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An Assessment of Technology Alternatives for Telecommunications and Information Management for the Space Exploration Initiative

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SUMMARY

On the 20th anniversary of the Apollo 11 lunar landing, President George Bush set forth ambitious goals for expanding human presence in our solar system. The Space Exploration Initiative addresses these goals beginning with Space Station Freedom, followed by a permanent return to the Moon, and a manned mission to Mars. A well-designed, adaptive Telecommunications, Navigation, and Information Management (TNIM) infrastructure is vital to the success of these missions. Utilizing initial projections of user requirements, a team under the direction of NASA's Office of Space Operations developed overall architectures and point designs to implement the TNIM functions for the Lunar and Mars mission scenarios (refs. 1 and 2). Based on these designs, an assessment of technology alternatives for the telecommunications and information management functions was performed.

INTRODUCTION

This technology assessment identifies technology developments necessary to meet the telecommunications and information management system requirements for the Space Exploration Initiative. Technology requirements, technology needs and alternatives, the present level of technology readiness in each area, and a schedule for development are presented. Table 1.1 gives the definitions for the NASA technology readiness levels. The schedules for technology development are targeted to provide a technology readiness level of 5 and are given in relative years from the start of a program.

OVERVIEW OF TNIM ARCHITECTURES

The baseline TNIM architecture is shown in figure 2.1. The Mars and lunar communications systems provides necessary data, voice, and image transmissions to link together the mission elements. These systems support robotic and manned presence, scientific experiments, and planetary observation. The communications systems includes surface terminals that serve as hubs for the collection and distribution of signals originating in the near vicinity, and relay satellites which provide the major communications link back to Earth and local communications between science stations, rovers, outposts, and transfer vehicles. Frequencies used are Ka-band (18 to 40 GHz) and UHF (800 MHz) for normal operations, and X-band (7 to 8 GHz) for uplinks and emergencies. Data rates range from 100 kbps to several 100 Mbps.

The TNIM architectures for both the lunar and Mars systems contain a great deal of similarities, but several major physical differences result in individual technology needs. The Moon to Earth path length results in a transmission delay of approximately 1.25 seconds, while from Mars the delay can be as long as 20 minutes. Also, the Moon orbits the Earth, and their relationship to each other is relatively constant, while both Mars and the Earth revolve around the Sun and their relationship is constantly changing.

The different path lengths coupled with the vastly different geometries produce major differences in the number and function of relay satellites. The lunar system has one relay satellite in a halo orbit that revolves about the stable L2 libration point at a distance of 65,000 km from the moon's surface. The Mars system has two relay satellites in the aerostationary orbit that circles Mars with a radius of 20,405 km. These differences impact the spacecraft design in areas such as connectivity, transmit power, antenna size and coverage, station-keeping, pointing and tracking, and solar array design.

Imbedded within the telecommunications system is the information management system. This system operates in an unattended mode and is responsible for efficient management of channel allocations and emergency situations. The navigation system provides guidance and landing support to transit users and position determination for surface users. In the lunar system, the small transmission delay allows for Earth-based navigation support, while the Mars navigation system will probably require a space-based autonomous system.

TNIM TECHNOLOGY ISSUES

The technology trade-offs for the telecommunications system are based on transmission data rate requirements, frequency selection, link availability, and bit error requirements. For the lunar telecommunications system, high return data rates are achievable due to the close range, but limitations exist due to data processing volume constraints. Achievable return data rates for the Mars telecommunications system are much lower due to the longer range. Ka-band frequencies allow modest data rates within realizable spacecraft power/mass constraints. Increased data rates beyond that afforded by Ka-band are feasible with higher frequencies, but technology research is in the infant stage. Another alternative is optical communications, but it also is less technologically mature and introduces pointing accuracy and stability problems.

Another issue that affects the telecommunications technology development is the system complexity. Changing surface coverage patterns may require advanced antenna development. In addition, all hardware designs are directly affected by lifetime/reliability requirements. Many of the already proven spaceflight technologies have lifetime ratings that fall well short of those required by the exploration missions. Research into extending the life of the system components is necessary along with maintainability and repairability design considerations.

The information management technology needs are influenced by several factors. The data rate requirements will ultimately decide such things as the compression ratios required, the types of algorithms used for data compression, and the data storage technology needs in the areas of input rates and retrieval rates as well as storage capacities. The bit error rate requirements will also impact the choice of compression algorithms since a critical parameter in compression is robustness to errors. The overall complexity of the system will dictate architectural choices and network control strategies.

TELECOMMUNICATIONS TECHNOLOGY ASSESSMENT

Once the TNIM system architectures and requirements have been defined, the enabling technology can be identified. In the telecommunications area, Ka-band communications was identified to meet the mission requirements, while millimeter-wave

and optical communications were identified as an alternative if the required data rates were to increase significantly. To meet the necessary technology readiness level within the mission timeframe and to provide the level of reliability for manned exploration missions, needed technology developments were identified in the areas of: Ka-band transmitters, antennas, and monolithic microwave integrated circuits (MMIC) applications. A detailed discussion of these technologies follows and a summary is given in table 4.1.

TRANSMITTERS

Traveling wave tube amplifiers (TWTA) and solid-state power amplifiers (SSPA) are entirely different technologies that perform the same basic function; final amplification of the signal prior to transmission over the link. Both TWTA's and SSPA's have been flown successfully in space. TWTA's are the more mature technology in general, though SSPA's have become an accepted alternative at some frequencies and power levels. Each technology has unique benefits which are specific to the application being considered. The large variety of communication needs being fore-seen for manned space exploration missions will undoubtedly require both technologies.

TWTA's can achieve higher power levels than SSPA's, and at these high power levels they also have higher overall efficiency. TWTA's can easily support broadband transmissions. In space applications, high reliability has been proven. This is important for manned missions, as the communication links are the sole tie with the astronauts, and increased redundancy imposes a weight penalty. TWTA's have been designed to have very long lifetimes (100,000 hr are typical). Conversely, TWTA's require complex high-voltage power supplies, they are not as efficient at low transmit power levels (<10 W), and in general they are relatively heavy.

Solid state power amplifiers do not require high-voltage power supplies since they operate at lower power levels in the range of 1 to 20 W. SSPA's provide higher efficiencies than TWTA's at the lower power levels because they do not require a 5 W cathode heater. They have the potential to provide a higher reliability, though this has not yet been demonstrated. Finally, SSPA's have the potential to be lower cost, and they are more amenable to phased-array applications.

The state-of-the-art (SOA) for TWTA technology, both Helix and Coupled-Cavity, is shown in table 4.2. These results show that the technology is highly mature for X-band and 20 GHz. The upper region of Ka-band (30 GHz) and W-band has had little commercial or government use and therefore minimal technology development has occurred in these bands. (The military has been considering W-band, but that information is classified or not available.)

Table 4.3 shows the state-of-the-art for SSPA technology (X-band is not considered due to the high power requirements). The primary device technologies are FET's (field effect transistors), IMPATT (impact avalanche and transit time) diodes, and HEMT (high electron mobility transistors). SSPA technology is still at an early development stage, though a large amount of R&D activity is taking place at a fairly high rate. Areas requiring research include materials growth and device processing.

Figures 4.1 (a) to (c) and 4.2 (a) and (b) show an estimate of the technology level of readiness for the baseline TNIM power requirements for TWTA's and SSPA's, respectively. It can be seen where technology development is necessary by noting the readiness deficiencies. Though these plots show that SSPA's require more development

than TWTA's, the advantages of SSPA's may support their funding for specific applications.

