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COMMUNICATIONS SYSTEM EVOLUTIONARY SCENARIOS FOR MARTIAN SEI SUPPORT

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FINAL REPORT

PREPARED FOR:

NASA LEWIS RESEARCH CENTER
CLEVELAND, OHIO

PREPARED UNDER:

CONTRACT NUMBER: NAS3-25091

PREPARED BY:

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RONALD C. BRUNO

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SECTION 1: INTRODUCTION

In the Space Exploration Initiative (SEI) mission scenarios, expanding human presence is the primary driver for high data rate Mars-Earth communications. To support an expanding human presence, the data rate requirement may grow from an initial 10 Mbps up to as much as 1 Gbps. But the growth in the data rate requirement will be gradual, following the phased implementation over time of the evolving SEI mission. Similarly, the growth and evolution of the space communications infrastructure to serve this requirement will also be gradual to efficiently exploit the useful life of the installed communications infrastructure and to ensure backward compatibility with long-term users. In work conducted over the past year, a number of alternatives for supporting high data rate Mars-Earth communications have been analyzed with respect to their compatibility with gradual evolution of the space communications infrastructure. The alternatives include RF, millimeter wave (MMW), and optical implementations, and incorporate both surface and space-based relay terminals in the Mars and Earth regions. Each alternative is evaluated with respect to its ability to efficiently meet a projected growth in data rate over time, its technology readiness, and its capability to satisfy the key conditions and constraints imposed by evolutionary transition. As a result of this analysis, a set of attractive alternative communications architectures have been identified and described, and a road map is developed that illustrates the most rational and beneficial evolutionary paths for the communications infrastructure.

1.1 STUDY OBJECTIVE, SCOPE, AND APPROACH

The objective of this study has been to analyze and compare several microwave and optical communications systems in order to determine their feasibility and relative advantages and disadvantages in providing Mars-to-Earth communications for the SEI. Given the large separation between Mars and Earth, and the potential high data rate requirements, high frequency systems with their large gain are natural candidates for implementations. In this study, RF (32 GHz and 60 GHz), MMW (94 GHz and 300 GHz), and optical link implementations are examined. For optical systems, both direct detection and coherent (i.e., heterodyne or homodyne) detection schemes are investigated. The communications systems considered embody a variety of Mars to Earth connectivities. These connectivities include a Mars Relay Satellite (MRS) to Earth Relay Satellite (ERS) link, and a MRS to Earth Surface Terminal (EST) link. A Mars Surface Terminal (MST) link to a EST or ERS is also given consideration for the highest data rates. The return data rate requirements considered in the study are 10 Mbps, 100 Mbps, and 1 Gbps at three time frames: 2010, 2020 and beyond 2030, respectively.

A flow diagram for the general study approach is given in Exhibit 1-1. The report is organized as follow. In Section 2, a set of applicable need dates (and relevant technology cut-off dates) for the 10 Mbps to 1 Gbps data rate requirements is identified. In order to meet the projected growth in data rate requirements at the various need dates, logical alternatives for evolution and transition in the Mars-Earth communications system are defined and discussed. In Section 3, a preliminary evaluation of architecture alternatives is conducted. Preliminary technology constraints/bounds applicable to each need date are also defined. Baseline candidates and other alternatives at key need dates are identified and evaluated with inputs from link budget analysis and technology assessment. In Section 4, a subset of attractive architectures for each need dates are described in more details. Finally, preliminary conclusions are provided in Section 5.

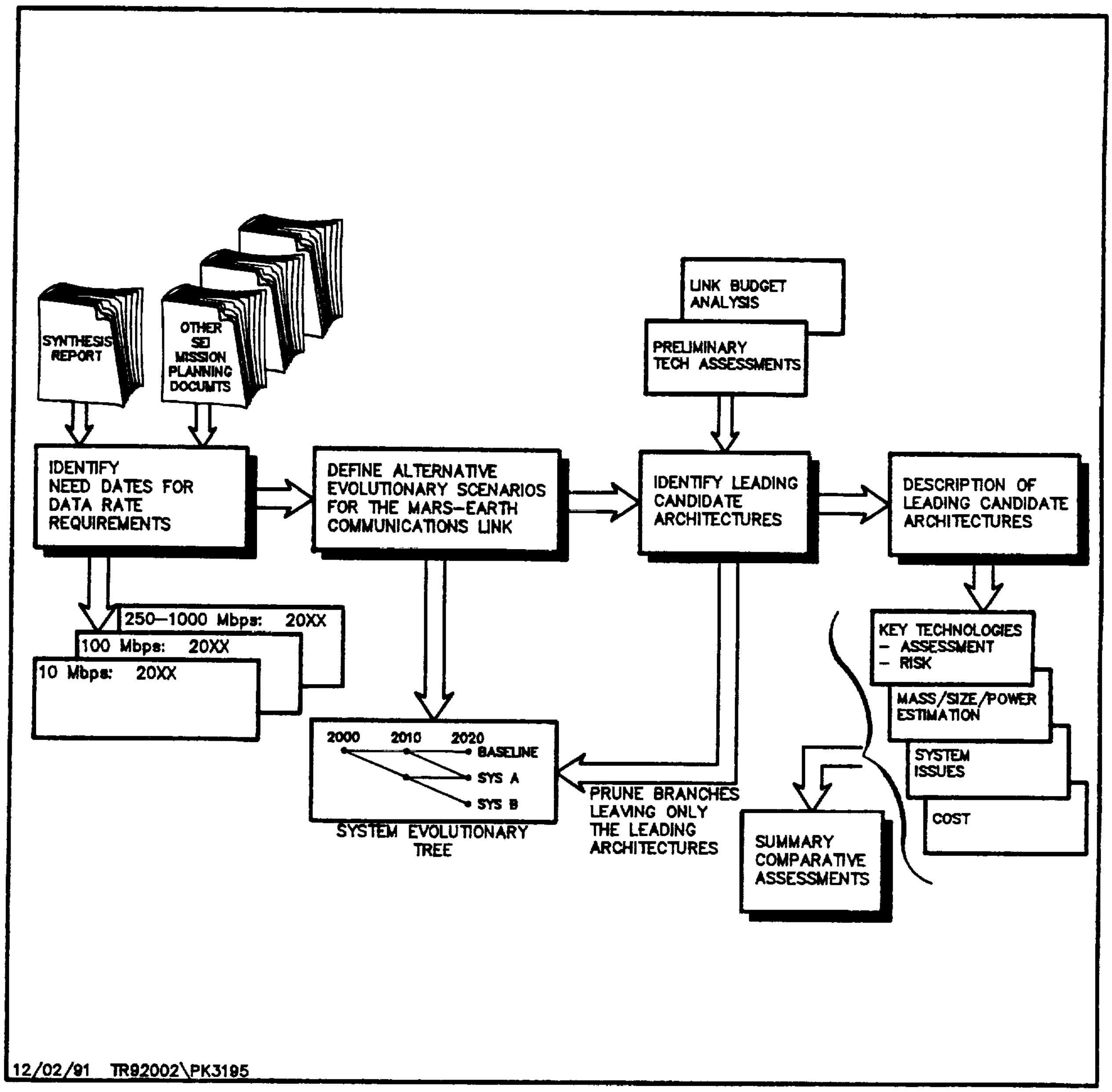

Exhibit 1–1: Overall Study Approach

1.2 RESULTS SUMMARY

In this study, a set of attractive architectures for the evolving Mars-Earth SEI space communications link have been identified and characterized. All together, they define a road map that illustrates the most logical and efficient evolutionary paths for the SEI Mars-Earth link. This road map provides valuable insight and guidance with respect to strategic planning of the SEI communications system including such issues as the proper emphasis and timing for long-lead technology development. This road map is illustrated in Exhibit 1-2. The basic features of the road map contain three alternative evolutionary paths that can meet the data rate requirements that may grow from 10 Mbps to 1 Gbps from 2010 to beyond 2030. All three begin with a Ka-band MRS-EST baseline link in the year 2000, and diverge from this baseline as time progresses. Note that there will be only one transition over the time frames. These three evolutionary paths are as follows:

The Ka-band Path

In this path the communications system remains at Ka-band to 2030 and beyond. Up to 100 Mbps, the MRS-EST connectivity is maintained, and upgrades are implemented by increasing the transmitter power and aperture, and the receiver aperture. When the requirement for a 1 Gbps return link materializes (after 2030), this is met by keeping the EST capability essentially fixed, and replacing the MRS transmitter with the MST which is free of the power and aperture constraints of the MRS. The virtue of this Ka-band path is that it is the path with the least technology risk and transition impact, and the most backward compatibility. For the 2010 MRS-EST link, the required transmitter power is about 200 W with a 5-m transmitter antenna and 70-m receiver antenna. In 2020, the transmitter power remains roughly the same while the transmitter and receiver antenna size will increase to 10 m and 110 m, respectively. For the 2030 MST-EST link, the transmitter/receiver antenna size remains at 10 m and 110 m, but the transmitter power of the MST can be as high as 3000 W.

The Optical Path

In this path, the system evolves from the Ka-band baseline to an optical link supported by a MRS-ERS link. The schedule of evolution is such that in 2010, the system remains a Ka-band MRS-EST system, but optical experimentation via a MRS-EST link is conducted as a test bed for the transition to the optical MRS-ERS system. By 2020, the system transition to an optical MRS-ERS system is complete, and future growth in data rate requirements in following years are met via increasing the MRS transmitter power and aperture. For the optical system, the increase in transmitter aperture will be small (from 30 cm to 50 cm) over the evolution (year 2010-2030). The major increase in requirement is the optical transmitter power (from 10 W to 90 W).

The MMW Path

In this path, the system evolves from the Ka-band baseline to a MMW frequency (as high as 300 GHz) supported by a MRS-ERS link. The schedule is such that in 2010, the system remains a Ka-band MRS-EST system, but by 2020 the transition to a MMW system is underway. The highest feasible MMW frequency available (consistent with adequate power and low noise amplifier technology development) is preferred in order to achieve the maximum gain for a given aperture. Increases in data rate requirements after 2020 would be met by increasing the MRS transmitter power and aperture. For a 300 GHz MRS-ERS link, 50 m receiver aperture is required and this aperture size will remain constant over the evolution. As the data rate requirement increases, the MRS transmitter power and aperture also increases from 170 W to 320 W and 5 m to 10 m, respectively.

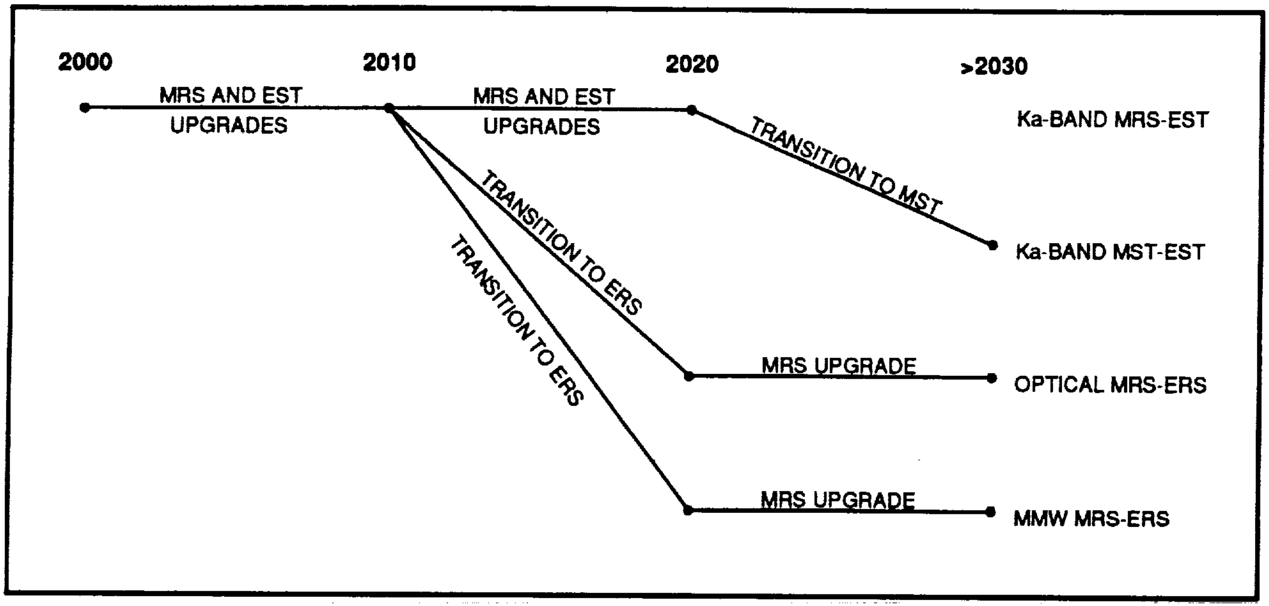

Exhibit 1-2: Transition Map for SEI Communication System

FREQUENCY	TIME FRAME	DATA RATE (MBPS)	MARS-EARTH CONNECTIVITY	TRANSMITTER		RECEIVER APERTURE (M)
				APERTURE (M)	POWER (W)	
32 GHz	2010	10	MRS-EST	5	200	70
	2020	100	MRS-EST	10	210	110
	2030	1000	MST-EST	10	3000	110
OPTICAL	2010	10	MRS-EST	0.3	10	10
	2020	100	MRS-ERS	0.4	25	15
	2030	1000	MRS-ERS	0.5	90	15
300 GHz	2020	100	MRS-ERS	5	170	50
	2030	1000	MRS-ERS	10	320	50

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Exhibit 1-3: Link Parameters for Leading Architectures

SECTION 2: SYSTEM REQUIREMENTS AND CONSTRAINTS

In Section 2-1, a set of applicable need dates (and relevant technology cut-off dates) for the 10 Mbps to 1 Gbps data rate requirements is identified. Alternative system connectivities are then discussed in Section 2.2. In order to meet the projected growth in data rate requirements at the various need dates, logical alternatives for evolution and transition in the Mars-Earth communications system are defined and discussed in Section 2.3.

2.1 PROJECTED NEED DATES

Based on the report of the Synthesis Group for SEI [1], time table for alternative architectures and missions to support the Mars exploration is listed in Exhibit 2-1. With this input, the estimated need dates and technology cut-off dates for applicable data rates in each scenario are presented in Exhibit 2-2. As shown in the table, expanding human presence is the primary driver for high data rate Mars-Earth communications. To support an expanding human presence, the data rate requirement may grow from an initial 10 Mbps (by year 2010) up to as much as 1 Gbps (beyond year 2030.) However, the growth in the data rate requirement will be gradual over a period of roughly 20 years, following the phased implementation of the evolving SEI mission. In conjunction with the need dates, a set of technology cut-off dates is also given. These dates provide a frame of reference for technology assessment of the implementations.

SEI Architecture	Precursor Missions	Cargo Missions	Piloted Missions
Mars Exploration	1998 2003 2005	2012 2014	2014 2016
Science Emphasis for the Moon and Mars	1998(2) 2003 2005 2007	2012 2014 2016 2018	2014 2016 2018 2020
Moon to Stay and Mars Exploration	1998(2) 2003 2005	2012 2014	2014 2016
Space Resource Utilization	1998(2) 2003 2005	2014 2016	2016 2018

Exhibit 2-1: Mission Time Table for Mars Exploration: Synthesis Report

	Data Rate Requirements		
	10 Mbps	100 Mbps	250 - 1000 Mbps
Need Date	2010	2020	> 2030
Technology Cut-Off Date	2002	2012	2022

Exhibit 2-2: Assumed Need Dates for Data Rate Requirements

2.2 DESCRIPTION OF ALTERNATIVE SYSTEM CONNECTIVITIES

As shown in Exhibit 2-3, four Mars-to-Earth communication links are considered in this study: MRS-EST, MRS-ERS, MST-ERS, and MST-EST. These are all long haul return links. The additional relatively short links needed for end-to-end connectivity, such as the Mars-to-MRS and ERS-to-Earth are not addressed in this study. The MRS-EST link is considered to be the baseline for the communications system supporting the Martian SEI mission in the year 2000. A key driving factor for any MRS-EST link is the Earth's atmosphere which limits the choice of frequency. For example, 60 GHz is not a feasible choice for this link because of the severe atmospheric absorption. The propagation effects of the Earth's atmosphere can be avoided by communicating between the MRS and a ERS, and thereby enable the use of higher frequencies with a corresponding increase in antenna gain for the same size aperture. Communications using a MST has the benefit of avoiding limiting factors of power, pointing stability and aperture size associated with the MRS. The MST could thus support the very high transmit gains and powers required to close a 1 Gbps link with a EST or ERS.

