be of real time or near real time interest. Weather, ocean state, and certain earth emergency sensors are examples. Other data from experiment type missions—such as astronomy, solar radiation, and application experiments may not require real time processing. This latter group of data producers needs investigation to determine the most effective way to return data to the ground. Three techniques can be utilized. These are (1) direct real time data dump, (2) onboard data storage and subsequent data dump, and (3) onboard "hard data" storage (either magnetic tape or film) with regular physical collection and return to ground.

Each of these must be integrated into the total mission model to trade off against contact times with ground network stations or TDRS capability and resupply flights for hard data collection. Table 4-5 (pp 4-36) illustrated the variety of satellite requirements. Contact requirements from three minutes per orbit to 30 minutes per contact and data rates ranging from 20 kbps to 100 or 200 Mbps are anticipated. In addition to the satellites there are manned elements such as the MSS and EOS and unmanned elements such as tug, RAM, CPS, and RNS, that must also be considered in establishing the data flow to and through ground control. A total mission timeline needs to be developed to coordinate scheduling of the TDRS, ground network, and the hard data return.

Present operation with the TDRS is limited by the system capability--40 low data rate users and 4 high data rate users at one time. A high percentage of contact time per orbit is available from the TDRS. It is 90 percent or better and is increased as higher orbits are used. Acquisition and tracking of orbital elements and the criteria for time of acquisition, for handover from one TDRS to the other, the scheduling of contacts and the technique for ordering link acquisition must be considered.

Ground network operations have many of the same problems plus the addition of a few more constraints. The acquisition, tracking, handover, and scheduling are all magnified when ground stations are used. Besides the limited data capacity and low contact times per station, the ground antennas must slew from one element to another at higher rates and over greater angular ranges than TDRS antennas. TDRS VHF antennas cover the whole orbital spread with no tracking. TDRS Ku antennas have a beamwidth of approximately 1^o (3 db points) but at its approximately 20,000 n mi distance from low earth orbits, it subtends a minimum of approximately a 350-n mi orbital path. An 85-foot (S-band) ground antenna, however, has a beamwidth of less than 0.5 degree and subtends less than 5 miles of orbit at 500 n mi altitude. Thus, it must track an element continuously for the duration of the contact. This limits its usefulness in the number of satellites it can support in sequential coverage.

Figure 4-6 illustrates the minimum element separation that will permit sequential contact between one ground station and two elements. The data is based upon an idealized orbital relationship of the two elements. Both elements would have to be at the same altitude and have the same ground traces. The maximum coverage would be slightly less for a realistic coplanar dual element pass. The ground traces of the two elements would be slightly different. For example, at an orbital altitude of 270 n.mi. if the first element passed directly over the ground station, the second element's ground trace would be about 90 n.mi. from the ground station at its nearest approach point.

Higher orbits will improve contact time with each station but will require larger separation to allow sequential coverage. Different orbital inclinations can be used to enhance contact time.

Another major constraint of the ground network is the real time limitation of the station to control center or user communication link of 72 kbps. This necessitates the implementation of ground station high data rate recording and then data dump at the 72 kbps rate or physical transportation of data. Five minutes of 1 Mbps recording would take 70 minutes of dump at 72 kbps.

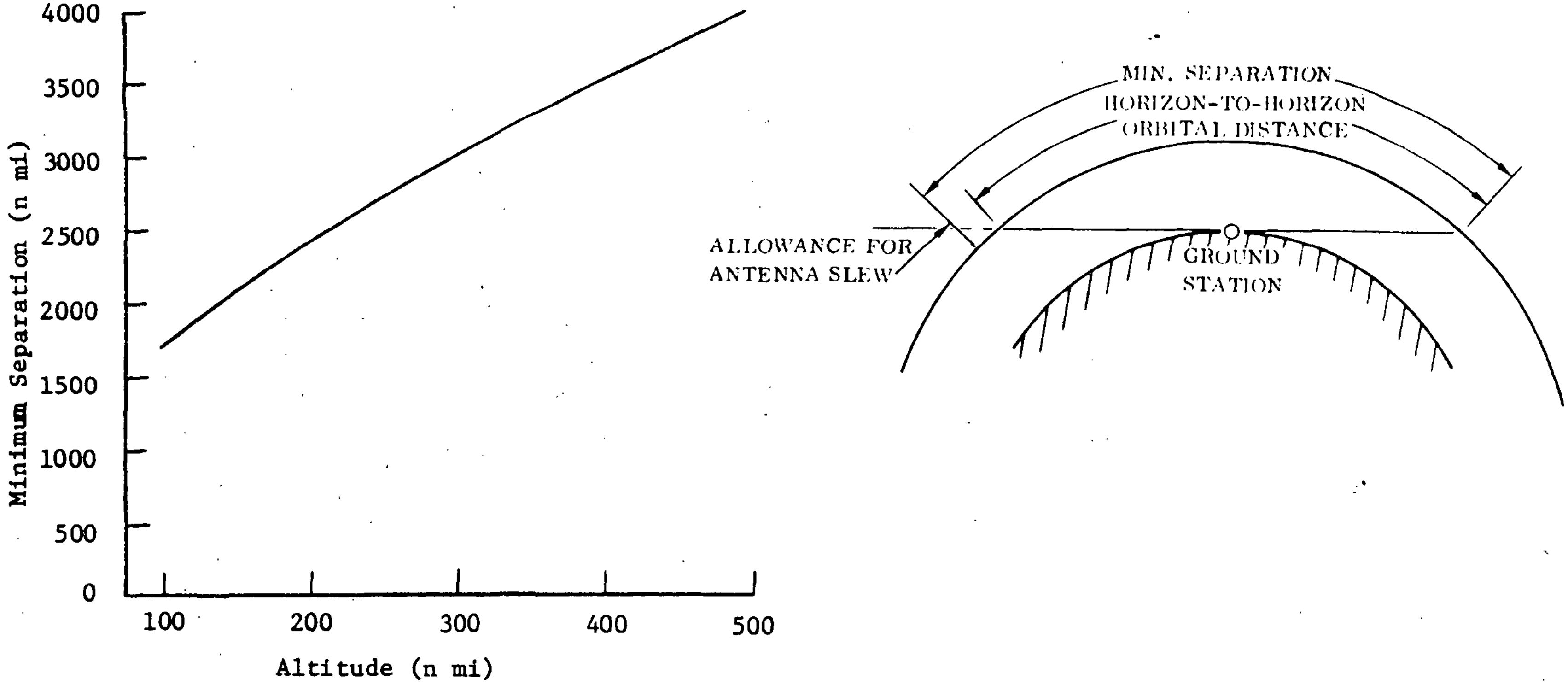


Figure 4-6. Minimum Separation Required for Same Ground Trace Orbits (At The Same Altitude) to Provide Maximum Sequential Coverage from One Ground Station

If a number of satellites were contacted in sequence, the data dump capability would soon be saturated. Only 20 satellites per day (or 20 passes per day) recording 5 minutes of 1 Mbps each, would saturate the ground link to the control center. Thus, other methods of data transfer to the control center will need to be implemented. Either the physical transportation, as mentioned above, or an increased capacity route will probably be required.

Acquisition of the desired element, maximum use of data channels, prescheduling of contact with the multitude of orbital elements, handover from one station to the next (either TDRS or ground network), optimization of orbital characteristics, and logistics flight coordination all are indicated as major considerations that should be included in a subsequent integrated missions analysis study. The data from the Orbital Operations study, especially the results of the analyses of the Data Management group of interfacing activities, can provide an integrated baseline of orbital element data transfer requirements and capabilities.