The technology difference between TWTA's (electron beam technology) and SSPA's (transistor theory) results in greatly varying methods of design. A TWTA development (fig. 4.3) requires approximately 3 years to produce an experimental tube relating to a technology readiness level of 7. A similar SSPA development (fig. 4.4) takes approximately 4 years.

ANTENNAS

The requirements from the TNIM designs which directly impact the antenna technology needs are the system architectures, transmission frequencies, coverage/connectivity requirements, size and weight constraints, and the potential developmental need dates. Ka-band antennas offer the advantages of higher gain and smaller antenna dimensions over the lower frequency bands previously used for exploration missions. Specialized coverage areas and tracking needs of the proposed lunar and Mars scenarios will require Ka-band multiple beam technology using both fixed and scanning beams. Direct radiating phased array antennas using electronically steered beams offer an alternative to mechanically steered beams by reducing extraneous mass and inertia. Incorporation of MMIC components into phased array feeds provides significant size and mass reduction. Alternatively, phased arrays can be driven either by integral MMIC power amplifiers or by miniature TWTA's. Additional improvements may be realized using optical rather than RF interconnects.

Electronically steerable antennas are desirable for spacecraft communication since they offer high gain and fast beam switching without affecting the spacecraft pointing or introducing vibrations. This obviates the need for using mechanical components which may be subject to failure. Because of its fast response time, an electronically steered antenna can compensate for variation in the attitude of the satellite, as well as the relative motion between the transmitting and receiving spacecraft. Thus the electronically steerable antennas will be applicable to orbiting satellites, surface rovers, and piloted vehicles. Reconfigurable antennas also are a technology driver. These antennas can dynamically reconfigure their radiation pattern either electronically by changing the feed pattern or mechanically by altering a flexible reflector.

There are several antenna performance issues to be considered. The first is dynamic output control of the power amplifiers. This is an important requirement for active radar/rover arrays. For broadband phased arrays, one concern is discrete phase-shifters designed to operate at a specific frequency. Large variations in frequency, such as found in broadband systems, will cause beam-squinting or beam pointing jitter. Real-time delay phase-shifter network technology compensates for the real-time frequency variations to maintain steady, accurate beam-pointing. The final area is that of reflector technology. The two major issues in this area are surface accuracy and areal density. Presently, there are three kinds of reflector surfaces: solid, mesh, and inflatable surfaces. A rigid, solid surface gives a very high accuracy (well under 1 mm rms error), but it has a high areal density. A mesh surface which has low areal density needs an appropriate subdivision of the surface and corresponding complex support structures in order to get a better surface accuracy. Current mesh antenna design is limited by reflection losses which become very large as the frequency approaches 30 GHz. Lower reflection loss levels have been projected for antenna designs having smaller mesh spacings. Inflatable surfaces are in the infancy of their development.

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MMIC APPLICATIONS

Monolithic microwave integrated circuits (MMIC) are defined as circuits in which all active elements and their associated passive elements and interconnections are formed into the bulk, or onto the surface, of a semi-insulating substrate by semiconductor processing techniques such as epitaxy, ion implantation, sputtering, evaporation, etc. Many of the advantages of the monolithic approach can be seen by considering the traditional approach, a hybrid microwave integrated circuit (MIC). Figure 4.5 shows a comparison of a state-of-the-art hybrid MIC amplifier to an MMIC amplifier using two FET's. Immediately apparent is the dramatic size and weight reduction provided by MMIC technology. Also, MMIC technology has eliminated all the wire bonds and interconnects and therefore many of their associated problems, such as reliability and performance limitations. MMIC's are also advantageous in areas such as: reproducibility, circuit design flexibility, MSI (medium scale integration) feasibility, enabling of new system concepts, potential low cost through batch fabrication, uniformity among circuits, high frequency capability, and radiation hardening, to list a few. MMIC's also have several disadvantages. First, the development of an MMIC circuit is costly and time consuming. Also, MMIC's cannot be tuned to optimize performance, such as hybrid MIC's.

In principal, all of the microwave circuitry in a conventional bent-pipe transponder is a candidate for replacement by MMIC's. An initial list of MMIC applications would include transponder components (receiver, signal processing equipment and transmitter), receive and transmit antenna arrays, and synthetic aperture radar (SAR). Within the receiver portion of the transponder, MMIC's could be designed for low-noise amplifiers (LNA), mixers, and local oscillators. MMIC power devices could be combined for an SSPA transmitter. Components for on-board signal processing, such as active filters, bulk demodulators and switch matrices may also benefit from high-speed GaAs VLSI. GaAs MMIC's have the greatest potential for active antenna array applications. These arrays require large numbers of identical active circuits, and the circuits must be small enough to meet the constraints imposed by the size of the array. In addition, the circuits must be low cost, highly repeatable and have assured reliability. MMIC modules for receive arrays would contain LNA's, phase-shifters, variable gain amplifiers, and all necessary circuitry to receive and down-convert the signal. An MMIC module for a transmitting array would contain a power amplifier along with a variable power amplifier and phase-shifters.

A recent assessment (ref. 3) of millimeter wavelength GaAs MMIC technology has shown that considerable development has taken place for low noise and power amplifiers, phase-shifters, switches, and variable gain amplifiers under sponsorship by NASA, the Air Force, and private industry. The three main approaches for power devices are: MESFET (MEtal Semiconducting Field Effect Transistor), HEMT (High Electron Mobility Transistor) and psuedomorphic HEMT, and HBT (Heterojunction Bipolar Transistor). Up to the 30 GHz frequency range, MESFET technology is the more mature of the three. Recent reports have shown that power devices capable of producing 53 mW with 41% power added efficiency have been demonstrated. HEMT technology is presently at the 25 to 100 mW power range with efficiencies between 20 to 30%. HBT's, although at the early stages of development, offer significant promise for microwave and millimeter wavelength power devices. Devices at 400 mW with efficiencies as high as 50% have been reported. Table 4.4 shows a summary comparison of power MESFET's, HEMT's, and HBT's.

During the past 15 years, the device of choice for low noise amplifiers has been the MESFET. More recently, HEMT's and psuedomorphic HEMT's have been shown to out-perform conventional MESFET's. Psuedomorphic HEMT's are grown with an additional layer of InGaAs that provides a mismatch in lattice constants that results in superior device performance. Figure 4.6 shows a comparison of noise figures for MESFET's and HEMT's. This data is for device noise figure which is never attainable in complete amplifiers due to circuit mismatch. Differences between device capability and the complete amplifier noise figure increases with increasing bandwidth. For MESFET LNA's, recently reported results show noise figures in the 4 to 6 dB range up to 10 GHz. Results for HEMT LNA's give noise figures from 3 to 5 dB for frequencies as high as 50 GHz.

OPTICAL TECHNOLOGIES

The major benefits of employing an optical communications package for the exploration missions can be divided into two categories. The first category includes a number of advantages gained by using optical communications technology over the conventional RF technology alternative. Briefly listed, these include: substantial increase in link capacity, smaller size and mass of the communications package, less required operating power, and less impact to the spacecraft structure design.

The second category contains benefits obtained directly from the optical technology itself. This includes precise navigational tracking and additional scientific opportunities - "light science." With the use of optical communications, tracking of a deep space vehicle can be accomplished with less difficulty than with RF signals. With optical signals, the signal can be imaged directly against the stellar background, enabling both angle coordinates to be measured directly from a single optical telescope. The optical signals also enable scientific measurements such as: planetary atmospheric absorption at optical wavelengths, fine-scale scattering from planetary ring systems, and integrated forward scattering over interplanetary distances in the solar system dust field (ref. 4).