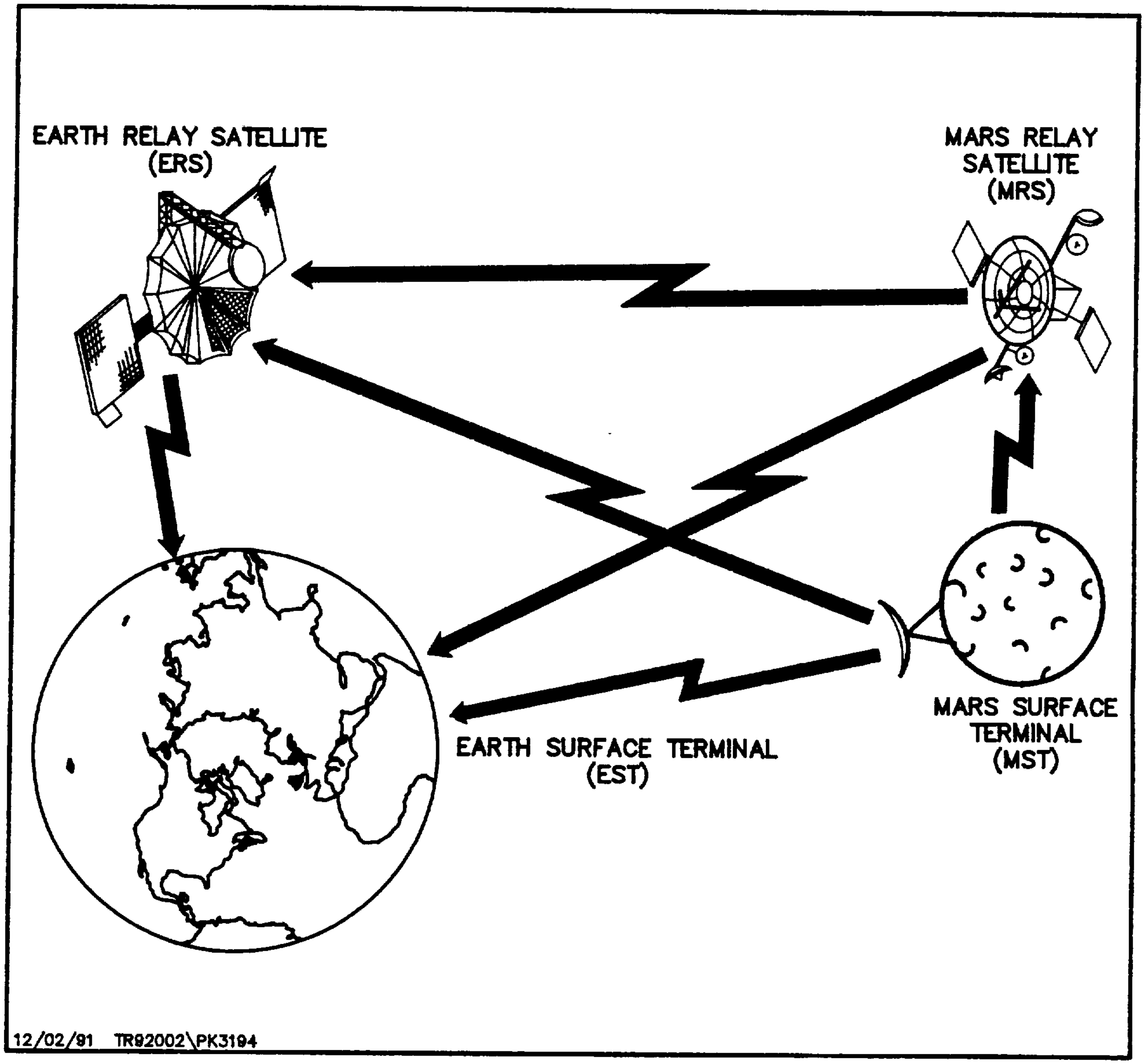

Exhibit 2–3: Mars–to–Earth Communication Links Considered

2.3 LOGICAL EVOLUTION AND TRANSITION

The currently planned Ka-band upgrade of the existing Deep Space Network (DSN) is considered as the SEI communication system baseline for the year 2000. In order to efficiently exploit the useful life of the installed communications infrastructure, the growth and evolution of the system should build upon existing infrastructure as much as possible. This will tend to minimize both system life-cycle costs and transition impacts to long-term missions. Thus, it is assumed that evolution from the baseline will be driven only by either the inability of the Ka-band baseline to meet a growing data rate requirement, or the promise of a lower life cycle cost with an alternative system. The evolutionary path taken will in general tend to minimize number of transitions and technology risk. In addition, the next transition stage from the Ka-band baseline should be upgradeable to 100 Mbps and beyond. New technologies limited to 100 Mbps or less are not as attractive as those that promise to support data rates well beyond 100 Mbps.

Exhibit 2-4 illustrates the possible evolutionary paths from the baseline system in the year 2000 to an advanced system that will support the Martian SEI beyond the year 2030. Note that at each milestone time frame one is confronted with a decision regarding the next step in system evolution. For the year 2010, the key decision is whether to extend the capability of the Ka-band MRS-EST baseline to 10 Mbps versus migrating to a higher frequency or to optical. By the year 2020, the decision involves both frequency and whether to migrate from a MRS-EST link to a MRS-ERS link. With the assumption of a semi-permanent human settlement sometime after the year 2030, it also becomes natural to consider whether a large surface based terminal on Mars (the MST) is a feasible way to support a high data rate link to a EST or ERS.

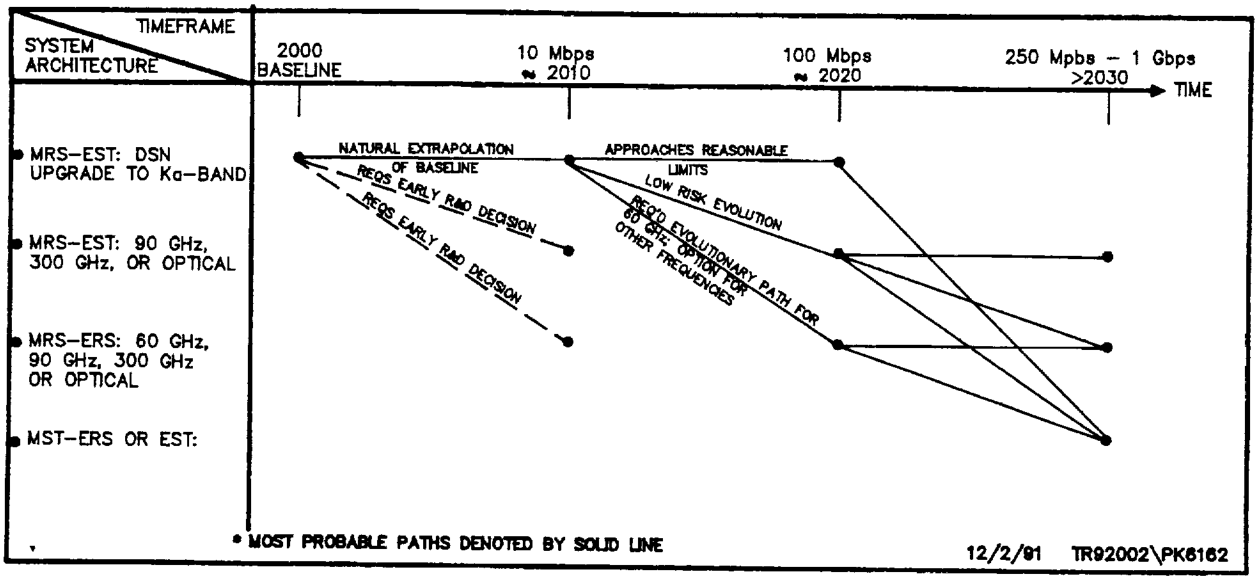

Exhibit 2–4: Potential Evoluationary Paths for Meeting Mars–Earth Return Link Requirements*

SECTION 3: IDENTIFICATION OF ATTRACTIVE ARCHITECTURES

The ability of a communications system architecture to meet the growing data rate requirements is largely dependent on the maturity of its supporting technologies. Accordingly, attractive architectures are identified via a process involving technology assessments and parametric link budget analysis: the comparison of the derived link parameters (e.g. power and aperture) for the alternative systems with the results of the technology assessments is a key factor in determining the relative attractiveness of alternatives.

3.1 APPROACH FOR DEFINING TECHNOLOGY LIMITS

The supporting technology for each of the four system elements, the MRS, EST, ERS, and MST of the space communication infrastructure has different limiting factors and constraints within the applicable time frames from 2010 to beyond 2030. These are qualitatively summarized in Exhibit 3-1.

The MRS terminal is an essential system element for all MRS-EST and MRS-ERS links. In the early phase of the SEI communications system implementation (2010), the major limiting factor for the MRS is the projected device state-of-the-art. However, in the mature stage of development (beyond 2030), the projection of device performance ceases to be a limiting factor, but is replaced by more fundamental constraints such as prime power, mass, and deployability. For 2010, the technology limits assumptions are based on projections from a data base of current device performance and technology readiness.

In the early stage of EST development, the key limiting factor is the practical evolution rate from the assumed baseline Ka-band 70 m effective aperture receiver. For example, it seems unlikely that the investment in the planned Ka-band upgrade to the DSN would be discarded as early as the year 2010. However, as time passes, additional system upgrades involving migration to new frequencies or investment in larger effective apertures become increasingly likely.

The ERS terminal requires a large on-orbit antenna or telescope. Initially, in 2010, the implementation is limited to those concepts which have been developed and demonstrated in other existing programs. Thus the ERS in 2010 has only a very limited set of options. However, in the far-term, all advanced concepts for large structures (including deployable and erectable apertures) in space are considered.

The feasibility of MST is appears likely only when implemented concurrently with the establishment of a Mars base with permanent human presence. Therefore this alternative is only considered in the latest stage of the evolution for the SEI communications system, beyond the year 2030. The key technology limit is probably the capability to transport and assemble modified Earth surface technology to Mars. It is assumed that much more prime power will be available to the MST as compared with MRS.

SYSTEM ELEMENT	APPLICABLE TIMEFRAME 2010	2020	>2030
MRS	• PROJECTIONS FROM DATA BASE OF CURRENT DEVICE PERFORMANCE AND TECHNOLOGY LEVEL OF DEVELOPMENT • CURRENT DEVICE SOA IS THE CHIEF LIMITING FACTOR	←——→	• CURRENT SOA NOT A LIMITING FACTOR • CHEIF LIMITING FACTORS ARE PRIME POWER NEED AND REQMT FOR DEPLOYABLE APERTURES
EST	• PROJECTIONS FROM DATA BASE OF CURRENT DSN IMPLEMENTATION AND PLANNED UPGRADE • REASONABLE EVOLUTION RATE IS THE CHIEF LIMITING FACTOR	←——→	• LARGE EFFECTIVE APERTURE ACHIEVABLE BY COHERENT COMBINATION OF MANY SMALLER 34M APERTURES • EVOLUTION RATE NOT A MAJOR CONSTRAINT
ERS	• BASED ON DEMONSTRATION AND CONCEPTS OF DEPLOYABLE ANTENNAS • REQUIREMENT FOR DEPLOYABLE APERTURE ASSUMED	←——→	• BASED ON ALL ADVANCED CONCEPTS FOR LARGE STRUCTURE IN SPACE • DEPLOYABLE AND ERECTABLE APERTURES ARE CONSIDERED
MST	N/A	N/A	• TRANSPORT & ASSEMBLY OF EARTH SURFACE TECHNOLOGY • MUCH MORE PRIME POWER AVAILABLE AS COMPARED WITH MRS

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Exhibit 3–1: Approach to Technology Assessment

3.2 PARAMETRIC LINK BUDGET ANALYSIS

The link budget analysis generates range of system parameters that accommodate each data rate at a given time frame. Parameters such as required transmit power and antenna aperture size can be calculated with inputs from preliminary technology assessment on key system components. Parametric curves are also developed to provide a point of departure for transmit power versus aperture trades.

The basic link budget assumptions are listed in Exhibit 3-2. One key parameter is the range between Mars and Earth which is a variable depending on the relative positions of the two planets. The cumulative distribution of Earth-Mars distances (from year 2010 to year 2020) had been calculated by NASA LeRC [2] and is presented in Exhibit 3-3. As shown, a range of 2.5 AU corresponds to approximately 90% of cycle which is considered reasonable for Mars-Earth communication links. Other assumptions are based on typical digital RF or optical link budget calculations. Digital modulation is assumed in all links. Digital modulation is compatible with other signal processing functions such as data compression and channel coding. In this study, concatenate coding is used in all RF links to take advantage of the coding gain.

- RANGE = 2.5 AU CORRESPONDS TO 90% OF CYCLE (MARS–EARTH DISTANCE)
- 10 BER
- CHANNEL CODING FOR ALL RF LINKS (3.5dB REQUIRED Eb/No)
- 3 dB LINK MARGIN
- SUN ILLUMINATED MARS BACKGROUND

Exhibit 3–2: Basic Link Budget Assumptions

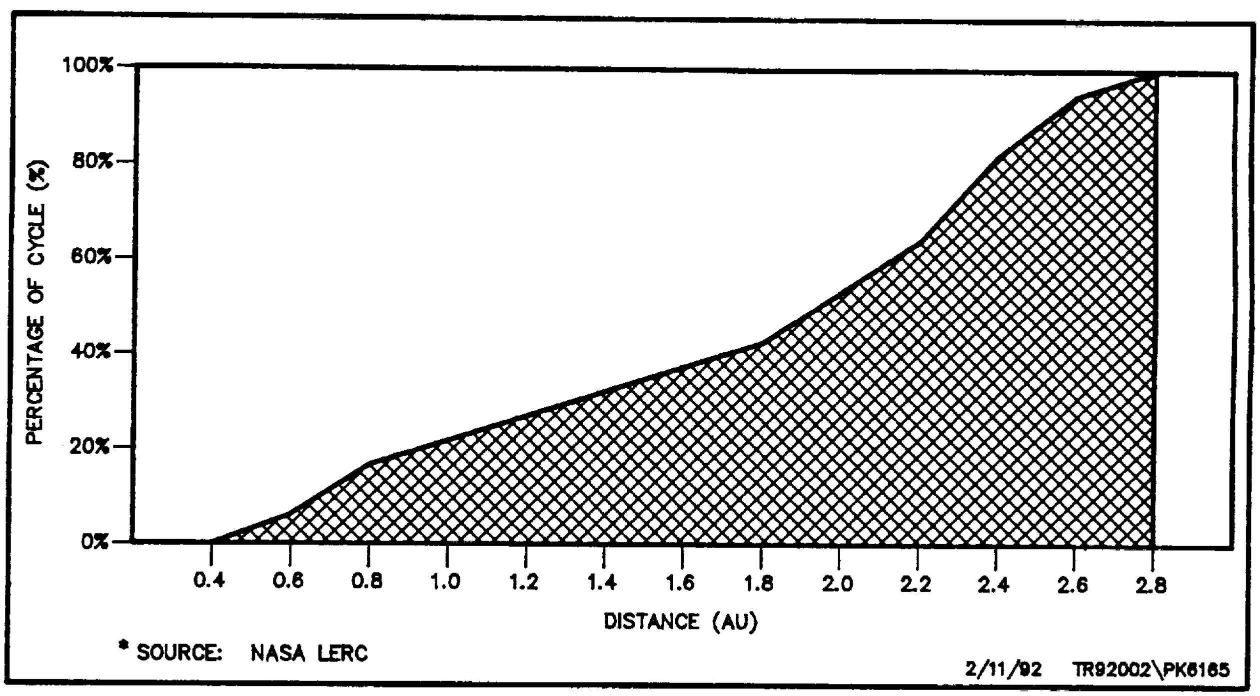

Exhibit 3–3: Cumulative Distribution of Earth–Mars Distances (2010 to 2018)

In Exhibit 3-4, key system parameter constraints such as antenna aperture size, transmitter power, and receiver sensitivity for each architecture and time frame are presented. The range of values given in the table reflected both trade space and variation of alternative RF and optical implementations; i.e., 32 GHz vs. 94 GHz, optical direct detection vs. heterodyne. The size of MRS and ERS antennas is limited by technology constraints (e.g., surface tolerance) and stowing capability. The transmitter power and receiver sensitivity are either derived or projected from state-of-the-art RF and optical technology.

	10 Mbps (Year 2010)		100 Mbps (Year 2020)		250 - 1000 Mbps (Beyond Year 2030)	
	RF	**Optical**	**RF**	**Optical**	**RF**	**Optical**
Antenna Aperture Size						
– MRS	1-5 m	20-30 cm	5-10 m	20-50 cm	5-15 m	20-100 cm
– MST	NA	NA	NA	NA	10-15 m	20 - 100 cm
– ERS	5-40 m	5-10 m	10-50 m	10-15 m	15-50 m	15-20 m
– EST	10-70 m	5-15 m	20-110 m	15-20 m	30-150 m	20-30 m
XMitter Power						
– MRS	50-200 W	1-10 W	100-300 W	10-30 W	150-400 W	20-40 W
– MST	NA	NA	NA	NA	1-10 KW	20-40 W
Receiver Sensitivity	25-500° K	10-100 Photons/Bit	15-200° K	10-50 Photons/Bit	10-200° K	5-30 Photons/Bit

- ANTENNAS USED FOR ERS TERMINALS:
  - RF: LARGE DEPLOYABLE ANTENNA
  - OPTICAL: PARABOLIC MIRROR
- SIZE OF MRS AND ERS ANTENNAS IS LIMITED BY TECHNOLOGY CONSTRAINTS (E.G., SURFACE TOLERANCE) AND STOWING CAPABILITY
- RANGE OF VALUES REFLECTED BOTH TRADE SPACE AND VARIATION OF ALTERNATIVE RF AND OPTICAL IMPLEMENTATIONS; I.E., 32 GHz vs 94 GHZ, DD vs HET

Exhibit 3-4: Assumed System Parameter Constraints

Given the assumptions and link parameters discussed above, example parametric curves of attractive communications systems architectures at key time frames are presented in Exhibits 3-5, 3-6 and 3-7.

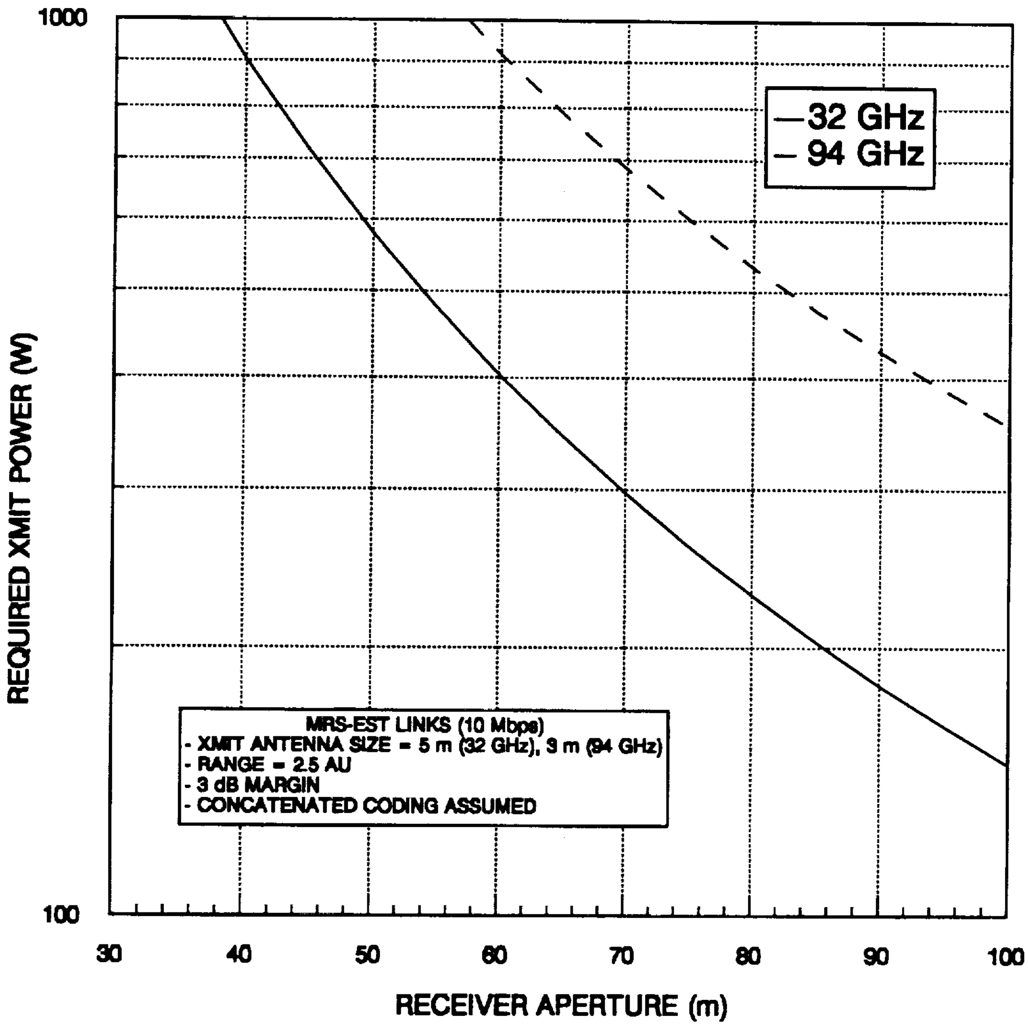

Exhibit 3-5: Required Xmit Power vs. Rcvr Aperture For MRS-EST Links (10 Mbps)

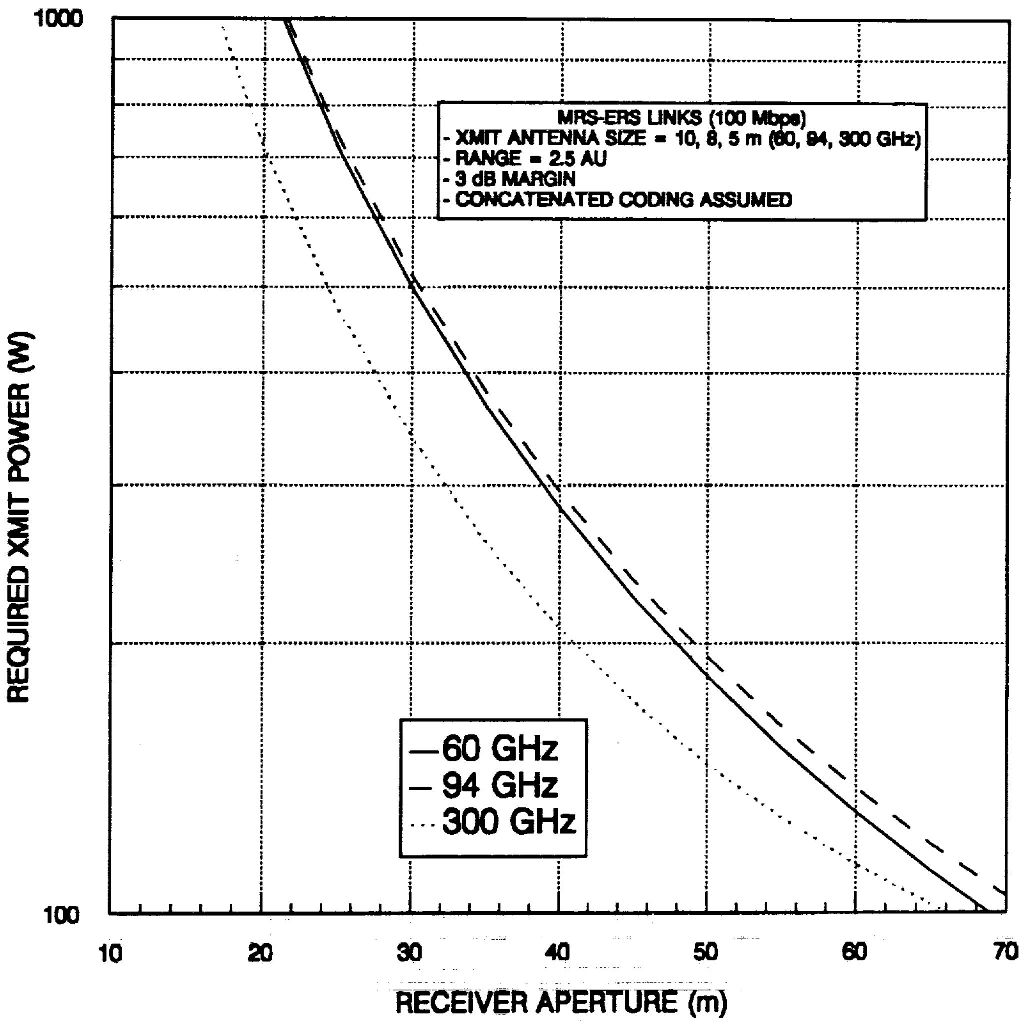

Exhibit 3-6: Required Xmit Power vs. Rcvr Aperture For MRS-ERS Links (100 Mbps)

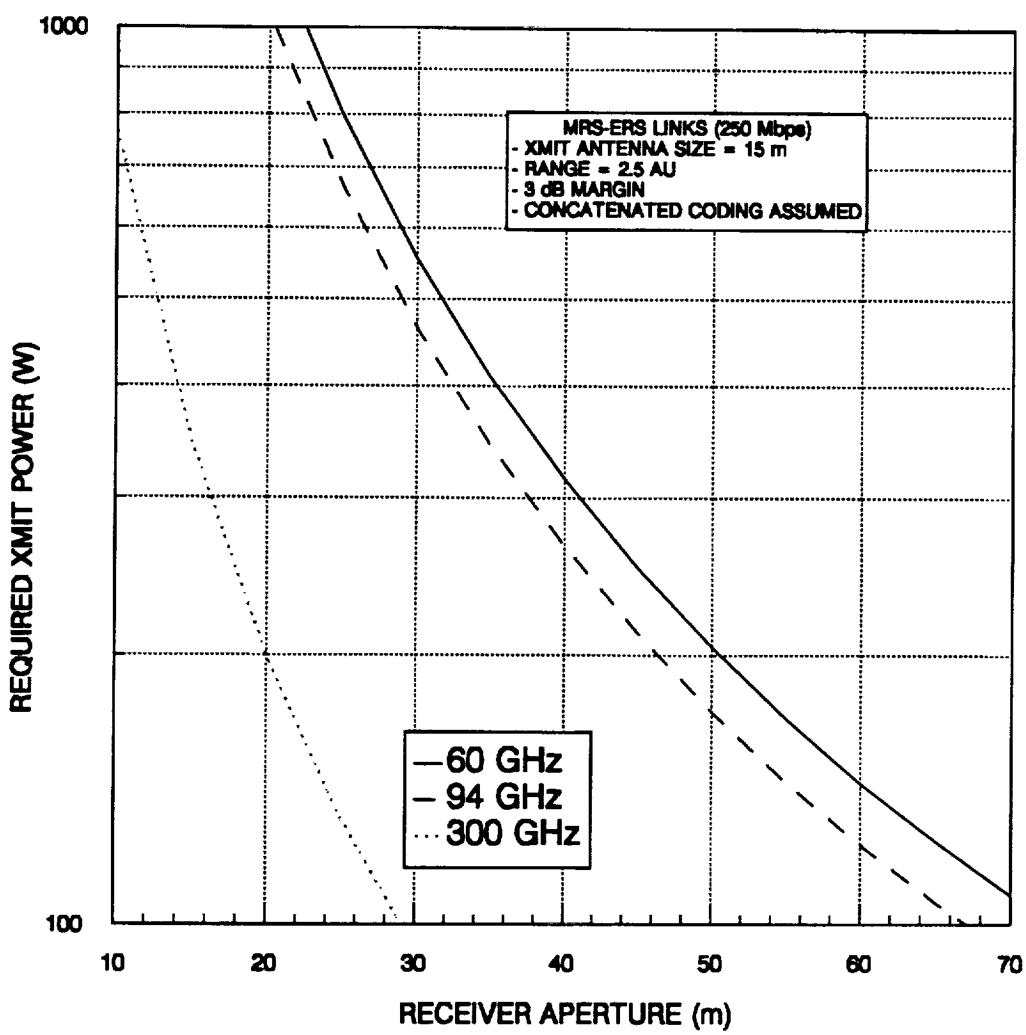

Exhibit 3-7: Required Xmit Power vs. Rcvr Aperture For MRS-ERS Links (250 Mbps)

3.3 EVALUATION OF ARCHITECTURE ALTERNATIVES

Leading architectures (along with their key link parameters) for Mars-Earth link implementation at each need dates are delineated in Exhibit 3-9 , 3-10 , 3-11 . The selection is based on link budget analysis and preliminary technology assessment of all the alternatives. Rationales for the selection are discussed below.

To support a 10 Mbps link in the year 2010, a ground-based terminal (EST) is probably the most logical and least risky choice for the Earth region node. A 32 GHz system is preferred for the 10 Mbps MRS-to-EST link implementation because of its mature technology base and for continuity with the assumed year 2000 baseline. The frequencies of 60 GHz and 300 GHz are not viable alternatives due to large absorption by the atmosphere. A 94 GHz system may be feasible, but still requires very high transmit power in order to overcome atmospheric attenuation and is therefore regarded as a high risk alternative. An optical direct detection MRS-EST system is a viable alternative to the 32 GHz baseline system. This system requires only modest transmit power and much smaller transmitter and receiver aperture sizes than any RF or MMW system. However, this implementation typically needs spatial diversity with 3 or more sites to combat cloud cover. The optical heterodyne detection scheme is not selected due to the detrimental impact of atmospheric turbulence on the coherent signal.

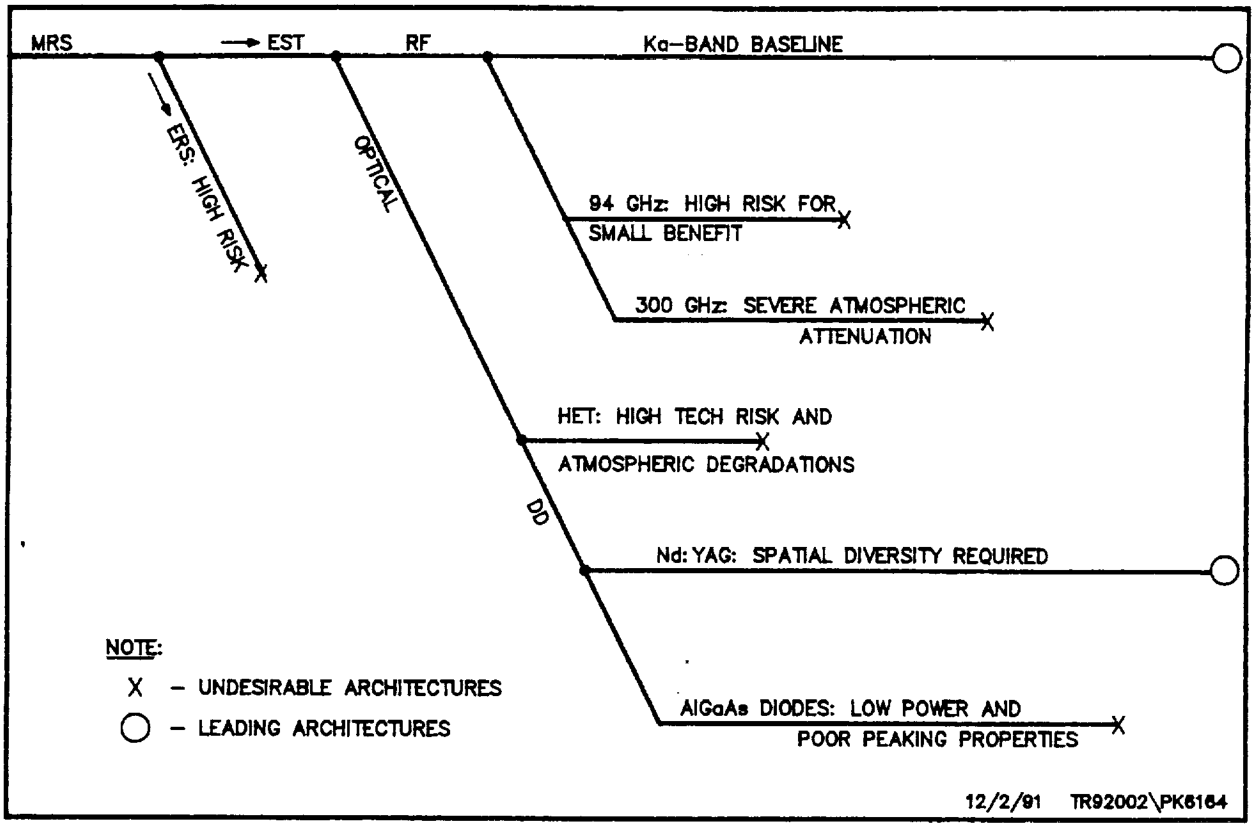

Exhibit 3–9: Identification of Leading Architectures at 10 Mbps (YR 2010)

For a 100 Mbps link (year 2020) the upgraded Ka-band MRS-EST is still a viable option, but the required power and apertures are large. This architecture has relatively low transition risk and complete backward compatibility with the forerunner Ka-band system. In this time frame, however, as an alternative to the continued extrapolation of the year 2000 baseline, the implementation of a large ERS aperture at RF, MMW or optical frequencies appears to be feasible. By that time, it is expected that the technology of deploying or erecting large apertures in space will mature sufficiently to achieve the required tolerances on the surface deformation. Currently, a number of approaches to building the required apertures are being explored so that by 2020, it is reasonable to anticipate apertures up to 50 m for RF/MMW and 15 m for optical. In this time frame, the optical receiver on the ERS could utilize coherent detection schemes (i.e., heterodyne and homodyne) as well as direct detection schemes.