Opposite these potential benefits, optical technology has several disadvantages. The first is that it is less technologically mature than RF technology. And second, the beam pointing requirements and signal acquisition for optical signals will be a major technical challenge.

An optical package (ref. 5), shown in figure 4.7, using a 5 W doubled Nd:YAG laser transmitter with a 0.5 m transmit aperture and a 10 m receive spaceborne photon bucket can provide a 100 Mbps Mars-to-Earth link capacity, and was estimated to weigh under 250 lb and require less than 250 W to operate. In comparison, a more mature equivalent RF system was estimated to weigh ~400 lb and require 725 W to operate. The major technical challenges foreseen for the optical communications system were: pointing accuracies of <0.2 μrad, large optics fabrication, laser reliability, and acquisition that requires coarse pointing of the spacecraft to <<1 mrad. A developmental road map for a deep space optical communications system is shown in figure 4.8. The entire program is estimated to take a total of 6 years and require slightly over $100 million to fund.

INFORMATION MANAGEMENT TECHNOLOGY ASSESSMENT

In the area of Information Management, two major areas have been identified for technology development to meet the exploration mission requirements: data compression and data storage.

DATA COMPRESSION

Data compression is needed for information management in the Lunar and Mars exploration missions to reduce real-time space-to-Earth data transmission requirements for high data rate video and data. Some examples of data rates, resolution and compression ratios are given as preliminary requirements as shown in table 5.1. Primary data compression needs are in the areas of high rate video, science imaging cameras, telerobotics video, telemetry data, and other science instrument data. None of these requirements have been sufficiently defined so as to allow a complete assessment of precise technology needs. Thus, data compression is assessed at a functional level and various alternatives are reviewed.

In the exploration missions, data compression is required to significantly reduce the high data rate requirements to allow for a practicable design of the telecommunications system. By reducing data transmission rates, power and/or antenna requirements can be reduced. These advantages can be translated into a weight and power savings for the communications systems. Alternatively, reduced data rates could lead to an improvement in bit error performance of the data links. Reduced data rates would also reduce storage requirements and read/write rates to the storage devices.

Information on data compression was obtained from several sources (refs. 6 to 8). Although there are many data compression schemes not aimed specifically at video, such as the commonly used Lempel-Ziv algorithm, most of the data compression schemes examined herein are for video data compression since that is the area where data rate reduction is greatest.

Compression techniques can basically be put into two categories: reversible image or lossless compression techniques, and lossy techniques. Since the requirements are not well-defined at this time, it is not obvious which might be the "best" compression techniques for the individual video types to be used in the exploration missions. In some cases, it may be necessary to use a reversible image technique to satisfy the quality requirements for a given video type. However, in general, truly lossless techniques do not provide much in the way of compression. Thus, a compromise must usually be reached between desired compression and desired quality. An acceptably lossy technique may be able to provide sufficient quality with very good compression. Many techniques provide excellent compression and very good quality at the expense of high overhead or implementation complexity. These types of techniques may be applicable to low rate transmissions. Therefore, there are a large number of candidate techniques which are applicable and the proper choice of compression technique will be application dependent.

Reversible techniques include run-length coding (RLC), contour coding, Huffman and arithmetic coding, conditional replenishment, and bit-plane encoding. Lossy techniques can be further subdivided into several categories. Predictive methods operate by using previous pixel information to predict the characteristics of a given pixel. Most often this is done by transmitting the difference between the predicted value and the actual value which is known as differential pulse code modulation

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(DPCM). Other predictive methods include motion compensation and delta modulation. Additionally, predictive methods are often used in conjunction with other methods to yield good compression. Block coding methods such as vector quantization treat a block of pixels as a single element. All block coding techniques map an input sequence into an alternate coordinate system. In this respect, transform coding is a subset of block coding. Human visual system coding techniques deal with the elimination of image information that is basically imperceptible to the human eye anyway, regardless of the entropy or information content of this information. These methods are, in essence, attempts to achieve data reduction on a psychophysical basis through the modeling of the human visual system. One general drawback to most of these techniques is their complexity of implementation. Finally, fractals may offer incredible compression possibilities due to their inherent resolution. A summary of many of these methods is given in tables 5.2 to 5.6 with each table devoted to a different set of methods.

DATA STORAGE

The proposed exploration mission data storage requirements are given in tables 5.7 and 5.8. As with data compression requirements, the data storage requirements are not well defined. Thus, various methods of data storage are reviewed to determine the advantages and disadvantages of each with respect to the exploration mission requirements.

Determination of applicability is based on several criteria commonly associated with data storage media. The input/write rate that the storage device can accept is very important to the various applications and requirements. Data may be generated in a real-time application at megabyte data rates and the storage device will need an appropriate input/write rate to accommodate such applications. Similarly, the retrieval rate and access time for the storage device are very important in that they are the limiting factors on retrieving and outputting data transmitted from data storage. Mass data storage capacity is obviously an important parameter and in many cases it will be the determining factor for the choice of data storage devices. In real-time, continuous-use data storage systems, the number of allowable read/write cycles is a critical parameter. Finally, due to the demands of the space-based exploration communications networks, the space qualifiability and power requirements of the various storage media and devices are critical parameters for consideration of mass data storage systems.

Data storage is an important technology for the exploration missions for several reasons. It can be used as an on-line buffer for bursty transmissions. It can be used to prevent loss of data during emergency communications at low data rates. Data storage is required due to the periodic outages which will occur, especially in the Mars exploration scenarios, and due to any unforeseen unavailability of data links. Data storage also allows for the processing of certain science instrument data off-line rather than in an on-line continuous mode.

The results of this assessment are a survey of the technologies currently available and a brief overview of the advantages, disadvantages, and possible applications of each. The areas of data storage media to be covered include magnetic media, WORM (Write Once/Read Many) disk storage, CD-ROM (Compact Disc - Read Only Memory), Erasable Optical Disks or Devices (EOD), and digital paper. These are summarized in table 5.9.

CONCLUSIONS

The TNIM Technology Development Plan shown in figure 6.1 depicts a timetable for research and development of the identified technologies. It is meant to illustrate the relative development times needed for each of the technologies. The first milestones shown on the plan represent an initial study period in which alternative designs are evaluated, resulting in a final design. The next milestone shows the development of a proof-of-concept hardware implementation followed by a technology demonstration corresponding to a technology readiness level 5. The last milestones depict when space qualification is complete, and, where necessary, a flight demonstration or precursor mission would occur. The Technology Development Plan assumes reasonable, appropriate funding and it results, where possible, in a technology demonstration.