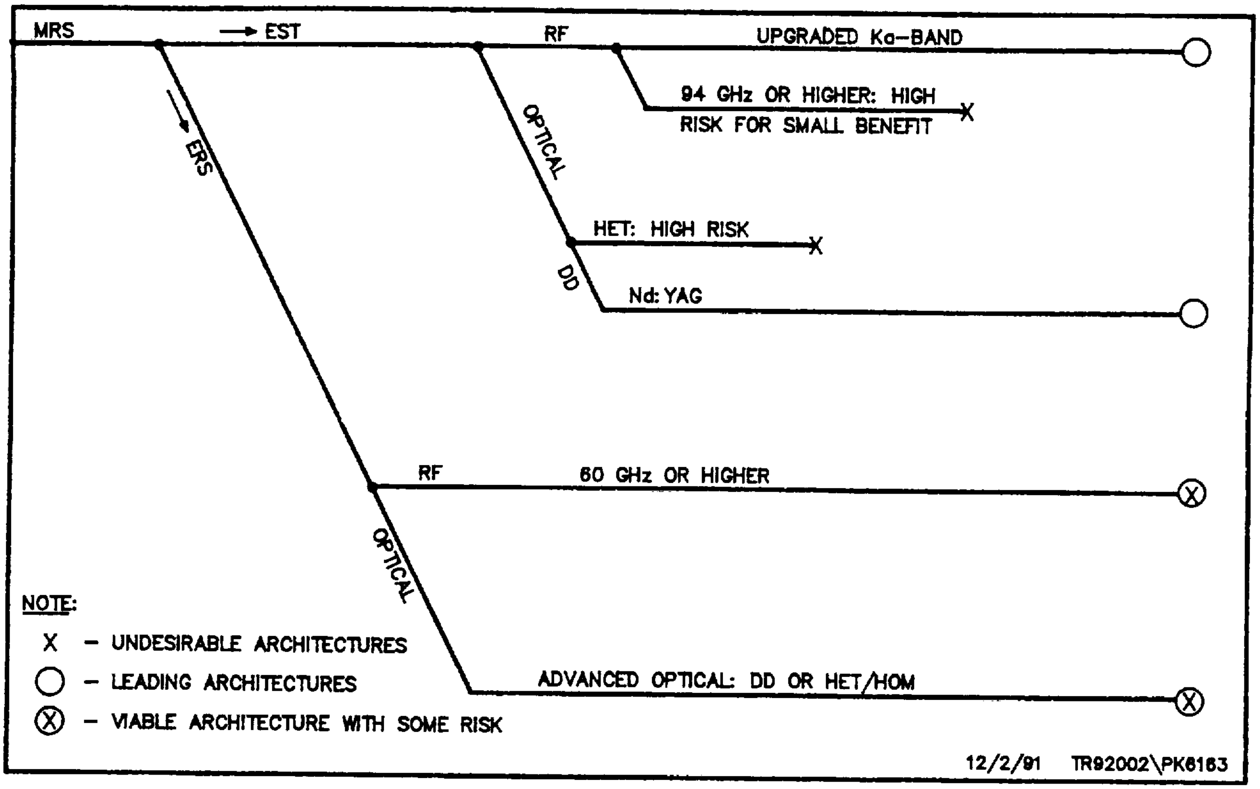

Exhibit 3–10: Identification of Leading Architectures at 100 Mpbs (YR 2020)

In the year 2030, it appears that the Ka-band MRS-EST architecture could not reasonably support a 1 Gbps data link. However, as human activity expands, the option of using a large high power MST to close a 1 Gbps data rate link with the EST becomes a serious option. A Mars based 32 GHz terminal can have access to a large power supply (as compared to a MRS terminal) and transmit from a very stable platform. Operation of the MST in the harsh Martian environment would have to be carefully studied. As an alternative to this, a MRS-ERS link using MMW or optical frequencies could be implemented to support the assumed 1 Gbps requirement beyond 2030.

The link parameters for leading architectures are presented in Exhibit 3-12.

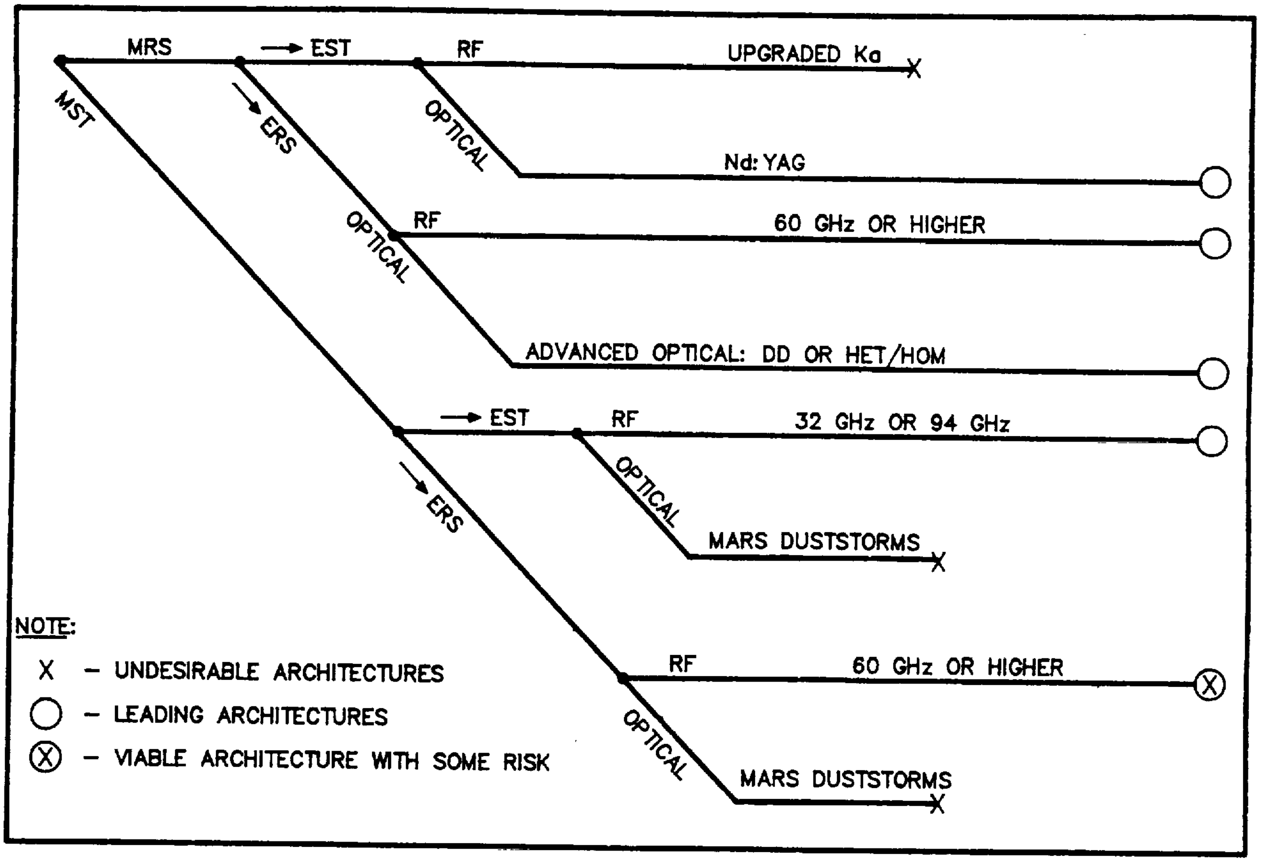

Exhibit 3–11: Identification of Leading Architectures at 1000 Mbps (> YR 2030)

FREQUENCY	TIME FRAME	DATA RATE (Mbps)	MARS–EARTH CONNECTIVITY	TRANSMITTER		RECEIVER APERTURE (M)
				APERTURE (M)	POWER (W)	
32 GHz	2010 2020 2030	10 100 1000	MRS–EST MRS–EST MST–EST	5 10 10	200 210 3000	70 110 110
OPTICAL	2010 2020 2030	10 100 1000	MRS–EST MRS–ERS MRS–ERS	0.3 0.4 0.5	10 25 90	10 15 15
300 GHz	2020 2030	100 1000	MRS–ERS MRS–ERS	5 10	170 320	50 50

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Exhibit 3–12: Link Parameters for Leading Architectures

SECTION 4: DESCRIPTION OF LEADING CANDIDATES

As discussed above, the leading candidates for each need dates are selected based on link budget analysis and technology assessment. The leading candidates identified in Section 3 are:

1. MRS-EST.
   a. RF.
   b. Optical.
2. MRS-ERS.
   a. RF/MMW.
   b. Optical.
3. MST-EST.
   a. RF.

Below, key features of the leading candidates are briefly described in terms of connectivities, link parameters, supporting technology, and ROM cost and mass estimates.

4.1 DESCRIPTION OF RF MRS-EST LINK

The goals of RF MRS-EST communications link are given below:

Time Frame	Data Rate (Mbps)	Frequency	Transmitter		Receiver Aperture (m)
			Aperture (m)	Power (W)	
2010	10	32 GHz	5	200	70
2020	100	32 GHz	10	300	110

Technology assessment of key items such as:

1. DSN antennas and LNA,
2. MRS antenna and HPA,

will be discussed in Section 4.1.1. In addition, ROM cost analysis for the RF DSN terminal will be given in Section 4.1.2.

4.1.1 RF MRS-EST Technology Assessment

Ground Segment

The ground terminal technology of this system will be based on the planned Ka-band upgrade of the DSN. This involves the upgrade of the 34 m DSN antennas to Ka-band and the development of a Ka-band maser amplifier at 1.6° K (liquid Helium) with <25° K noise temperature, 3 GHz bandwidth, and >30 dB Gain. The effective receiver aperture is made up by coherently combining n 34-m antennas (e.g., n = 4 for the 70 m receiver aperture.) Antenna technology will be likely evolved from the Ka-band link experiment (KABLE) with Mars observer and Goldstone 34-m DSS-13 antenna and the CRAF/CASSINI (1996) and solar probe missions. The 1990's baseline technology for the DSN RF subsystem is summarized in Exhibit 4-1.

Space Segment

The MRS payload technology is focused on high power transmitter sources and large RF antennas. Both deployable and solid parabolic antennas up to 5 m are well within the state-of-the-art. However, the solid reflector size is limited by launch vehicle (e.g., maximum 4.5 m diameter if launched by space shuttle.) Other supporting antenna technology such as pointing/acquisition and tracking (PAT) system is also available given the >1 mrad Ka-band beam width which makes open loop antenna pointing feasible. For example, PAT can be done by using a monopulse tracking system. Ka-band TWTAs with high output

- EVOLUTION IN OPERATING FREQUENCIES
  - KA-BAND LINK EXPERIMENT (KABLE) WITH MARS OBSERVER AND GOLDSTONE 34M DSS-13 ANTENNA WILL PROVIDE DATA ON KA-BAND TELEMETRY LINK
  - CRAF/CASSINI (1996) AND SOLAR PROBE WILL EVOLVE OPERATIONAL BASELINE TO 32 GHZ (TELEMETRY)/34 GHZ (Cmd) FOR FUTURE DEEP SPACE MISSIONS
- LOW NOISE AMPLIFIER (LNA) TECHNOLOGY
  - KA-BAND MASER AMPLIFIER AT 1.6-K (LIQUID HELIUM) UNDER JPL DEVELOPMENT (< 25°K NOISE TEMP., 3 GHZ BW, > 30 DB GAIN)
- ANTENNA TECHNOLOGY BASELINE
  - UPGRADE OF DSN ANTENNAS TO KA-BAND (34 M) AND EVOLUTION OF "STANDARD" 34 M SUBNET TO "HIGH EFFICIENCY FEED (HEF)" MULTIFREQUENCY (S, X, AND KA) ANTENNAS
  - JPL DEVELOPMENT OF BEAM WAVEGUIDE OPTICS AND FREQUENCY SELECTIVE SURFACES WILL ENABLE INCREASED EFFICIENCY AND MULTIFREQUENCY OPERATIONS ON USER S/C AND DSN

Exhibit 4-1: RF MRS-EST (DSN 1990 Baseline) Technology Assessment

power (>200 watts) and high efficiency (>30%) are available now (1991) and will almost certainly be space qualified by year 2010.

4.1.2 Ka-Band Ground Terminal ROM Cost Estimation

The EST Rough Order Magnitude (ROM) cost estimate model is based on the second TDRSS ground terminal (STGT) ROM cost and cost breakdown. Ka-band 34-m antenna cost estimated by JPL has been used as input to the model. The cost estimates include equipments and facilities for 3 sites which provide 24-hours link coverage. The cost estimates assume completely new EST construction. This implies that cost savings may be achieved by sharing resources and facility with existing infrastructure. In addition, all user data is assumed to be routed back to CONUS for processing.

The ROM costs for 2010 and 2020 Ka-band GTs are summarized in Exhibit 4-2. The key cost driver is the antenna systems. For the 2010 GT system, four 34-m antennas (equivalent to a 70 m aperture) are required at each of three sites. For the 2020 GT system, ten of these 34-m antennas are needed at each of three sites. The detail cost estimates for both GT systems are presented in Exhibit 4-3 and 4-4.

	GT (2010)*	GT (2020)**
Facilities	16,900	41,000
Antenna Systems	126,900	314,100
User Services	64,100	70,900
Depot	18,700	25,300
Program Level	52,800	88,000
Total	**279,400**	**539,300**

* 4 x 34-m antennas at each of 3 sites
** 10 x 34-m antennas at each of 3 sites

Note: All costs in FY 91 $K

Exhibit 4-2: Ka-Band GT ROM Costs Summary

ITEM	STGT ROM 91		STGT ROM 91		% OF STGT ROM		FY 91 $K	
	NREC	REC	NREC	REC	NREC	REC	NREC	REC
1. FACILITIES								
DESIGN	6,200	6,200	6,448	6,448	20%	10%	1,300	600
BUILDING, LANDSCAPE, SECURITY, ETC.	–	14,710	–	15,298	–	30%	–	4,600
							1,300	5,200
1st SITE								5,200
2nd SITE								5,200
3rd SITE								
SUBTOTAL							1,300	15,600
2. ANTENNA SYSTEMS	2,000	10,000	2,080	10,400	100%	400%	2,100	41,600
4 X 34-M ANTENNA/SITE, LNAs, FEEDS, WAVEGUIDE, ETC.								
1st SITE							2,100	41,600
2nd SITE								41,600
3rd SITE								41,600
SUBTOTAL							2,100	124,800
3. USER/SATELLITE SERVICES	100	900	104	936	100%	75%	100	700
DIVIDERS/COMBINERS, ETC.	7,468	8,004	7,767	8,324	100%	50%	7,800	4,200
HIGH RATE USER CHAINS	581	1,590	604	1,654	0%	0%	0	0
TT&C CHAINS	5,384	5,688	5,599	5,916	50%	50%	2,800	3,000
PMMS	1,858	400	1,932	416	100%	100%	1,900	400
CTFS	3,418	4,870	3,555	5,065	35%	35%	1,200	1,800
DIS/ICS	974	5,443	1,013	5,661	25%	25%	300	1,400
OPS/DATA LAN (H/W)	65,217	3,495	67,826	3,635	45%	100%	30,500	3,600
(S/W)	6,500	6,250	6,760	6,500	30%	30%	2,000	2,000
OPS CTR					–	–	–	400
LOCAL SPARES (3% REC H/W)								
SUBTOTAL							46,600	17,500
4. DEPOT								
FACILITIES	2,091		2,175		30%	–	700	–
TEST EQUIPMENT, JIGS, ETC.	6,901		7,177		30%	–	2,200	–
HW SPARES (Site Spares x 3 Sites x					–	–	12,000	–
10 Years)					–	–	3,800	–
SMTF								
SUBTOTAL							18,700	0
5. EARTH STATION PROGRAM LEVEL								
SYSTEMS ENGINEERING (25% NRE-							28,600	
C/REC, 1st SITE)							24,200	–
PROGRAM MANAGEMENT (15% Total Program)								
SUBTOTAL							52,800	0
							121,500	157,900
GRAND TOTAL							279,400	

*Note: Cost Basis for User / Satellite Services is one SGLT within STGT

Exhibit 4-3: 2010 Ka-Band GT ROM Costs (Initial Deployment)

ITEM	STGT ROM 91		STGT ROM 91		% OF STGT ROM		FY 91 $K	
	NREC	REC	NREC	REC	NREC	REC	NREC	REC
1. **FACILITIES**								
DESIGN	6,200	6,200	6,448	6,448	40%	20%	2,600	1,300
BUILDING, LANDSCAPE, SECURITY, ETC.	–	14,710	–	15,298	–	75%	–	11,500
							2,600	12,800
1st SITE								12,800
2nd SITE								12,800
3rd SITE								
SUBTOTAL							2,600	38,400
2. **ANTENNA SYSTEMS**	2,000	10,000	2,080	10,400	100%	1000%	2,100	104,000
10 X 34-M ANTENNA/SITE, LNAs, FEEDS, WAVEGUIDE, ETC.								
1st SITE							2,100	104,000
2nd SITE								104,000
• 3rd SITE								104,000
SUBTOTAL							2,100	312,000
3. **USER/SATELLITE SERVICES**	100	900	104	936	110%	100%	100	900
DIVIDERS/COMBINERS, ETC.	7,468	8,004	7,767	8,324	100%	110%	7,800	9,200
HIGH RATE USER CHAINS	581	1,590	604	1,654	0%	0%	0	0
TT&C CHAINS	5,384	5,688	5,599	5,916	50%	50%	2,800	3,000
PMMS	1,858	400	1,932	416	100%	100%	1,900	400
CTFS	3,418	4,870	3,555	5,065	50%	50%	1,800	2,500
DIS/ICS	974	5,443	1,013	5,661	40%	25%	400	1,400
OPS/DATA LAN (H/W)	65,217	3,495	67,826	3,635	45%	100%	30,500	3,600
(S/W)	6,500	6,250	6,760	6,500	30%	30%	2,000	2,000
OPS CTR					–	–	–	600
LOCAL SPARES (3% REC H/W)								
SUBTOTAL							47,300	23,600
4. **DEPOT**								
FACILITIES	2,091		2,175		60%	–	1,300	–
TEST EQUIPMENT, JIGS, ETC.	6,901		7,177		30%	–	2,200	–
HW SPARES (Site Spares x 3 Sites x 10 Years)					–	–	18,000	–
SMTF					–	–	3,800	–
SUBTOTAL							25,300	0
5. **EARTH STATION PROGRAM LEVEL**								
SYSTEMS ENGINEERING (25% NREC/REC, 1st SITE)							48,100	
PROGRAM MANAGEMENT (15% Total Program)							39,900	–
SUBTOTAL							88,000	0
							165,300	374,000
GRAND TOTAL							539,300	

*Note: Cost Basis for User / Satellite Services is one SGLT within STGT

Exhibit 4-4: 2020 Ka-Band GT ROM Costs (Initial Deployment)

4.2 DESCRIPTION OF OPTICAL MRS-EST LINK

The goals of optical MRS-EST communications link are given below:

Time Frame	Data Rate (Mbps)	Frequency	Transmitter		Receiver Aperture (m)
			Aperture (m)	Power (W)	
2010	10	optical	0.3	10	10

Technology assessment of key items such as:

1. Optical large apertures,

2. High power laser transmitters,

will be discussed in Section 4.2.1. System performance issues will be addressed in Section 4.2.2. In addition, ROM cost analysis for the optical ground terminal will be given in Section 4.2.3.

4.2.1 Optical MRS-EST Technology Assessment

Ground Segment

As an alternative to the RF system, an optical implementation of the MRS-to-EST link using a direct detection 128-ary PPM scheme is envisioned with the following characteristics: 20 photons/bit receiver sensitivity, a 10 watt Nd:YAG laser transmitter, a 30 cm transmit aperture and a 10 m receiver aperture. This level of power is barely beyond the state-of-the-art and will almost certainly be achieved by 2002 (technology cut-off date.) For the ground segment of the link, JPL is currently studying the feasibility of a 10 m photon bucket receiver. The design is similar to the Keck Telescope located at Mauna Kea, Hawaii. The primary collector will consist of light-weight, rigidly mounted, hexagonal reflecting segments. The design concept is basically an assembly of large aperture from many sub-apertures with active and continuous segment alignment. Construction techniques for light weight mirrors are available from at least four sources:

1. Post and Plate Construction (Kodak).

2. Evaporated SiC (CVD).

3. Jet Abrasion (ITEK).

4. SiC Fused Sand (UTOS).

In order to maintain communications at small solar elongations, heat (solar) rejection device is required. A sunshade or a diamond substrate filter can be used to reject direct sunlight. Both techniques are well within state-of-the-art. However, diamond substrate filter is a much preferred solution due to its simplicity and light weight. Sunshade is heavy and bulky and must be mounted either on the dome or on the telescope.

Space Segment

One of the key components for optical MRS terminal is the high power laser transmitter. For 2010 system, AlGaAs diode pumped Nd:YAG (direct detection) laser is the prime candidate for implementation. Other types of lasers such as: AlGaAs diode arrays and CO_2 will only be considered in year 2020 or beyond for advanced optical implementations. The output power of Nd:YAG laser is dependent on its operating mode. The two most common operating modes are: Q-switched mode and cavity dumped mode. Nd:YAG lasers operating in Q-switched mode can generate 1500-2000 watts peak power (150 mW average) at 10-20 KHz modulation rate. With the same average power, the laser can generate 50 watts peak power at 10's MHz modulation rate. High average power (10 W) Nd:YAG laser for laser ranging application is under development at GE laboratory. The fundamental operating frequency of Nd:YAG laser is at 1064 nm. However, the laser can be frequency doubled to 532 nm through nonlinear crystal conversion (with approximately 50% loss.) The frequency doubled Nd:YAG has a significantly higher detector efficiency (0.8 - 0.9) than its counterpart at 1064 nm. The beam divergence of the 532 nm Nd:YAG is also only half that of the 1064 nm. As a result, there is a 4X increase in power density for the 532 nm Nd:YAG. However, the end-to-end efficiency at 532 nm is only about 3 - 5% as compared to 5 - 10% at 1064 nm. Therefore, the key driver for Nd:YAG technology is the increase in end-to-end efficiency and lifetime.

The other laser candidates: AlGaAs diode arrays, CW Nd:YAG (for coherent detection), and CO_2 lasers are more likely to be applicable in the 2020 time frame. ESA has demonstrated a 1.3 W average output power CO_2 laser with 20% efficiency. One major concern for CO_2 laser is its uncertain lifetime and reliability although some progress had been made to demonstrate 20,000 hours sealed-off operation in laboratory. Single substrate AlGaAs diode arrays hold promise of several watts output power in 5 - 10 years. The power conversion efficiency of AlGaAs diode array is high (up to 50%.) The technology driver of diode arrays is high power output with narrow spectral linewidth (which is required for heterodyne modulation.) For homodyne detection using Nd:YAG laser, external modulator is required. Currently, commercial electro-optic modulators have relatively low power capability (approx. 300 mW.) An externally modulated 1-W CW Nd:YAG is under development by Dornier in Germany.

4.2.2 Optical MRS-EST System Issues

Spatial Diversity

One major requirement for the space-to-ground optical link is spatial diversity with 3 or more sites in order to combat cloud attenuation. Cloud cover results in link outages. However, through 3-fold diversity, 95% link availability can be achieved. Example diversity results are given in Exhibit 4-5. A

BEST LOCAL DIVERSITY SYSTEM	BEST LARGE-SCALE DIVERSITY SYSTEM OF M STATIONS			
(WSNM, M = 3)	M = 2	3	4	5
TUCSON ROSWELL ABILENE	DAGGET ROSWELL	DAGGET ROSWELL VERO BEACH	DAGGET ROSWELL VERO BEACH HUNTSVILLE	DAGGET VERO BEACH TUCSON ABILENE GSFC
0.921	0.912	0.962	0.981	0.991

- LINK AVAILABILITIES ABOVE 95% CAN BE ACHIEVED
- LARGE-SCALE DIVERSITY SYSTEMS OUT-PERFORM LOCAL DIVERSITY SYSTEM (FOR EQUAL NUMBER OF TERMINALS)
- CLOUD COVER STATISTICS BASED ON ALLEN/MALICK MODEL

Exhibit 4-5: Summary of Diversity Results for NASA Locations

side issue relevant to spatial diversity is the potential requirement of active beam switching due to the narrow transmit beam width (relative to angle subtended by the Earth.) This issue requires further investigation.

MRS Pointing

Before actual communication can be proceeded, mutual acquisition, pointing and tracking between MRS terminal and EST terminal must be first established. The pointing, acquisition, and tracking requirements of optical systems being considered are very stringent (i.e., sub-microradian tracking.) In addition, because of the long signal delay, close-looped tracking and pointing is not possible. JPL is now investigating the possibility of using a high bandwidth Earth imaging array to support pointing (open-looped.) [3]

4.2.3 Optical GT ROM Costs

Similar to the RF system, the optical EST ROM cost estimate model is also based on the second TDRSS ground terminal (STGT) ROM cost and cost breakdown. Telescope system cost estimated by JPL has been used as input to the model. The cost estimates include equipments and facilities for 3 sites which provide spatial diversity to combat cloud cover. However, the cost for linking diversity sites together is not included in the estimates which can be significantly high. Like the RF system, the cost estimates assume completely new EST construction. The ROM costs for the year 2010 optical GT are summarized in Exhibit 4-6. The detailed ROM costs are given in Exhibit 4-7.

Facilities	16,800
Telescope Systems	81,100
User Services	67,600
Depot	24,200
Program Level	48,800
Total	**238,600**
Note: All costs in FY 91 $K	

Exhibit 4-6: Optical GT ROM Costs Summary

ITEM	STGT ROM 91		STGT ROM 91		% OF STGT ROM		FY 91 $K	
	NREC	REC	NREC	REC	NREC	REC	NREC	REC
1. **FACILITIES**								
DESIGN	6,200	6,200	6,448	6,448	20%	10%	1,300	600
BUILDING, LANDSCAPE, SECURITY, ETC.	–	14,710	–	15,298	–	30%	–	4,600
1st SITE							1,300	5,200
2nd SITE								5,200
3rd SITE								5,200
SUBTOTAL							1,300	15,600
2. **ANTENNA SYSTEMS** TELESCOPE, OPTICS, PATS, DETECTORS, ETC.	3,000	25,000	3,120	26,000	100%	100%	3,100	26,000
1st SITE							3,100	26,000
2nd SITE								26,000
3rd SITE								104,000
SUBTOTAL							3,100	78,000
3. **USER/SATELLITE SERVICES**	100	900	104	936	100%	75%	100	700
DIVIDERS/COMBINERS, ETC.	7,468	8,004	7,767	8,324	100%	50%	7,800	4,200
HIGH RATE USER CHAINS	581	1,590	604	1,654	0%	0%	0	0
TT&C CHAINS	5,384	5,688	5,599	5,916	80%	80%	4,500	4,700
PMMS	1,858	400	1,932	416	100%	100%	1,900	400
CTFS	3,418	4,870	3,555	5,065	35%	35%	1,200	1,800
DIS/ICS	974	5,443	1,013	5,661	25%	25%	300	1,400
OPS/DATA LAN (H/W)	65,217	3,495	67,826	3,635	45%	100%	30,500	3,600
(S/W)	6,500	6,250	6,760	6,500	30%	30%	2,000	2,000
OPS CTR					–	–	–	500
LOCAL SPARES (3% REC H/W)								
SUBTOTAL							48,300	19,300
4. **DEPOT**								
FACILITIES	2,091		2,175		50%	–	1,100	–
TEST EQUIPMENT, JIGS, ETC.	6,901		7,177		60%	–	4,300	–
HW SPARES (Site Spares x 3 Sites x 10 Years)					–	–	15,000	–
SMTF					–	–	3,800	–
SUBTOTAL							24,200	0
5. **EARTH STATION PROGRAM LEVEL**								
SYSTEMS ENGINEERING (25% NREC/REC, 1st SITE)							25,800	
PROGRAM MANAGEMENT (15% Total Program)							23,000	–
SUBTOTAL							48,800	0
							125,700	112,900
GRAND TOTAL							238,600	

*Note: Cost Basis for User / Satellite Services is one SGLT within STGT

Exhibit 4-7: 2010 Optical GT ROM Costs (Initial Deployment)

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4.3 DESCRIPTION OF RF/MMW MRS-ERS LINK

The goals of RF MRS-ERS communications link are given below:

Time Frame	Data Rate (Mbps)	Frequency (GHz)	Transmitter		Receiver Aperture (m)
			Aperture (m)	Power (W)	
2020	100	60	10	210	50
		94	10	190	50
		300	5	170	50
>2030	1000	60	15	600	60
		94	15	400	60
		300	10	320	50

Technology assessment of key items such as:

1. High power RF/MMW TWT,
2. Low noise amplifier,
3. Large space aperture,

will be discussed in Section 4.3.1. In addition, ERS RF system mass analysis and parametric cost analysis will be given in Section 4.3.2 and 4.3.3, respectively.

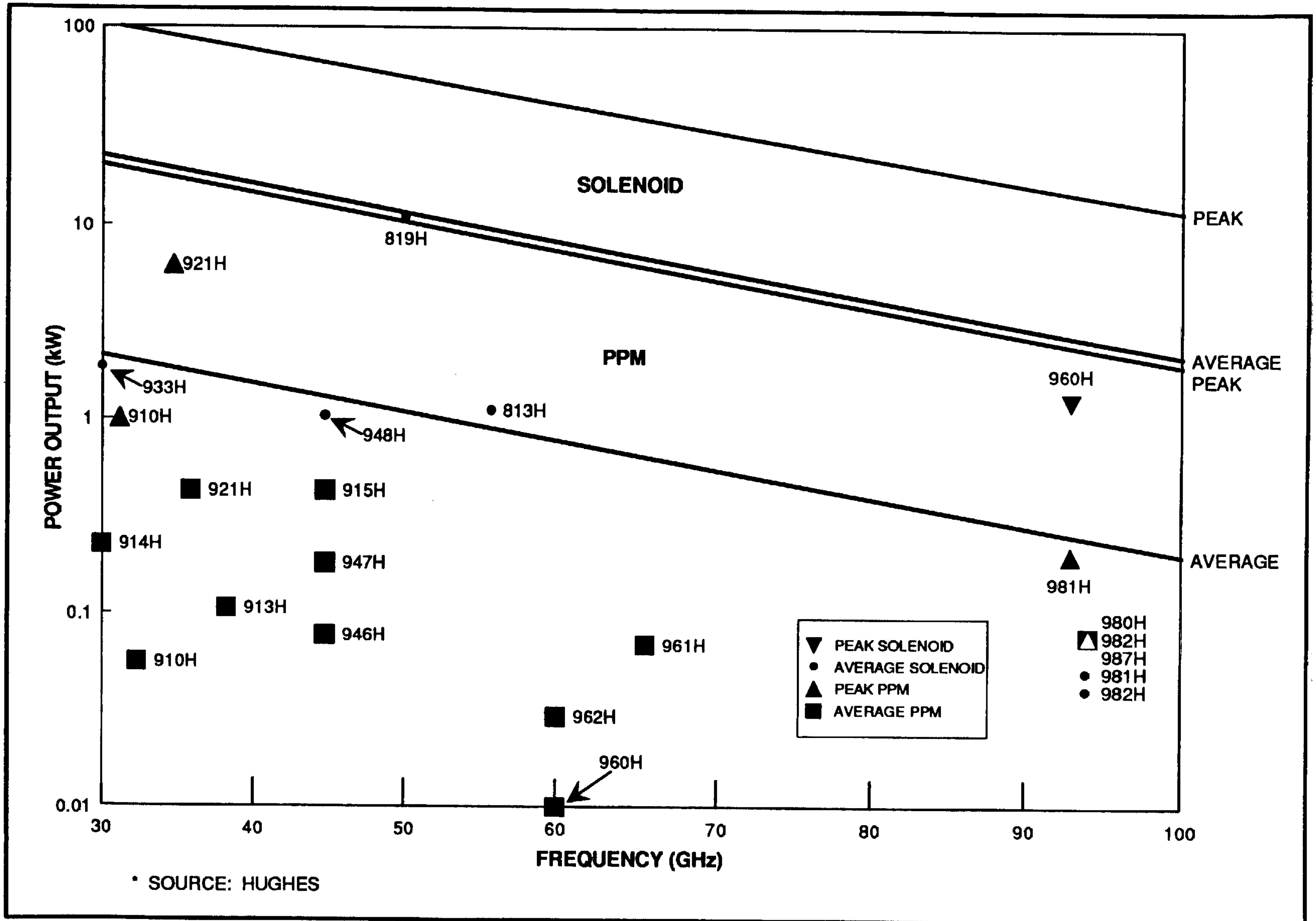
4.3.1 RF/MMW MRS-ERS Technology Assessment

MRS RF/MMW TWT HPA

There are many MMW TWTAs available in the frequency range of 30 GHz to 94 GHz. The output power ranges from 10 to 1000 watts with various bandwidth and efficiency. Technology status of a selected list of devices is summarized in Exhibit 4-8. The list shows many different design approaches: coupled cavity, helix, folded waveguide, ...etc. with varying degree of maturity. It appears that the power level required by the MRS-ERS link is well within the state-of-the-art. The projected average and peak power limits for some MMW TWTs are delineated in Exhibit 4-9. As shown, the output power decreases with the increase of operating frequency.