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TABLE 1.1 – TECHNOLOGY MATURATION MILESTONES

Basic
Research

1 Basic Principles Observed and Reported

2 Technology Concept / Applications Formulated

3 Analytical and Experimental Critical Function and / or Characteristic Proof-of-Concept

Focused
Technology

4 Component and / or Breadboard Validation in the Laboratory

5 Component and / or Breadboard Demonstrated in Relevant Environment

6 System Validation Model Demonstrated in Relevant / Simulated Environment

7 System Validation Model Demonstrated in Actual Environment

FIGURE 2.1 – BASELINE TNIM ARCHITECTURE

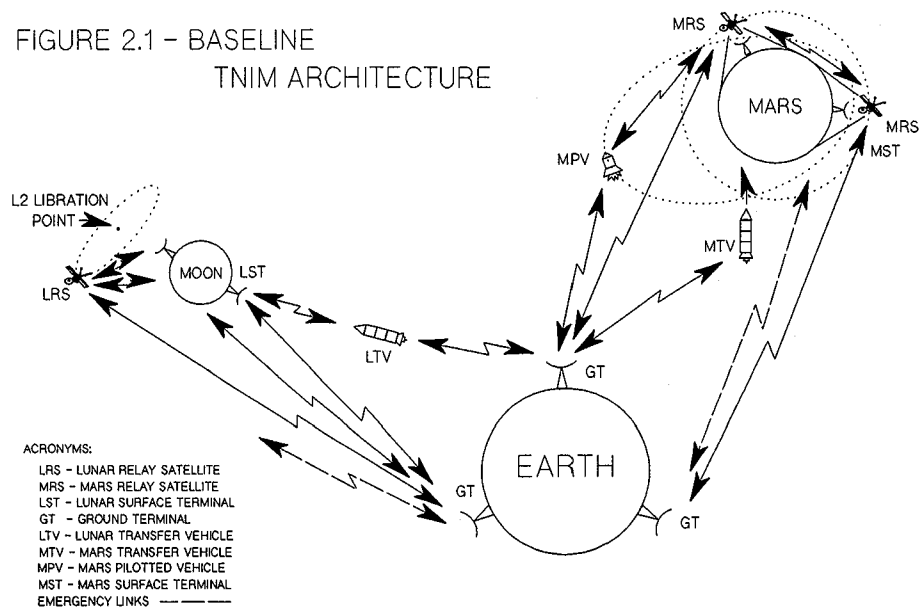ACRONYMS:
LRS – LUNAR RELAY SATELLITE
MRS – MARS RELAY SATELLITE
LST – LUNAR SURFACE TERMINAL
GT – GROUND TERMINAL
LTV – LUNAR TRANSFER VEHICLE
MTV – MARS TRANSFER VEHICLE
MPV – MARS PILOTTED VEHICLE
MST – MARS SURFACE TERMINAL
EMERGENCY LINKS — — — —

TABLE 4.1 - TNIM TECHNOLOGY REQUIREMENTS CHART

	EXPLORATION TECHNOLOGY REQUIREMENT	TECH READ. LEVEL
KA-BAND TECHNOLOGY		
TWTA TRANSMITTERS	10-150 W HIGH-EFFICIENCY	3-4
SSPA TRANSMITTERS	1-15 W HIGH EFFICIENCY	2-3
MECH. STEERED SINGLE REFLECTOR ANT	UP TO 5m DIAMETER	4
ELECTRONICALLY STEERED MBA	10-20 SIMULTANEOUS BEAMS	4
MMIC ELECTRONICALLY STEERED MBA	10-20 SIMULTANEOUS BEAMS	2-3
DIRECT-RADIATING MMIC PHASED ARRAY	10 X 10 ARRAY	3
RECONFIGURABLE ANTENNAS	OPERATION AT KA-BAND	2
MMIC TECHNOLOGY	HIGHER POWER / LOWER NOISE FIGURE	3-4
OPTICAL TECHNOLOGY		
LASER TRANSMITTER SOURCE	LONG-LIFE/HIGHER POWER LASERS	3
OPTICAL DETECTOR	HIGH GAIN-HIGH QUANTUM EFFICIENCY	3
OPTICS	LARGER LENS/IMPROVED RESOLUTION	2-3
INFORMATION MANAGEMENT		
DATA COMPRESSION	10:1 LOSSLESS COMPRESSION	2
DATA STORAGE	10^{12} BYTE STORAGE/FAST RETRIEVAL	2
AUTONOMOUS NETWORK CONTROL	COMPLETE FULL AUTONOMY	2
NAVIGATION TECHNOLOGY		
NAV TRANSPONDERS	10m ACCURACIES	3
SENSORS	IMU/ALTIMETER/PRESSURE/TEMPERATURE	3
COMPUTERS	AUTONOMOUS NAV CAPABILITY	3

TABLE 4.2 - TECHNOLOGY READINESS OF REPRESENTATIVE Ka AND W BAND TWTs

CENTER FREQ (GHz)	RF POWER (W)	EFFICIENCY (%)	TECHNOLOGY READINESS LEVEL	ADDITIONAL COMMENTS
18	33	41	>7	AEG TL20031 (SCS)
19	4	20	>7	
20	4	17	>7	
20	75-100	55	4	NASA LeRC CONTRACT
19.5	75/25	40/25	>7	DUAL-MODE
20	15	35	>7	
20	20	38	>7	AEG TL20019 (DFS)
20	34	41	>7	AEG TL 20032 (OLYMPUS)
20	60	43	>7	AEG TL20060
22	10	35	6	OPERATIONAL, NOT SPACE QUALIFIED
22	3-30	30	6	OPERATIONAL, NOT SPACE QUALIFIED
29-31	12	29	>7	AEG TL30011
30	1	10	2	NASA LeRC MINI-TWT
31	3	15	>7	
32	5	15	7	OLYMPUS
32	7	43	3	NASA CONTRACT (CASSINI)
60	15	35	2	EXPERIMENTAL
60	40	30	1	HELIX-DERIVED
60	75	40	3	NASA CONTRACT (COUPLED-CAVITY)

TABLE 4.3 – TECHNOLOGY READINESS OF REPRESENTATIVE
UHF, Ka AND W BAND SSPAs

TECHNOLOGY	FREQUENCY BAND	RF POWER (W)	EFFICIENCY (%)	TECHNOLOGY READINESS LEVEL	ADDITIONAL COMMENTS
TRANSISTOR	UHF	5	65	6	OPERATIONAL, NOT SPACE-QUALIFIED
TRANSISTOR	UHF	30	55	6	OPERATIONAL, NOT SPACE-QUALIFIED
FET	20 GHz	2	30	4	HUGHES
FET	20 GHz	2	15	4	MSC, RAYTHEON
FET	20 GHz	1.96	24	4	HUGHES
FET	20 GHz	3	20	4	PROJECTED
FET	20 GHz	3.5	18	4	HUGHES
FET-SSPA	20 GHz	10	12	5	GE
FET-SSPA	20 GHz	12	15.5	4	HUGHES
IMPATT-SSPA	20 GHz	10	12	4	LNR – IR&D
IMPATT-SSPA	20 GHz	20	12	4	LNR – IR&D
HEMT	30 GHz	460 mW	24.2	3	TEXAS INSTR.
FET	28 GHz	481 mW	11.2	4	COMSAT
FET	34 GHz	1	5.8	4	TEXAS INSTR.
Si-IMPATT	29 GHz	20	10	4	TRW-LeRC CONTRACT
IMPATT-SSPA	30 GHz	10	10	3	PROJECTED
HEMT	60 GHz	300 mW	20-30	7	GE
HEMT-SSPA	60 GHz	2	15-20	7	GE
IMPATT-SSPA	60 GHz	1.8	6.5	3	LNR
IMPATT-SSPA	60 GHz	6-10	5	3	PROJECTED

TABLE 4.4 – COMPARISON OF POWER MESFETs, HEMTs, AND HBTs

Category	MESFET	HEMT	HBT
Performance			
f_t (GHz)	low	medium	high
f_{max} (GHz)	medium	high	low
Power Density	medium	medium	high
Efficiency	low	medium	high
Breakdown	medium	medium	high
Advantages	simple process	relative simple process	lax lithography
Disadvantages	---	---	complex process
	recess uniformity	recess uniformity	---
	critical lithography	critical lithography	---
	material uniformity	material uniformity	material uniformity