VENDOR	FREQ. (GHz)	POWER (WATTS)	BANDWIDTH (GHz)	EFF (%)	MODEL #	QUALIFICATION STATUS	NOTES
HUGHES	30	400	1	–	914H	IN PRODUCTION	–
HUGHES	DUAL BAND 23/32.5	10	1	38	950HA	X	–
HUGHES	30	1000	1	–	933H	IN PRODUCTION	SOLENOID FOCUSING
HUGHES	32.5	75	5	20	8900H	IN PRODUCTION	–
HUGHES	44	25	2	15	8901H	FINAL DEVELOP.	–
HUGHES	44	50	4	25	898H	R&D PHASE	HELIX WITH DIAMOND SUPPORTS
HUGHES	44	150	2	–	926H	R&D PHASE	RING BAR DESIGN
TELEFUNKEN	60	10	5	10	–	R&D PHASE	–
HUGHES	60	200	–	–	–	DEVEL. MODEL	FOLDED WAVEGUIDE (RADC CONTRACT)
HUGHES	60	50	5	18	–	–	FEASIBILITY MODEL
WJ	60	65	1.8	33	–	QUALIFIED	COUPLED CAVITY
HUGHES	65	75	3.0 - 5.0	40	961H	–	COUPLED CAVITY (NASA/LeRC CONTRACT)
HUGHES	94	100	–	–	987H	EARLY DEVELOP.	–

Exhibit 4-8: MRS RF/MMW TWT HPA Technology Status (30 - 94 GHz): Summary



02/07/92 TR92002\PK3519

Exhibit 4-9: Projected Average and Peak Power Limits for PPM and Solenoid Focused Millimeter - Wave TWTS

ERS RF/MMW LNA

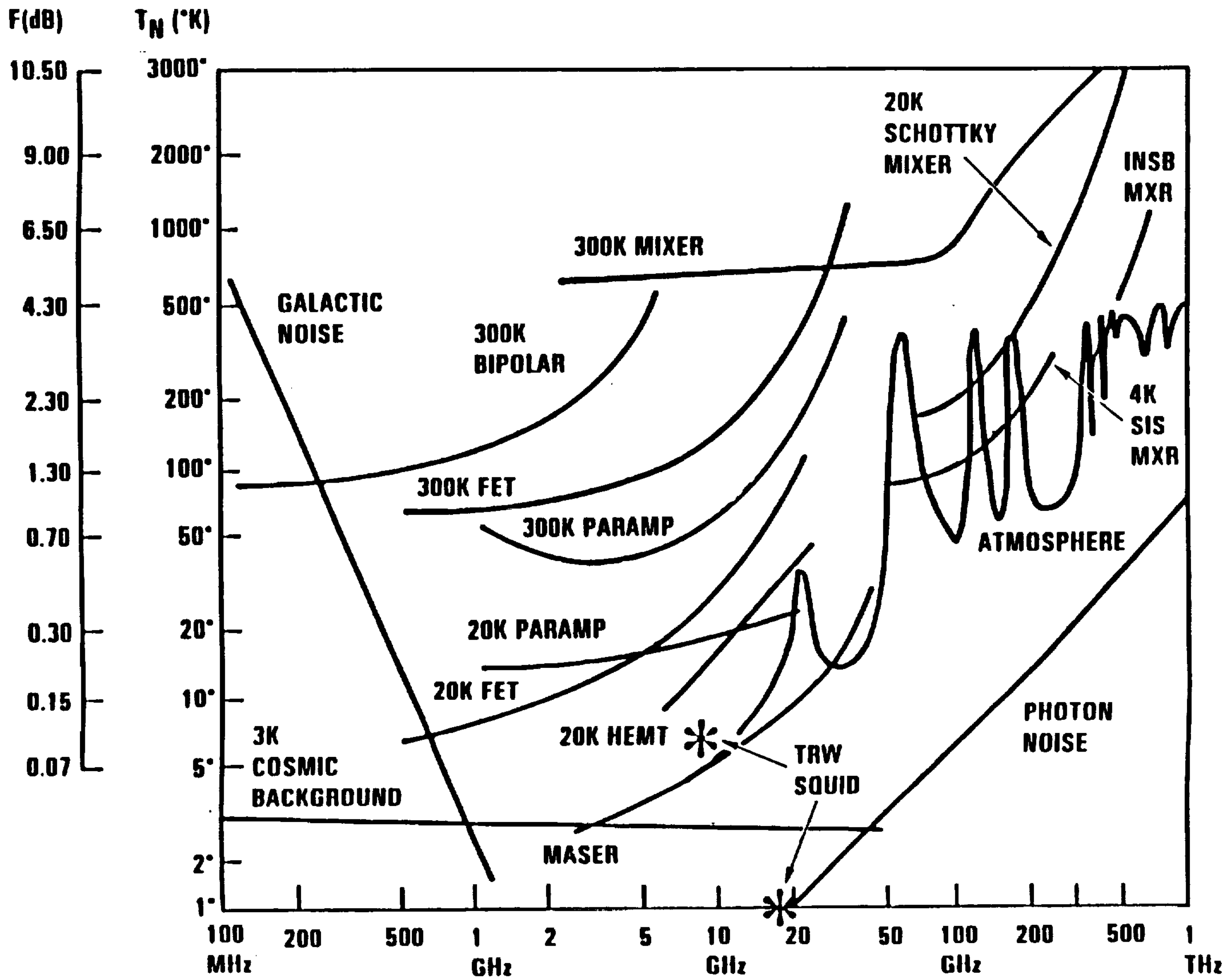
Several low noise amplifier (LNA) alternatives are presented in Exhibit 4-10. Among all the LNA alternatives, InP-based high electron mobility transistor (HEMT) has probably the best noise figure and gain ratio. InGaAs Pseudo-morphic HEMT also offers low noise figure but with slightly lower gain. Pseudo-morphic HEMT had been space qualified since 1987, and the same will be performed for InP-based HEMT in early 1992. Other devices such as GaAs MESFET and HEMT have also demonstrated reasonably low noise figure, high gains and wide bandwidths. Exhibit 4-11 shows noise figure and noise temperature for various devices and natural limits. There are very few devices operating at or beyond 100 GHz. Almost all of them are mixers with rather high insertion loss.

LOW NOISE AMPLIFIER (LNA) ALTERNATIVES	32 GHz		60 GHz		94 GHz	
	GAIN(dB)	NOISE FIGURE (dB) (ROOM TEMP.)	GAIN(dB)	NOISE FIGURE (dB) (ROOM TEMP.)	GAIN(dB)	NOISE FIGURE (dB) (ROOM TEMP.)
• GaAs MESFET	20	3.5	25	4	–	–
• GaAlAs HEMT	15	3.5	23	3.8	–	–
• Ti/Pt/Au "T" GATE HEMT	–	–	6	1.8	–	–
• InGaAs PSEUDO–MORPHIC HEMT	2.2	2.2	8	1.4	6.3	2.1
• InP–BASED InGaAs HEMT	–	–	17.4	1.7	7	1.7
• MMIC GaAs FET	7.5	3.5	26	9.5	–	–

- GaAs MESFET AND HEMT DEMONSTRATED LOW NOISE FIGURES, HIGH GAINS, AND WIDE BANDWIDTHS
- FURTHER IMPROVEMENT ENVISIONED FOR GaAs MESFET AND HEMT
- PSEUDO–MORPHIC HEMT OFFERS EVEN LOWER NOISE FIGURE BUT WITH SMALLER GAIN
  - SPACE QUALIFIED SINCE 1987
- InP–BASED HEMT HAS BEST NF AND GAIN
  - TO BE SPACE QUALIFIED IN 1992

12/5/91 TR92001\PK6198

Exhibit 4–10: ERS RF/MMW LNA Technology: Status Overview



Source: TRW

Exhibit 4-11: Noise Figure (I) and Noise Temperature (T_N) for Various Devices and Natural Limits

ERS RF/MMW LARGE SPACE APERTURE

There are 3 major technology programs which have focus on large space aperture: Large Space Systems Technology (LSST), Control/Structures Interaction Technology (CSIT), and Large Deployable Antenna (LDA) [4]. The application of these large space apertures range from mobile communication satellite to radiometer. A technology program roadmap is given in Exhibit 4-12.

Many large space aperture concepts have been developed and can be grouped into 8 categories:

1. Continuous Solid Dishes.
2. Phased Array.
3. Erectables.
4. Deployable Mesh.
5. Membrane Reflector.
6. Truss-less Deployed Rigid/Semi-rigid Panels.
7. Truss Supported Solids.
8. Adaptive Flat Aperture Reflector (AFAR).

Each kind of concept has its key advantages and drawbacks. Comparison of these concepts and their representative implementations are presented in Exhibit 4-12. The applicability of each concept to the MRS-ERS link in terms of diameter, surface tolerance, and frequency is also evaluated and included in Exhibit 4-13.

PROGRAM	TIME FRAME	SPONSOR	LEAD	FOCUS	APPLICATIONS
LARGE SPACE SYSTEMS TECHNOLOGY (LSST)	1978 - 1984	NASA/OAST	NASA/LaRC	• LARGE ANTENNAS • SPACE PLATFORMS • ASSEMBLY EQUIPMENT • SURFACE SENSING/ CONTROL • CONTROL & STABI-LIZATION • ANALYSIS/DESIGN	• MOBILE COMM SATELLITE • VLBI • ODSRS • RADIOMETERS
CONTROL/STRUCTURES INTERACTION TECHNOLOGY (CSIT)	1982 - 1989	• NASA/OAST • DOD	• NASA/LaRC • DOD/AFWAL	• STRUCTURAL DYNAMICS • FLEX-BODY CONTROL • FLIGHT & GROUND TESTING • MODELLING • VIBRATION	• SPACE STATION • MOBILE COMM SATELLITE • LARGE DEPLOYABLE REFLECTOR • GEO PLATFORM • LUNAR BASE
LARGE DEPLOYABLE ANTENNA (LDA)	1990 -	NASA/OAST	NASA/LaRC	• TECHNOLOGY READINESS OF LARGE REFLECTORS	• RADIOMETER (6-60 GHz) FOR THE ESGP

- MISSION TO PLANET EARTH
  - EARTH OBSERVATION SYSTEM (EOS)
  - EARTH SYSTEM EXPLORER MISSION
  - EARTH SCIENCE GEO PLATFORM (ESGP)
- TECHNOLOGY SUPPORT (NASA/OAST)
  - CIVIL SPACE TECH INITIATIVE (CSTI)
  - GLOBAL CHANGE TECH INITIATIVE (GCTI)

Exhibit 4-12: ERS RF Large Space Aperture - Technology Program Roadmap

CONCEPT CATEGORY	KEY ADVANTAGES	KEY DRAWBACKS	REPRESENTATIVE IMPLEMENTATIONS: NAME	REPRESENTATIVE IMPLEMENTATIONS: VENDOR/SPONSOR	MRS–ERS LINK APPLICABILITY: DIAMETER	SURFACE TOLERANCE	FREQUENCY	OVERALL
CONTINUOUS SOLID DISHES	● SIMPLICITY	● DIAMETER LIMITED BY LAUNCH VEHICLE	● AT LEAST 4 TYPES	COMPOSITE OPTICS	○	●	●	○
PHASED ARRAY	● DEPLOYMENT/STRUCTURE FACILITATION ● ADAPTIVE BEAM CONTROL ● FINE POINTING IS LARGELY ELECTRICAL	● LARGE NUMBER OF ELEMENTS, EACH WITH TX/RCV	● SPACE–FED: WIRE WHEEL ● SPACE–FED: ROLL OUT ● CORPORATE FEED: FOLD OUT ● COPPATRUSS	GRUMMAN GRUMMAN BALL (SBR) GE	●	●	◒	◒
ERECTABLES	● NOT LIMITED BY LV CONSTRAINTS	● EXPENSIVE ● MAY REQUIRE EVA/ ROBOTICS ● MAY REQUIRE BOOST TO GEO	● PRECISION SEGMENTED REFLECTOR ● GEO–TRUSS + PANELS ● BOX–TRUSS + PANELS ● PAROBOLOIDAL EXTENDABLE TRUSS ● MODULAR EXTENDABLE TRUSS ● DEPLOYABLE CELL MODULE	ASTRO AREOSPACE CORP GENERAL DYNAMICS MARTIN MARIETTA GENERAL DYNAMICS GENERAL DYNAMICS GENERAL DYNAMICS	●	●	●	◒
DEPLOYABLE MESH	● RELATIVE LIGHTWEIGHT ● TRUSS STRUCTURE REQUIREMENTS REDUCED ● SURFACE ACCURACY FOR LARGE DIAMETERS UNCERTAIN ● SMALL STRUCTURAL PACKAGING VOLUME	● MESH LIMITED TO ABOUT 40 GHz ● COMPLEXITY GROWS WITH DIAMETER (RIBS + SUPPORT STRUCTURE)	● WRAP–RIB ● HOOP–COLUMN ● RADIAL RIB ● GEO–TRUSS ● BOX–TRUSS ● DEPLOYABLE TRUSS STRUCTURE ● CABLE CATENARY	LOCKHEED HARRIS HARRIS GENERAL DYMANICS MARTIN MARIETTA HARRIS TRW	◒	◒	◒	◓ < 40GHz ○ > 40GHz
MEMBRANE REFLECTOR 1. ELECTROSTATIC	● FACILITATES IN–ORBIT ADJUSTMENT ● VERY LIGHTWEIGHT ● LOW TOTAL PARTS COUNT ● VERY SMALL STRUCTURAL PACKING VOLUME	● NOT AMENDABLE TO DEEP DISHES ● SUPPORT STRUCTURE HEAVY ● UNTESTED IN SPACE ENVIRONMENT ● LIFETIME/RELIABILITY UNCLEAR	● WRAP–RIB ELECTROSTATIC ● 2 METER EXPERIMENT	NASA/LARC (1982) MIT/LOCKHEED	●	◒	○	◒
2. INFLATABLES (FULLY INFLATABLE & RIGIDIZID INFLATABLE)	● VERY LIGHTWEIGHT FOR f<32 GHz ● SMALL PACKAGED VOLUME ● FEW POINTS OF FAILURE	● ABOVE 30 GHz, NEED MORE PRESSURE AND WEIGHT INCREASES ● GENERALLY CONSIDERED INAPPLICABLE FOR f>30 GHz ● MATERIALS LACK LONG–TERM DIMENSIONAL STABILITY AND SUPER LOW COEFICIENT OF THERMAL EXPANSION ● DIFFICULT TO ADJUST IN ORBIT ● NEED TO HAVE MAKE–UP GAS	● INFLATABLE TORUS ● INFLATABLE	L'GARDE (LARC) CONTRAVES (ESA)	●	○	○	◒

LEGEND: ● ◓ ◒ ○ ↓ DECREASING BENEFIT

12/6/91 TR92002\PK6199

Exhibit 4–13: ERS RF Large Space Aperture Concepts

CONCEPT CATEGORY	KEY ADVANTAGES	KEY DRAWBACKS	REPRSENTATIVE IMPLEMENTATIONS: NAME	REPRSENTATIVE IMPLEMENTATIONS: VENDOR/ SPONSOR	MRS–ERS LINK APPLICABILITY: DIAMETER	MRS–ERS LINK APPLICABILITY: SURFACE TOLERANCE	MRS–ERS LINK APPLICABILITY: FREQUENCY	MRS–ERS LINK APPLICABILITY: OVERALL
3. SOLIDIFYING POLYMER OR FOAM	• POTENTIALLY COMPARABLE TO ELECTROSTATIC APPROACH	• CONCEPT HAS NOT BEEN INVESTIGATED	———	LDA REPORT	?	?	?	○
4. CONTINUOUS FURLABLE MEMBRANE	• APPLICABLE TO HIGH FREQUENCIES • NO SEAMS OR RELATIVE POSITIONING OF SEGMENTS	• SURFACE TOLERANCE NOT AS GOOD RIGID SEGMENTED PANELS • ACHIEVING LARGE DIAMETERS UNCLEAR • TRUSS SUPPORT STRUCTURE REQUIRED	• RING TRUSS/WIRE WHEEL • WIRELESS FOLDING RING • PACTRUSS • HOOP COLUMN/COMPOSITE MEMBRANE	LARC ASTRO, ROCKWELL LDA REPORT LDA REPORT	◑	◑	●	◑
TRUSS–LESS DEPLOYED RIGID/SEMI–RIGID PANELS	• ACCOMODATES HIGH FREQUENCY • RELATIVE LIGHT WEIGHT • RELATIVELY SMALL VOLUME BUT HAS NO TRUSS	• TRUSS SUPPORT REQUIRED AT LARGE DIAMETERS • SURFACE TOLERANCE IS A CONCERN	• SUNFLOWER • EPAR HEXAGONAL PANELS	TRW HARRIS	○	○	●	○
TRUSS SUPPORTED SOLIDS 1. SEGMENTED RIGID PANELS	• ACCOMODATES HIGH FREQUENCY • ACCOMODATES LARGE DIAMETERS • GOOD SURFACE TOLERANCE	• PACKAGING/ DEPLOYMENT DIFFICULT ESPECIALLY BEYOND 15–20 M	• PACTRUSS (SQUARE) • PACTRUSS (TRIANGULAR) • PACTRUSS (HYBRID) • CREST • CANNISTER DEPLOYED SEGMENTED REFLECTOR	ASTRO/LDA REPORT ASTRO/LDA REPORT ASTRO/LDA REPORT SEASAT LDA REPORT	◑	●	●	◕
2. SEMI–RIGID (FURLABLE) REFLECTOR STRIPS	• EASIER PACKAGING THAN SEGMENTED RIGID • ACCOMODATES HIGH FREQUENCY	• SURFACE TOLERANCE NOT AS GOOD AS SEGMENTED RIGID	• PACTRUSS (SQUARE) • GORED TRUSS • PETAL DEPLOYMENT	LDA REPORT LDA REPORT DORNIER (FIRST)	◕	◑	●	◑
ADAPTIVE FLAT APERTURE REFLECTOR (AFAR)	• PACKAGING AND DEPLOYMENT FACILITATION DUE TO FLAT GEOMETRY • AMENDABLE TO ELECTRICAL CORRECTIONS OF SURFACE GEOMETRY	• NEW, UNTESTED CONCEPT • MANUFACTURE OF PANEL/DIPOLES IS TBD IN TERMS OF COSTS AND RISK • TRUSS SUPPORT IS TBD	———	FAIRCHILD/MALIBU	●	●	●	●

NOTE: LDA REPORT: "LARGE DEPLOYABLE ANTENNA (LDA) PROGRAM: PHASE I–TECHNOLOGY ASSESSMENT AND MISSION ARCHITECTURE," NAS1–184711 (TASK 1), MAY 1991.

● ◕ ◑ ○ ↓ DECREASING BENEFIT

12/05/91 TR92002\PK2511

***Exhibit 4–13: ERS RF Large Space Aperture Concepts** (Cont'd)*

Key points concerning ERS RF large space aperture are summarized below:

- MESH REFLECTORS DO NOT WORK ABOVE ABOUT 40 GHz
  - INSUFFICIENT REFLECTANCE (NEED GRID SPACING < $\lambda/50$ WHICH IS UNATTAINABLE WITH MESH SURFACES)
  - SOLIDS REQUIRED FOR 60 GHz AND HIGHER
- TRUSS SUPPORT REQUIRED FOR LARGE SOLID REFLECTORS
  - NECESSARY TO MAINTAIN SURFACE TOLERANCE (ASSUMES NO ACTIVE COMPENSATION)
  - TRUSS DEPTH INCREASES WITH DIAMETER-SQUARED AND FREQUENCY
  - EXAMPLE: 3.3 METERS DEPTH FOR 40 M DIAMETER AND 60 GHz ($\varepsilon = \lambda/50$)
- LAUNCH VEHICLE CONSTRAINTS CRITICAL FOR DEPLOYABLE CONCEPTS
  - TITAN IV (SRMU) ENVELOPE: 15 M X 4.8 M; 13,500 lbs TO GEO
  - FUTURE CAPABILITIES UNCERTAIN, BUT CRITICAL

MAJOR BREAKPOINTS

- ABOVE 40 GHz, REFLECTORS MUST BE SOLIDS
- ABOVE 20-30 METERS, SOLID REFLECTORS REQUIRE TRUSSES
- DEPLOYABLES MUST BE CAPABLE OF BEING PACKAGED INTO 15 M X 4.8 M

After screening various concepts of large space apertures, there are 4 surviving concepts which warrant further consideration. The 4 possible options are: phased array, deployable mesh, truss supported solid (segmented rigid panels or furlable reflector strips), and AFAR. The rationale and recommended implementation for these surviving concepts are presented in Exhibit 4-14.

CONCEPT CATEGORY	DISMISS	POSSIBLE OPTIONS	RATIONALE	RECOMMENDED IMPLEMENTATION FOR SURVIVING CONCEPTS	
				SPONSER/NAME	RATIONALE
• CONTINUOUS SOLID DISH	●		• NOT AMENDALE TO SMALL STOWED VOLUME		
• PHASED ARRAY		●	• MAINTAIN TO DETERMINE LEAST NUMBER OF ELEMENTS • VIABILITY DETERMINATION NEEDS MORE INVESTIGATION • MAY SIMPLIFY DEPLOYMENT/POINTING	• GRUMMAN: SPACE-FED	• MORE TOLERANT TO EDGE DEFLECTION
• ERECTABLES	●		• DISMISS UNLESS NO DEPLOYMENT CONCEPT IS SHOWN FEASIBLE • BOOST TO GEO AND COST ARE MAJOR DRAWBACKS		
• DEPLOYABLE MESH		●	• PROVIDES LIGHTWEIGHT/SMALL STOWED VOLUME APPROACH • NEED TO RESOLVE HIGH FREQUENCY LIMITATIONS	• HARRIS: DEEP TRUSS SYSTEM	• ACCOMODATES LARGE DIAMETERS AND GOOD ε
• MEMBRANE REFLECTOR 1. ELECTROSTATIC	●		• CONCEPT NOT VERY MATURE (MAY REVISIT WITH TIME) • LARGE DIAMETERS/SMALL ∊ DEMAND MANY ELECTRODES		
2. INFLATABLES	●		• HIGH FREQUENCY/LOW ∊ OPERATION IS A CONCERN • LIFETIME CONCERNS WITH SURFACE MATERIALS AND MAKE-UP GAS		
3. SOLIDIFYING POLYMER	●		• CONCEPT IS NOT WELL DEFINED • SUPPORT STRUCTURE STILL REQUIRED		
4. CONTINOUS FURLABLE MEMBRANE	●		• SURFACE MATERIAL AND STRUCTURE NOT DEFINED FOR LARGE DIAMETERS/LIMITED STOWED VOLUME		
• TRUSS-LESS DEPLOYED RIGID/SEMI-RIGID PANELS	●		• LACKS SUFFICIENT SUPPORT TO PROVDE LOW ε FOR LARGE DIAMETERS		
• TRUSS SUPPORTED SOLID 1. SEGMENTED RIGID PANELS		●	• RECOMMENDED APPROACH FOR EARTH SCIENCE GEOSTATIONARY PLATFORM • ACCOMODATES HIGH FREQUENCY OPERATION	• LDA: PACTRUSS	• RECOMMENDED BY LDA PHASE 1 STUDY
2. FURLABLE REFLECTOR STRIPS		●	• DOES NOT PROVIDE AS GOOD A SURFACE TOLERANCE AS RIGID PANELS • MAY ACCOMODATE LARGER DIAMETERS DUE TO MORE EFFICIENT PACKAGING	• LDA: GORED TRUSS	• RECOMMENDED BY LDA PHASE 1 STUDY
• AFAR		●	• SIMPLIFIES DEPLOYMENT • ACCOMODATES ACTIVE COMPENSATION	• FAIRCHILD/MALIBU	• RECENT HERITAGE

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Exhibit 4-14: ERS RF Large Space Aperture Conclusions/Summary Findings

4.3.2 ERS RF System Mass Models

The simplified mass model is basically based on reflector mass values obtained from reports and proposals utilizing given designs/configurations. Current mass values on all configurations are limited to 40 meters diameter reflector. Values for larger diameters are obtained by extrapolation. The Fairchild/Malibu AFAR (also known as FLAPS) mass estimate includes Astro Aerospace truss. In general, reflector mass varies with diameter and feed mass varies with frequency. Electromagnetic Sciences Inc. (EMS) estimates feed array mass at approximately 100 lbs. Curves displaying mass as a function of reflector diameter are shown in Exhibit 4-15. For example, for a 50 meters reflector, the mass ranges from 11,000 lbs to 14,000 lbs, depending on the concept.

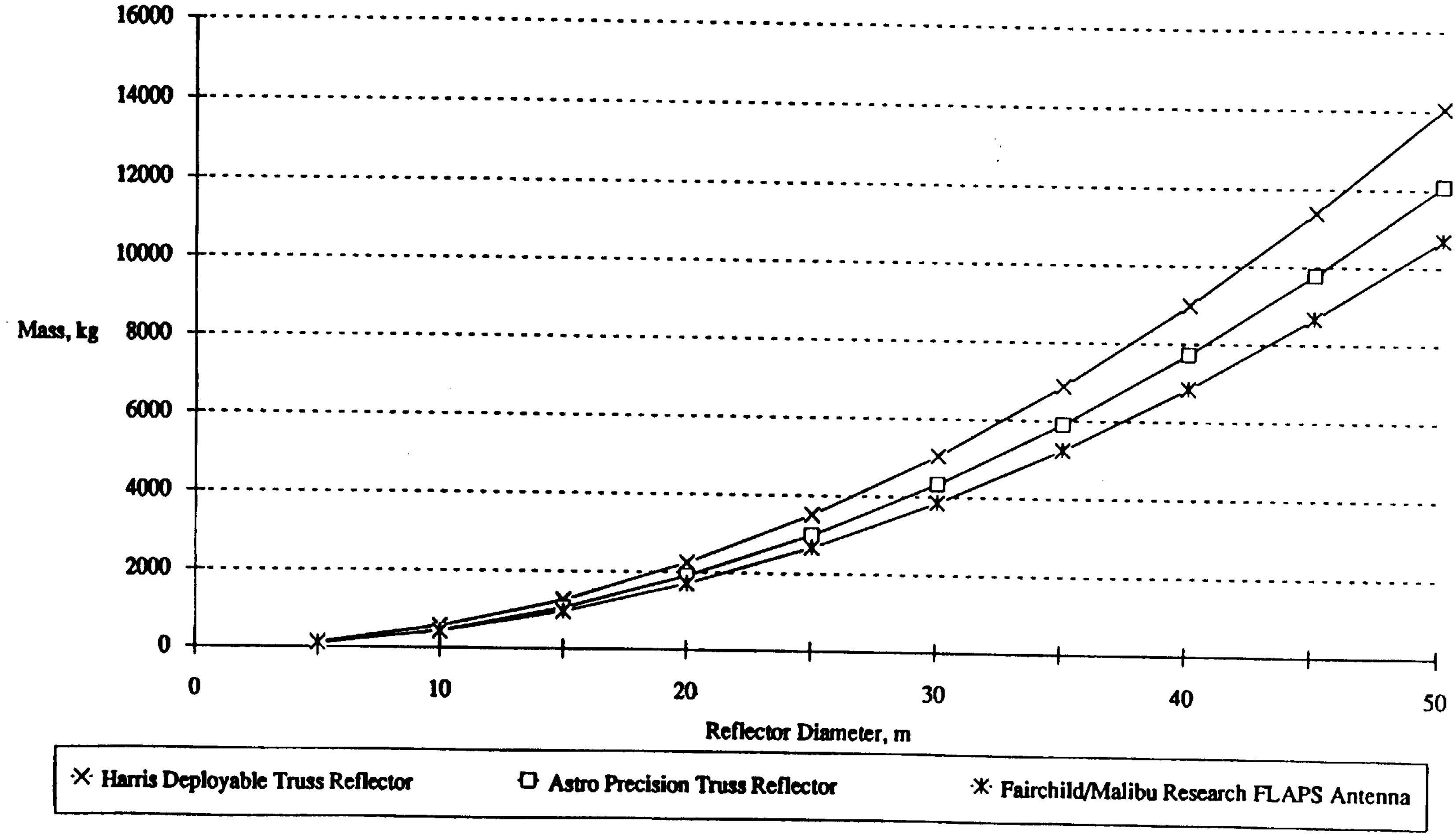

Exhibit 4-15: RF System Reflector Mass

4.3.3 General ERS Cost Models

The cost model for the ERS antenna/telescope system includes three types of cost: development, assembly, and launch costs. Note that the cost estimates presented herein are just some rough projections from costs for much smaller reflectors. The launch cost for erectable systems is estimated at $10K/lb (from STS user studies.) The launch cost for deployable systems is estimated at $110M (from TITAN III user's guide.) The assembly costs derived from FTS reports are as follow:

1. EVA: $95K/hour.

2. IVA: $15K/hour.

The assembly times are derived from Astro Aerospace report on erectable antennas. All the development cost has been multiplied by a complexity factor according to the following rules:

1. For operational configurations, assign a complexity of 1.0.

2. Or conceptual configurations, assign a complexity factor of 3.0.

3. For configurations similar to other operational configurations, assign a complexity factor of 1.0.

ERS RF System Cost Model

For RF system, reflector cost is based on the SAMSO model. This model is within 20% accuracy for 5 meters reflector (upper limit.) Costs for larger aperture are extrapolated from costs of much smaller apertures and therefore are much less accurate. GE 5000 series bus is used as baseline to calculate the bus costs. Typically, vendors of reflectors would not provide cost estimates unless a full specification is provided (for system to be delivered which including feed.) The feed cost estimated by EMS to be approximately $4M. Rough cost estimate curves for several reflectors are given in Exhibit 4-16. The cost for a 50-meters reflector systems ranges from $400M to $900M.

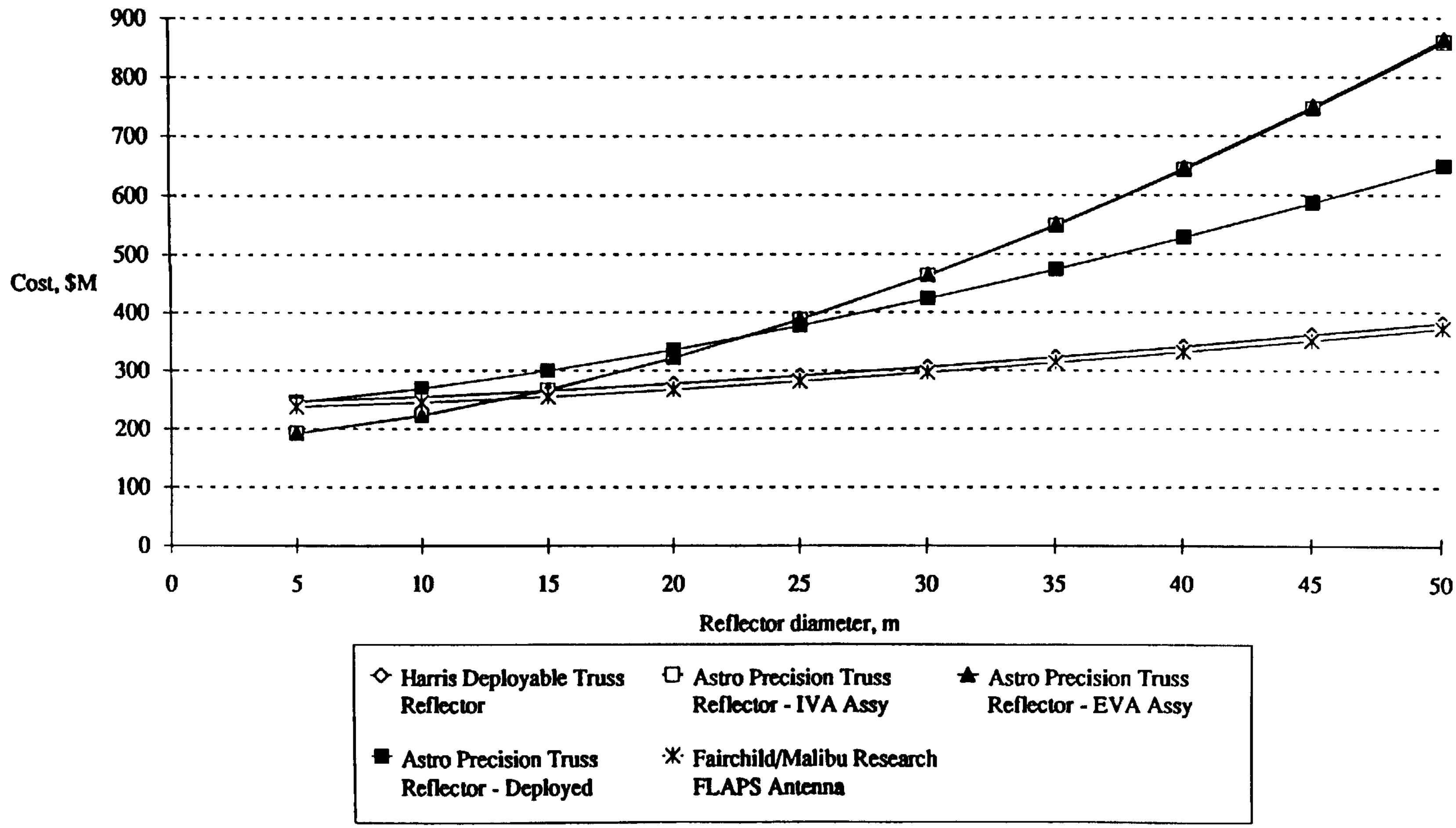

Exhibit 4-16: RF System Cost Estimates

4.4 DESCRIPTION OF OPTICAL MRS-ERS LINK

The goals of optical MRS-ERS communications link are given below:

Time Frame	Data Rate (Mbps)	Frequency	Transmitter		Receiver Aperture (m)
			Aperture (m)	Power (W)	
2020	100	optical	0.4	25	15
>2030	1000	optical	0.5	90	15

ERS optical system mass and cost analyses will be discussed in Section 4.4.1 and 4.4.2, respectively.

4.4.1 ERS Optical System Mass Models

The mass values are obtained from 4 vendors using different manufacturing techniques. These mass values reflect the current capability (i.e., smaller mirrors) of mirror vendors. Mass values for larger mirrors are extrapolated from current capability. In general, the metering structure and collector mass is approximately the same as mirror mass. In Exhibit 4-17, mirror mass is plotted against mirror diameter for 4 kinds of mirrors. As shown, for a 15-meter effective diameter mirror, the mass ranges from 2000 to 7000 kg with Kodak mirror on the high end and UTOS on the low end.