FIGURE 4.1a - REQUIRED TWTA TECHNOLOGY READINESS

FREQUENCY = 8.4GHz
30-50% EFFICIENCY

TECHNOLOGY READINESS LEVEL

RF OUTPUT POWER (W)

△ MARS EMERGENCY POWER REQUIREMENT

FIGURE 4.1b - REQUIRED TWTA TECHNOLOGY READINESS

FREQUENCY = 20 GHz
30-50% EFFICIENCY

TECHNOLOGY READINESS LEVEL

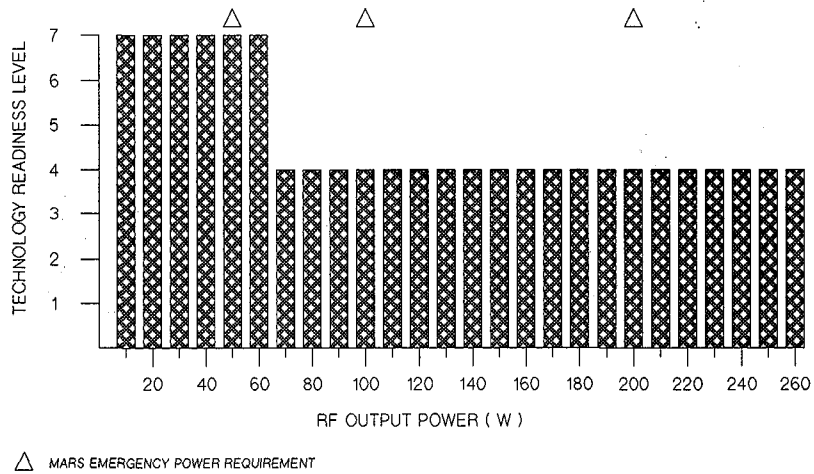☐ LUNAR POWER REQUIREMENT   RF OUTPUT POWER (W)
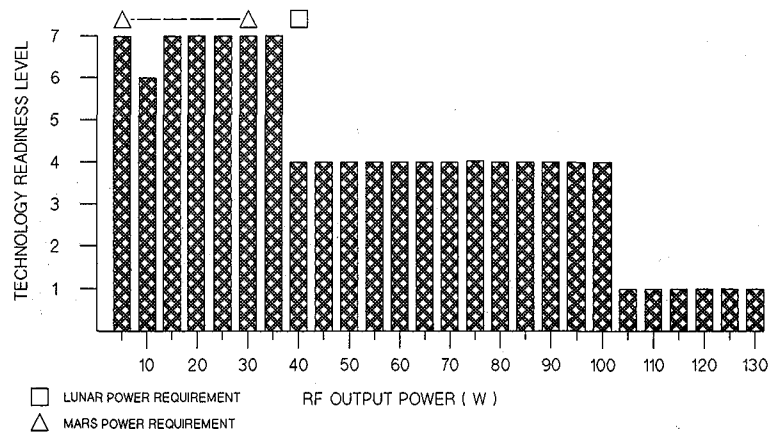△ MARS POWER REQUIREMENT

FIGURE 4.1c – REQUIRED TWTA TECHNOLOGY READINESS
FREQUENCY = 30 GHz
10-35% EFFICIENCY

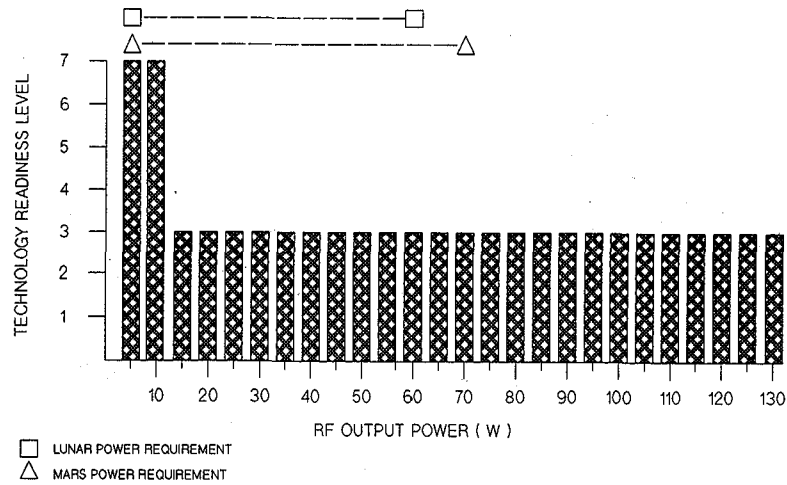FIGURE 4.2a – SSPA TECHNOLOGY READINESS LEVEL
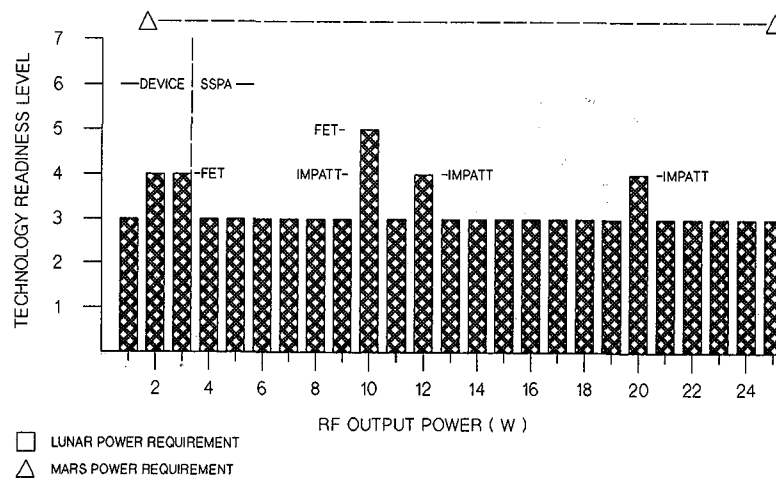FREQUENCY = 20 GHz
<20% EFFICIENCY

FIGURE 4.2b – SSPA TECHNOLOGY READINESS LEVEL

FREQUENCY = 30 GHz
<20% EFFICIENCY

TECHNOLOGY READINESS LEVEL

DEVICE | SSPA —

-FET
-Si-IMPATT
-IMPATT
-Si-IMPATT

RF OUTPUT POWER (W)

☐ LUNAR POWER REQUIREMENT
△ MARS POWER REQUIREMENT

FIGURE 4.3 – REPRESENTATIVE TWT DEVELOPMENT SCHEDULE

MONTHS	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
RF CIRCUIT REFINEMENT	△					▽																										
ELECTRON GUN REFINEMENT	△						▽																									
MAGNET FOCUSING REFINEMENT	△					▽																										
MULTI-STAGE COLLECTOR DESIGN		△					▽																									
PACKAGE DESIGN		△					▽																									
COLD TEST			△	▽																												
DESIGN AND FAB TOOLING			△				▽																									
PROCURE PARTS			△				▽																									
FABRICATE EXPERIMENTAL TWT						△		▽																								
TEST EXPERIMENTAL TWT								△	▽																							
SPACE QUALIFICATION										△																▽						
TWT DELIVERIES																												△				

FIGURE 4.4 – REPRESENTATIVE SSPA DEVELOPMENT SCHEDULE

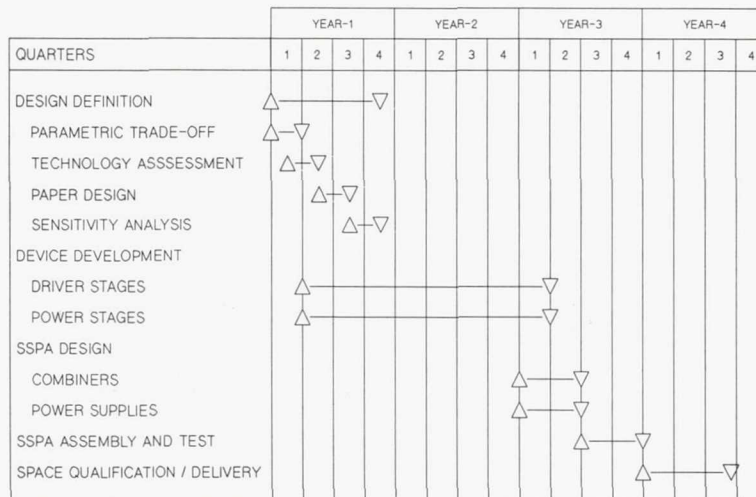| QUARTERS	YEAR-1				YEAR-2				YEAR-3				YEAR-4			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
DESIGN DEFINITION	△			▽												
PARAMETRIC TRADE-OFF	△	▽														
TECHNOLOGY ASSSESSMENT	△	▽														
PAPER DESIGN		△	▽													
SENSITIVITY ANALYSIS			△	▽												
DEVICE DEVELOPMENT																
DRIVER STAGES		△							▽							
POWER STAGES		△							▽							
SSPA DESIGN																
COMBINERS									△	▽						
POWER SUPPLIES									△	▽						
SSPA ASSEMBLY AND TEST											△	▽				
SPACE QUALIFICATION / DELIVERY												△		▽		

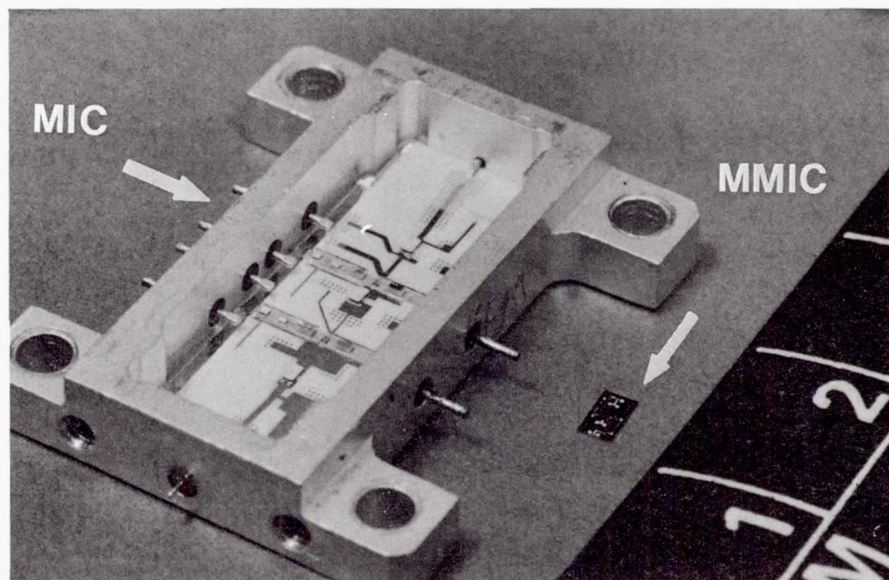## FIGURE 4.5 – COMPARISON OF S.O.A. HYBRID MIC vs MMIC

FIGURE 4.6 – COMPARISON OF HEMT AND FET NOISE FIGURES
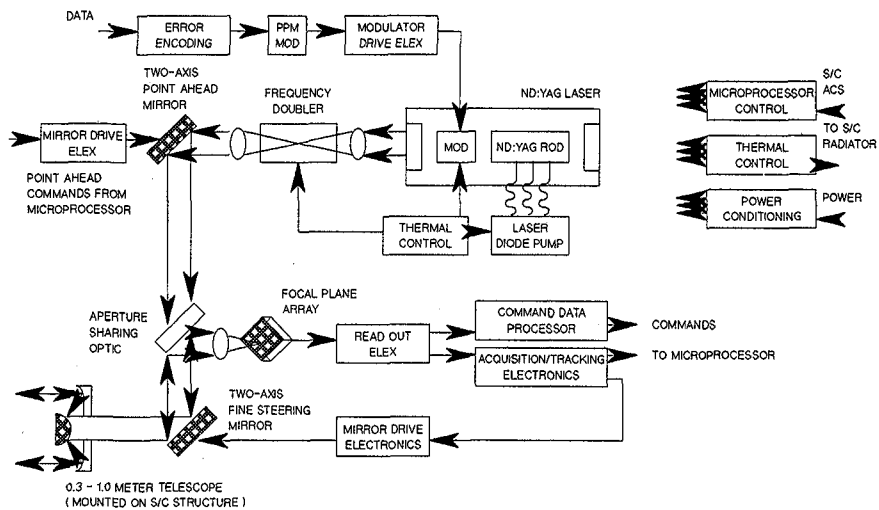

FIGURE 4.7 – LASERCOM SPACE SEGMENT BLOCK DIAGRAM

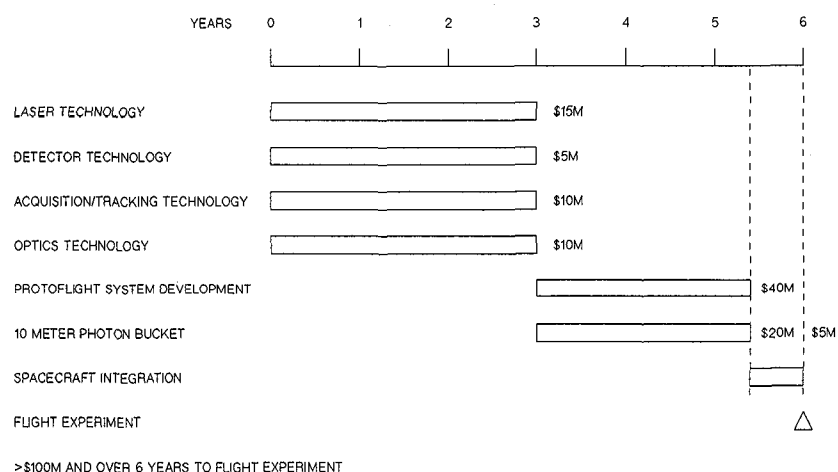## FIGURE 4.8 - DEEP SPACE LASERCOM DEVELOPMENT ROADMAP

	YEARS	0	1	2	3	4	5	6	
LASER TECHNOLOGY									$15M
DETECTOR TECHNOLOGY									$5M
ACQUISITION/TRACKING TECHNOLOGY									$10M
OPTICS TECHNOLOGY									$10M
PROTOFLIGHT SYSTEM DEVELOPMENT									$40M
10 METER PHOTON BUCKET									$20M $5M
SPACECRAFT INTEGRATION									
FLIGHT EXPERIMENT									△