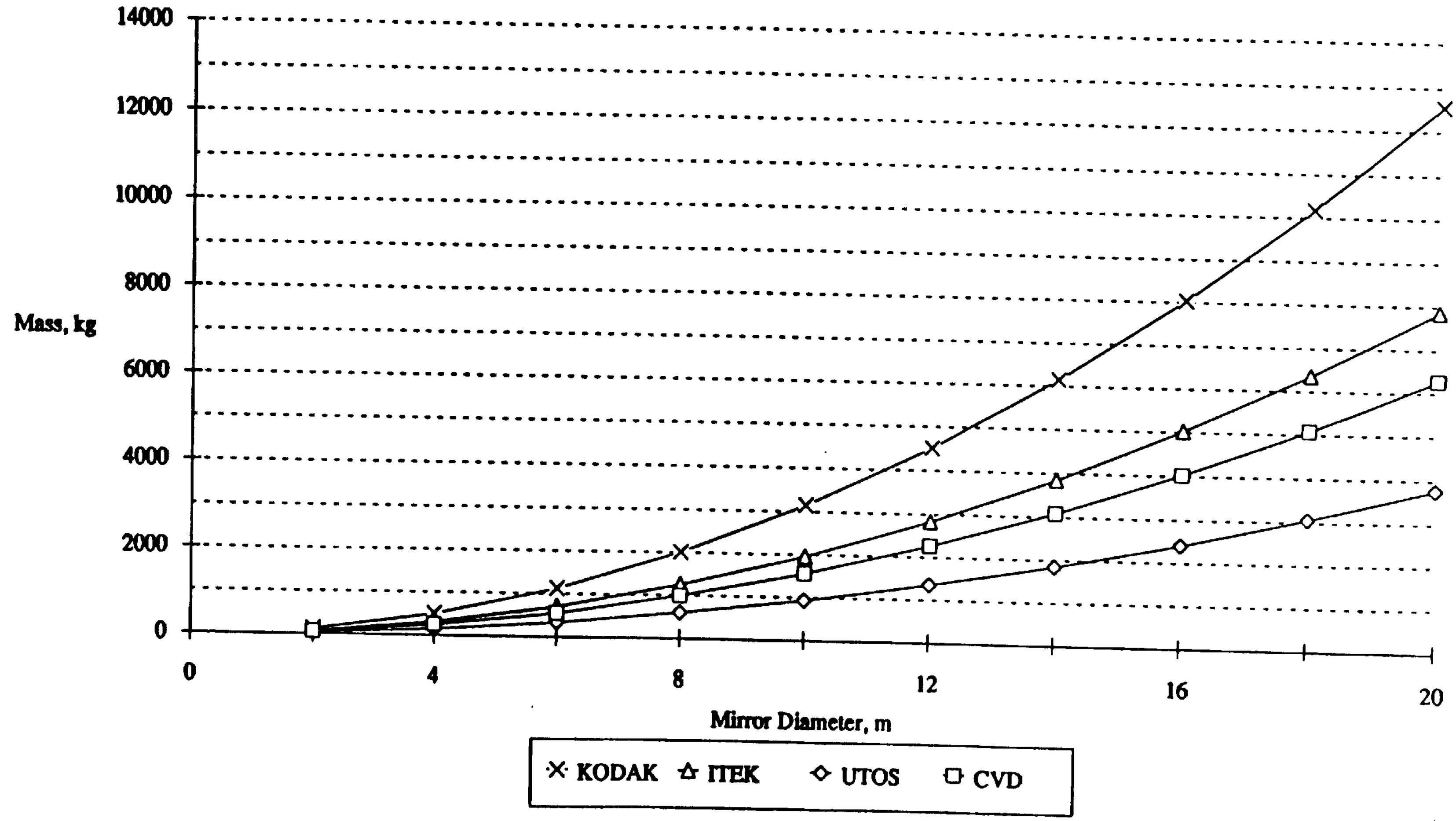

Exhibit 4-17: Optical System Mirror Mass

4.4.2 ERS Optical System Cost Model

Similar to the RF system, the cost estimates discussed herein are just rough projections from costs off recently delivered items. The mirrors cost estimates are obtained through contacts at vendors. The telescope cost estimates are based on mass and mirror cost formulas. The resulting cost curves as a function of mirror diameter are presented in Exhibit 4-18, assuming IVA assembly is used. The cost for a 15-meter mirror ranges from $500 M to $900 M.

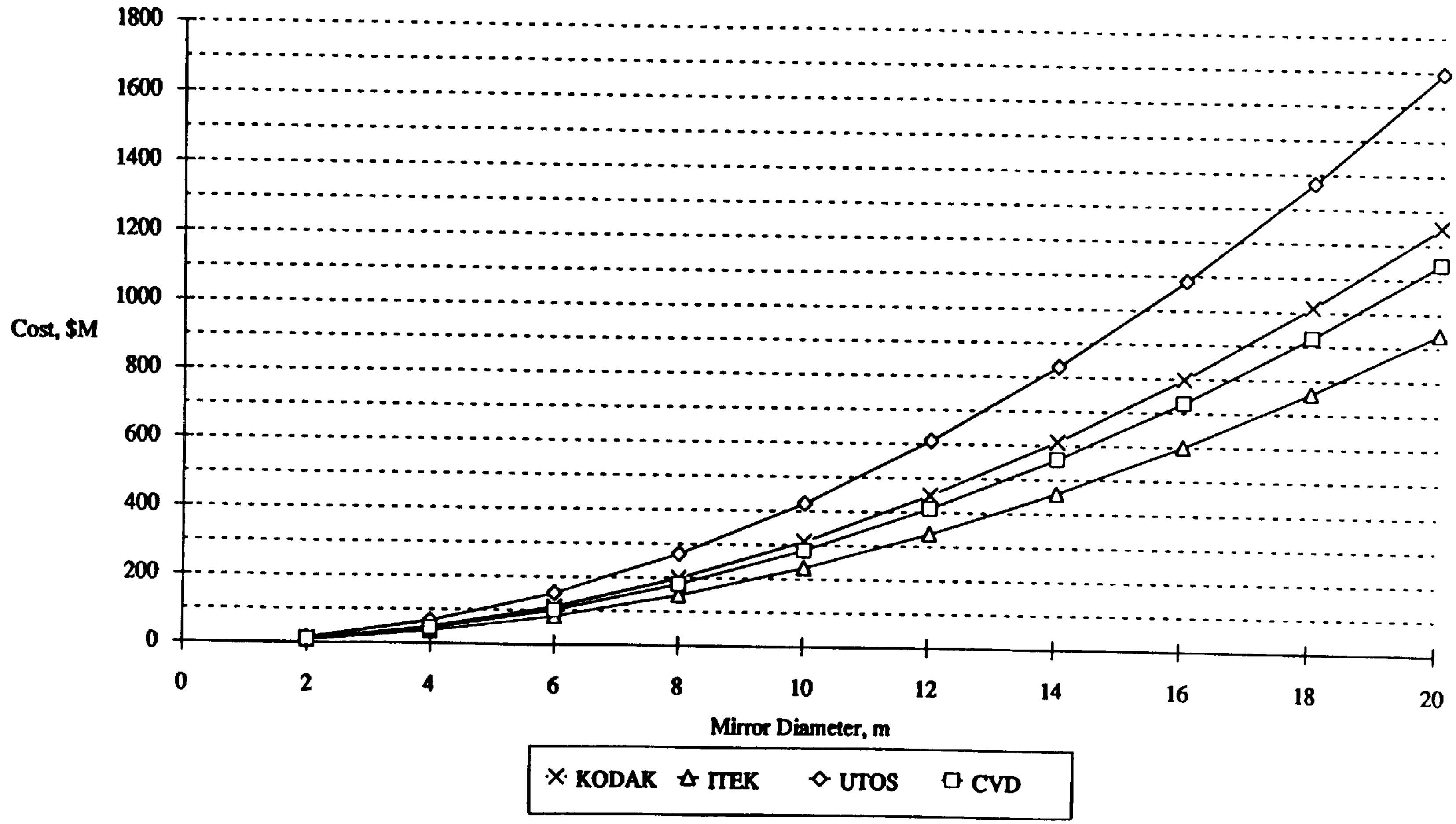

Exhibit 4-18: Optical System Cost Estimates - IVA Assy

SECTION 5: SUMMARY AND CONCLUSION

In this study, a set of attractive architectures for the evolving Mars-Earth SEI space communications link have been identified and characterized. All together, they define a road map that illustrates the most logical and efficient evolutionary paths for the SEI Mars-Earth link. This road map provides valuable insight and guidance with respect to strategic planning of the SEI communications system including such issues as the proper emphasis and timing for long-lead technology development.

This road map is illustrated in Exhibit 5-1. The basic features of the road map contain three alternative evolutionary paths that can meet the data rate requirements that may grow from 10 Mbps to 1 Gbps from 2010 to beyond 2030. All three begin with a Ka-band MRS-EST baseline link in the year 2000, and diverge from this baseline as time progresses. These three evolutionary paths are as follows:

The Ka-Band Path

In this path the communications system remains at Ka-band to 2030 and beyond. Up to 100 Mbps, the MRS-EST connectivity is maintained, and upgrades are implemented by increasing the transmitter power and aperture, and the receiver aperture. When the requirement for a 1 Gbps return link materializes (after 2030), this is met by keeping the EST capability essentially fixed, and replacing the MRS transmitter with the MST which is free of the power and aperture constraints of the MRS. The virtue of this Ka-band path is that it is the path with the least technology risk and transition impact, and the most backward compatibility.

The Optical Path

In this path, the system evolves from the Ka-band baseline to an optical link supported by a MRS-ERS link. The schedule of evolution is such that in 2010, the system remains a Ka-band MRS-EST system, but optical experimentation via a MRS-EST link is conducted as a test bed for the transition to the optical MRS-ERS system. By 2020, the system transition to an optical MRS-ERS system is complete, and future growth in data rate requirements in following years are met via increasing the MRS transmitter power and aperture.

The MMW Path

In this path, the system evolves from the Ka-band baseline to a MMW frequency (as high as 300 GHz) supported by a MRS-ERS link. The schedule is such that in 2010, the system remains a Ka-band MRS-EST system, but by 2020 the transition to a MMW system is underway. The highest feasible MMW frequency available (consistent with adequate power and low noise amplifier technology development) is preferred in order to achieve the maximum gain for a given aperture. Increases in data rate requirements after 2020 would be met by increasing the MRS transmitter power and aperture.

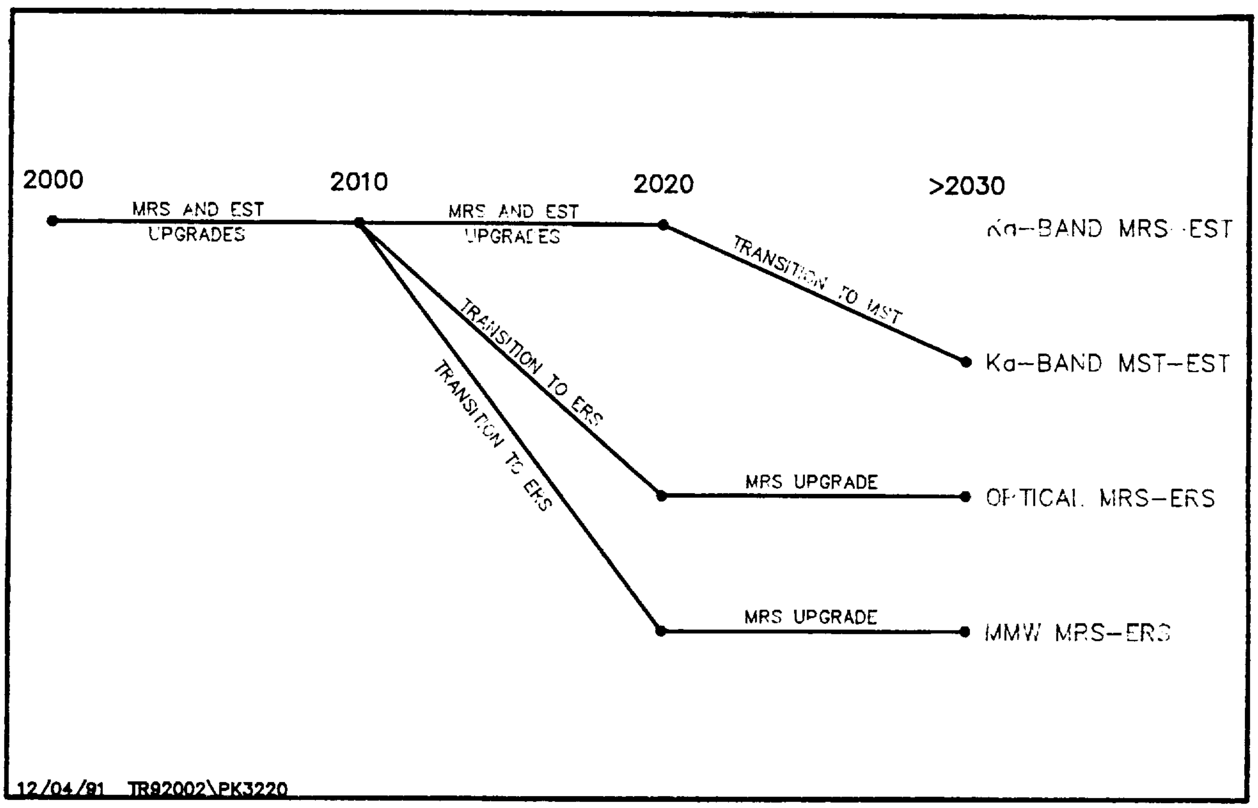

Exhibit 5-1: Transition Map for SEI Communications System

5.1 ASSESSMENT OF 2010 ALTERNATIVES

In the 2010 time frame, MRS-EST link is the most logical choice. Initial deployment cost for RF and optical EST systems are almost the same ($250 M to $300 M). However, the cost for linking diversity sites for optical EST together is not included in the estimate. Therefore the final cost for the optical system may be much higher than the estimate shown above if these costs are included. The MRS optical payload may be high in risk and cost due to its complicated and stringent pointing/acquisition/tracking system. The Ka-band EST system has the lowest risk and best backward compatibility among all alternatives for the 2010 time frame. A comparison of MRS-EST implementations for year 2010 has been performed in terms of technology risk, backward compatibility, complexity, antenna size, mass, and cost. The result is presented in Exhibit 5-2.

5.2 ASSESSMENT OF 2020 ALTERNATIVES

In 2020 time frame, the ground-based (EST) Ka-band system has the lowest cost ($540 M). The estimated cost for MMW and optical ERS systems are in the same range: $400 M to $900 M (MMW), and $500 M to $950 M (optical). Launch cost is the cost driver for ERS RF/MMW large aperture, while development cost in general is the cost driver for optical large space aperture. The MMW and optical systems have higher technological risk and require early R&D decision on key technology program. On the other hand, these systems possess capability to offer very high data rate (up to 1 Gbps) service. The 2030 architectures are logical evolution of 2020 architectures; therefore no major transition is required for earth region. Similarily, a comparison of MRS-ERS/EST implementations for year 2020 has been performed and the result is presented in Exhibit 5-3.

5.3 CONCLUDING REMARKS

1. Gradual increase of data rate requirement implies that decision on architectures for SEI COMM system should be evolutionary.

2. For 2010, Ka-Band MRS-EST system is the most logical choice.

    a. Optical EST is most viable alternative.

    b. Continue definition studies and technology development to keep this architecture open.

3. Decision on 2020 architecture transition may be made no later than year 2012 (Projected technology cut-off date).

    a. Key technology programs for ERS options (i.e., optical and MMW) should be maintained and further explored.

4. Significant cost savings may be achieved by sharing resources and joining effort with other NASA programs.

    a. E.g., large space aperture for ERS may share technology with LDA program for mission to planet earth.

Implementation		Technology Risk	Backward Compatibility	Complexity	Antenna Size (m)	Antenna Mass (kg)	Cost*
RF	EST (DSN)	• Relatively low	• Good	• Low to moderate	70	–	~ $280 M
	MRS	• Low	• Good	• Moderate	5	~ 60	–
Optical	EST	• Moderate	• Heritage non-existing	• Moderate to high	10	–	~ $240 M +**
	MRS	• Moderate to high (stringent PATS requirement)	• Heritage non-existing	• Moderate to high	0.3	~ 28	–

* ROM Cost (initial deployment in FY 91$

** Additional costs for linking diversity sites together can be significantly high

Exhibit 5-2: Comparison of MRS-EST Implementations for Year 2010

	Implementation		Technology Risk	Backward Compatibility	Complexity	Antenna Size (m)	Antenna Mass (kg)	Cost
MRS-EST	RF	EST (DSN)	• Low	• Good	• Low to moderate	110	–	~ $540 M
		MRS	• Low to moderate (large antenna required)	• Good	• Moderate	10	20-100	–
MRS-ERS	MMW	ERS	• Moderate	• Depending on early R&D decision	• Moderate	50	11,000 - 14,000	$400 M - $900 M
		MRS	• Moderate to high	• Depending on early R&D decision	• Moderate to high (stringent PATS)	5	~ 60	–
	Optical	ERS	• Moderate	• Moderate	• Moderate	15	2,000 - 7,000	$500 M - $950 M
		MRS	• Moderate to high	• Good if implemented in YR 2010	• Moderate to high (stringent PATS)	0.4	~ 35	–

* ROM cost (initial deployment) in FY 91 $

** Range of antenna mass reflects different type and design of large deployable antennas

*** Cost Driver for ERS Large Aperture:

- RF/MMW: Launch Cost
- Optical: Development Cost

Exhibit 5-3: Comparison of MRS-ERS/EST Implementations for Year 2020

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[2] "A Technology Assessment of Alternative Communications Systems for the Space Exploration Initiative," D. S. Ponchak, J. E. Zuzek, W. A. Whyte, Jr., R. L. Spence, and P. Y. Sohn, prepared for the Space Programs and Technologies Conference sponsored by the American Institute of Aeronautics and Astronautics, Huntsville, AL, 25-27 September 1990, NASA TM 103243.

[3] "Spatial Acquisition and Tracking for Deep-Space Optical Communication Packages," C. C. Chen, M. Jeganathan and J. R. Lesh, SPIE Vol. 1417 Free-Space Laser Communication Technologies III (1991), pp. 240-250.

[4] "Large Deployable Antenna Program," Final Report on Phase I: Technology Assessment and Mission Architecture, by Virginia Polytechnic Institute and State University, for NASA LaRC under contract NAS1-18471, Task 18, May 1991.