>$100M AND OVER 6 YEARS TO FLIGHT EXPERIMENT

TABLE 5.1 - SEI DATA COMPRESSION REQUIREMENTS

DATA TYPE	RAW DATA RATE	CODED DATA RATE	COMMENTS
High Rate Video	100 Mbps	10 Mbps	single channel, color, 512 X 512 pixels, 12 bits/pixel, 30 frames/sec requiring 10:1 data compression with no perceptible quality degradation. Includes intraframe and interframe compression
Edited High Rate Video	20 Mbps	1-2 Mbps	quality similar to teleconferencing with some frames dropped (transmit < 30 frames/sec, display at 30 frames/sec)
Low Rate Video	2 Mbps	0.2 Mbps	single channel, monochrome, 512 X 512 pixels, 8 bits/pixel, 1 frame/sec
Imaging Camera	2 Mbps	0.5 Mbps	1024 X 1024 pixels, 8 bits/pixel, RGB signal, 4 images/min with 4:1 "noise-free" compression for most scenes
Telerobotics Video	200 Mbps	20 Mbps	2 channels, color, 512 X 512 pixels, 8 bits/pixel, 30 frames/sec, requiring 10:1 data compression and no perceptible quality degradation to teleoperator
Science Telemetry	300 Mbps	30 Mbps	10:1 data compression required

TABLE 5.2 – PERFORMANCE OF REVERSIBLE METHODS

COMPRESSION TECHNIQUES	COMPRESSION bits per pixel	ERRORS %MSE	COMMENTS
1. RUN–LENGTH CODING	1.5 – 2.0	NOT APPLICABLE	THIS COMPRESSION IS POSSIBLE WITH LOW DETAIL IMAGES, ENCODED AT 8 bpp.
	3.5		THIS COMPRESSION IS POSSIBLE WITH TYPICAL TELEVISION IMAGES.
	up to 16		COMPRESSION POSSIBLE WITH HIGH DETAIL IMAGES.
2. CONTOUR CODING	DEPENDS ON NUMBER OF CONTOURS	NOT APPLICABLE	THIS TECHNIQUE IS MOST EFFECTIVE WHEN USED WITH TWO-TONE, LINE DRAWINGS.
3. HUFFMAN CODING	7.5	NOT APPLICABLE	THIS TECHNIQUE IS MOST OFTEN USED IN ADDITION TO LOSSY, ENTROPY REDUCING METHODS.
4. ARITHMETIC CODING	7.5	NOT APPLICABLE	PERFORMANCE IS SIMILAR TO HUFFMAN CODING
5. CONDITIONAL REPLENISHMENT	DEPENDS ON MOTION OR IMAGE CONTENT	NOT APPLICABLE	REVERSIBLE COMPRESSION RATIOS DEPEND ON AMOUNT OF MOTION OR BACKGROUND CHANGE IN THE IMAGE.
	≥ 1.0	*	THIS COMPRESSION YIELDS LOSSY COMPRESSION WITH GOOD QUALITY RECONSTRUCTED IMAGES.
6. BIT–PLANE ENCODING	*	*	METHOD OFFERS ADDITIONAL IMPROVEMENTS OVER PREVIOUS METHODS, ESPECIALLY WHEN USING GRAY CODES.

* – DATA NOT AVAILABLE IN LITERATURE REVIEWED

TABLE 5.3 – PERFORMANCE OF PREDICTIVE METHODS

COMPRESSION TECHNIQUES	COMPRESSION bits per pixel	ERRORS %MSE	COMMENTS
1. LINEAR PREDICTIVE CODING	DEPENDS ON IMAGE ENTROPY; REQUIRES TRANSMISSION OF DIFFERENCE SIGNAL	HIGHLY DEPENDENT ON QUANTIZATION	PREDICTION IS FUNCTION OF IMAGE'S STATISTICS.
2. DIFFERENTIAL PULSE CODE MODULATION (DPCM)	3.0 – 4.0	HIGHLY SUSCEPTIBLE TO TRANS ERRORS	THIS COMPRESSION IS POSSIBLE USING NON-ADAPTIVE QUANTIZATION.
	2.0 – 3.0	HIGHLY SUSCEPTIBLE TO TRANS ERRORS	THIS COMPRESSION IS POSSIBLE USING ADAPTIVE QUANTIZATION.
3. DELTA MODULATION	≥ 1.0	HIGHLY DEPENDENT ON QUANTIZATION; SUSCEPTIBLE TO TRANS ERRORS.	ANALOG INPUT SIGNAL SIMPLIFIES IMPLEMENTATION, BUT MUST BE SAMPLED AT RATE HIGHER THAN NYQUIST RATE. GREATEST COMPRESSION WHEN USING NON-ADAPTIVE TECHNIQUE.
4. MOTION COMPEN-SATION (MC)	1.5		AVERAGE COMPRESSION FOR GOOD QUALITY PICTURES.

TABLE 5.4 – PERFORMANCE OF BLOCK METHODS

COMPRESSION TECHNIQUES	COMPRESSION bits per pixel	ERRORS %MSE	COMMENTS
1. VECTOR QUANTIZATION (VQ)	0.5 – 0.8	0.1	COMPRESSION USING MONOCHROME IMAGES.
	1.5 – 2.0	0.1	COMPRESSION USING COLOR IMAGES.
	0.1 – 0.2	*	COMPRESSION POSSIBLE WITH MOTION COMPENSATION TECHNIQUE. BPP HOLDS TRUE IF MOTION IS < 20% IN THE IMAGE.
2. VECTOR DPCM	0.5	**	COMPRESSION USING MONOCHROME IMAGES.
	0.75 – 1.08	***	COMPRESSION USING COLOR IMAGES.
			IN GENERAL, VECTOR DPCM PRODUCES BETTER RESULTS THAN VQ AT SAME BIT RATE.
3. BLOCK TRUNCATION CODING	1.625	*	COMPRESSION USING MONOCHROME IMAGES.
	2.13	*	COMPRESSION USING COLOR IMAGES.
	0.9	*	COMPRESSION USING INTERFRAME CODING.
4. VARIABLE RESOLUTION CODING: a) MAPS	0.593	0.82	
b) TREE CODING	0.2 – 9.0	*	DEPENDING ON THE AMOUNT OF DETAIL, THIS METHOD CAN BE REVERSIBLE.

* – DATA NOT AVAILABLE IN LITERATURE REVIEWED
** – SQUARE ERROR < 18
*** – SQUARE ERROR < 200

TABLE 5.5 – PERFORMANCE OF HUMAN VISUAL SYSTEM COMPENSATION METHODS

COMPRESSION TECHNIQUES	COMPRESSION bits per pixel	ERRORS %MSE	COMMENTS
1. SYNTHETIC HIGHS	0.25 – 2.0	*	AMOUNT OF COMPRESSION DEPENDS ON THRESHOLD VALUES AND DESIRED IMAGE QUALITY.
2. PYRAMID CODING	0.7 – 1.6	< 1.0	QUANTIZATION ERRORS OCCUR AT HIGH FREQUENCIES.
3. REGION GROWING	0.3	*	TECHNIQUE DOES NOT YIELD GOOD RESULTS FOR SMALL OBJECTS OR DETAILS IN ORIGINAL IMAGE.
4. DIRECTIONAL DECOMPOSITION	0.13 / 0.04 – 0.08	* / *	COMPRESSION WAS ACHIEVED USING 8–BIT ORIGINAL. AT THIS COMPRESSION, THIS METHOD PRODUCES BLURRED BUT STILL RECOGNIZABLE IMAGES.
5. ANISOTROPIC NONSTATIONARY PREDICTIVE CODING	0.25 – 0.4	8	THIS TECHNIQUE DOES NOT HANDLE FINE TEXTURE AT HIGH COMPRESSION RATES.
6. MINIMUM NOISE VISIBILITY CODING	4.5 / 5.6	**** / ****	COMPRESSION USING MONOCHROME IMAGES COMPRESSION USING COLOR IMAGES.
7. CONSTANT AREA QUANTIZATION (CAQ)	1.08 / 1.2 / 1.0 – 1.3	3.0 / < 2.0 / 1.5 – 1.0	COMPRESSION WAS ACHIEVED BY INTRODUCING OVERSHOOT INTO THE METHOD. COMPRESSION WAS ACHIEVED USING PREDICTIVE CAQ
8. PERPETUAL SPACE CODING	0.1 / 0.25	0.72 / 0.36 – 3.30	A LOW DETAIL, MONOCHROME IMAGE WAS ENCODED RESULTING IN USABLE QUALITY REPRODUCTIONS. COLOR IMAGES OF VARYING DETAIL WERE ENCODED RESULTING IN EXCELLENT QUALITY REPRODUCTIONS.

* – DATA NOT AVAILABLE IN LITERATURE REVIEWED   **** – QUANTIZATION ERRORS AT HIGH FREQUENCIES

20

TABLE 5.6 – PERFORMANCE OF TRANSFORM CODING

COMPRESSION TECHNIQUES	COMPRESSION bits per pixel	ERRORS %MSE	COMMENTS
1. KARHUNEN–LOEVE TRANSFORM (KLT)	0.5 – 1.0	1.5 – 0.5	PRODUCES BEST RESULTS OVER WIDE RANGE OF IMAGES; LACKS FAST IMPLEMENTATION.
2. DISCRETE COSINE TRANSFORM (DCT)	0.5 – 1.0	0.75 – 0.2	WITH ADAPTIVE TECHNIQUES, PERFORMS CLOSE TO KLT
3. SLANT TRANSFORM	1.0 – 1.5	< 1.0	WITH ADAPTIVE TECHNIQUES, PERFORMS CLOSE TO DCT AND BETTER THAN HADAMARD AND HAAR
4. HADAMARD TRANSFORM	1.0 – 1.5	1.5 – 1.0	STRAIGHTFORWARD HARDWARE IMPLEMENTATION
5. HAAR TRANSFORM	0.7 – 1.7	0.8 – 0.2	WITH ADAPTIVE QUANTIZATION, BETTER PERFORMANCE THAN HADAMARD

TABLE 5.7 – LUNAR DATA STORAGE REQUIREMENTS

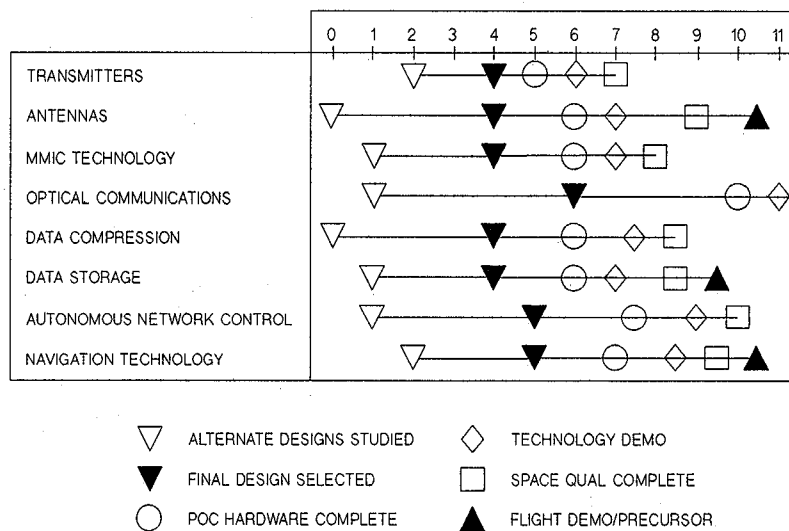| Data User/Node	Storage Type Archive	Storage Type Online	Duration (Hrs)	Reqs. (Online)	Comments
Orbiters	No	Sci/Eng	24	TBD	Available for video processing
Crew Vehicles	Video	Eng	24	NA	No video processing
Rovers	Video	Sci/Eng	24	TBD	No video processing
Selenoscience	Video	Sci/Eng	24	TBD	In situ processing, video processing
Lunar Habitat	Video	Sci/Eng	24	TBD	In situ processing, video processing
Support Equipment	Video	Sci/Eng	24	TBD	In situ processing, no video processing

TABLE 5.8 - MARS ONLINE DATA STORAGE REQUIREMENTS

Node	Minimum Storage (10^9 bytes)	Input / Write Rate (Mbps)	Time Window (Hrs)	Online Storage For Cont. Use (10^9 bytes)
Relay Satellite	15	5	6	-
MPV	23	(5,10)	(6,1)	5
Robotic Rover	3.5	1.5	4	0.5
Manned Rover	5	1.5	4	2
Habitat	23	(5,10)	(6,1)	5
Phobos	3.5	1.5	4	0.5
Deimos	1.4	0.5	4	0.5
MCSV	6.4	2	6	1
Imaging Probe	8.7	300	0.05	2

TABLE 5.9 - DATA STORAGE ASSESSMENT

Media Type	Advantages	Disadvantages	Applications
Magnetic	– Mature Technology – Mass Data in Small Space – Access Time of 20 ms – Large Number of R/W Cycles	– Access Times At Limit – Capacity At Limit – Susceptible To Magnetic Effects	– Database Storage – Image Storage – Archiving – Log Status Data
WORM	– Compact Size of Media – Mass Data In Small Space – Long Useable Life – Immunity To Magnetic Effects	– Access Times 90–200 ms – No Standard Format – Data Cannot Be Rewritten	– Database Storage – Image Storage – Archiving – Log Status Data
CD-ROM	– Standardized Format – Mass Data In Small Space – Compact Size/Long Life – Immunity To Magnetic Effects	– Access Times 90–200 ms – Data Is Written At Factory And Cannot Be Changed	– Fixed Databases – Storage of Maps, Instructions, Etc. – Storage of Manuals
EOD	– Mass Data In Small Space – Large Number of R/W Cycles – Compact Size/Long Life – Immunity To Magnetic Effects	– Nonstandard Formats – Acess Times 90–200 ms	– Database Storage – Image Storage – Archiving – Log Status Data
Digital Paper	– Standardized Format – Mass Data In Small Space – Compact Size/Long Life – Economical & Flexible	– Limited To Sequential Access of Data – Data Cannot Be Rewritten	– Database Storage – Image Storage – Archiving – Log Status Data

FIGURE 6.1 – TNIM TECHNOLOGY DEVELOPMENT PLAN

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National Aeronautics and
Space Administration

Report Documentation Page

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15. Supplementary Notes

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16. Abstract

On the 20th anniversary of the Apollo 11 lunar landing, President George Bush set forth ambitious goals for expanding human presence in our solar system. The Space Exploration Initiative addresses these goals beginning with Space Station Freedom, followed by a permanent return to the Moon, and a manned mission to Mars. A well-designed, adaptive Telecommunications, Navigation, and Information Management (TNIM) infrastructure is vital to the success of these missions. Utilizing initial projections of user requirements, a team under the direction of NASA's Office of Space Operations developed overall architectures and point designs to implement the TNIM functions for the Lunar and Mars mission scenarios. Based on these designs, an assessment of technology alternatives for the telecommunications and information management functions was performed. This technology assessment identifies technology developments necessary to meet the telecommunications and information management system requirements for the Space Exploration Initiative. Technology requirements, technology needs and alternatives, the present level of technology readiness in each area, and a schedule for development are presented. The schedules for technology development are targeted to provide a technology readiness level of 5 and are given in relative years from the start of a program.

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