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An Evolutionary Communications Scenario for Mars Exploration

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AN EVOLUTIONARY COMMUNICATIONS SCENARIO FOR MARS EXPLORATION

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As Mars exploration grows in complexity with time, the corresponding communications needs will grow in variety and complexity also. From initial Earth/Mars links, further needs will arise for complete surface connectivity for the provision of navigation, position location, and voice, data, and video communications services among multiple Mars bases and remote exploration sites. This paper addresses the likely required communications functions over the first few decades of Martian exploration and postulates systems for providing these services. Required technologies are identified and development requirements indicated.

INTRODUCTION

In recent years, direction and momentum have been building, both in the U.S. and the Soviet Union, towards long-term commitment to the exploration of Mars. In the U.S. the exploration of Mars has the potential of becoming a major new space activity leading ultimately to the manned exploration and settlement of that planet. The presidentially appointed "National Commission on Space" has recommended that the exploration of Mars become a major U.S. space goal and NASA has incorporated it as a major initiative in its long-range strategic planning activities.

The initial missions, those precursor to ultimate human presence, are being formulated now by both the U.S. and Soviets. These include the Mars Observer, to be launched probably in 1992, and the Mars Rover Sample Return Mission (MRSR) in the 1998 time frame. These missions will lead to establishment of the required knowledge base concerning planetary parameters, the Martian environment, and the potential for resource exploitation necessary for human activities to take place. The first manned mission could take place, depending on the Nation's objectives, as early as 2005 or perhaps more likely in the 2015-2030 era.

To effectively pursue this ambitious goal, a host of systems and supporting technologies must be developed and constructed. The appropriate vehicles, life support, and in general, the basic infrastructure for accomplishing goals of this magnitude, will have to be developed. Supporting technology areas include power, propulsion, structures, robotics, materials, communications, and others. Many of these needs, options, and issues have been identified and are well documented in the recent literature, conferences, and NASA planning activities.

This paper discusses some of the communications aspects of manned Mars activities and presents some potential communication system types for supporting those communications needs. Communications technology initiatives that need to be pursued now are identified and related current efforts at NASA Lewis Research Center and other NASA centers are discussed.

EXPLORATION SCENARIOS

Mars exploration (unmanned) began a number of years ago with the Mariner flyby mission and Viking orbiter/lander missions in the 1970's. Currently planned is the Mars Observer mission to be launched in 1992. The spacecraft will arrive at Mars in 1993 and will be placed in a 350 km near-polar orbit. Data will be collected for at least one Martian year (687 days) on the climatology, surface composition, topography, gravity field, and magnetic field of Mars. Following the Mars Observer, in 1998, will be the Mars Rover Sample Return (MRSR) mission. Although not yet an official mission, the MRSR mission will, as the name implies, return actual samples from the Martian surface. These will greatly enhance the understanding of the Martian regolith, its history, and the potential of using in-situ resources for construction, agriculture, propellant production, etc., for future human Martian surface exploration and habitation. Concurrently with the U.S. missions to Mars, the Soviet Union is proceeding with similar type missions. One of these in the early 90's will sample the surface of the Martian moon Phobos by vaporizing a small spot on the surface with a laser beam and analyzing the spectral emissions. The Martian moons, Phobos and Deimos, have been suggested as potential resource nodes from which to manufacture propellants, serve as observation posts, and as staging bases for Mars surface exploration. Missions to (and return from) the Martian moons (from Earth orbit) have less demanding energy requirements and are far less complex than those intended for landing on the surface. If propellants and possibly other necessities could be manufactured at the Martian moons, manned missions to the Martian surface would be greatly reduced in complexity. The possibility for U.S./Soviet cooperation in Mars exploration beginning in the late 1990's is being pursued. Beyond these missions, but not presently defined, will be more advanced precursor missions leading eventually to manned exploration missions and, perhaps ultimately to a continuous human presence.

Recently, attention in the U.S. has focused on developing the commitment to long-term space goals including solar system exploration and a broad set of initiatives required to accomplish them has been outlined. In 1985, a presidential commission, "The National Commission on Space (NCOS)," was formed to examine the U.S. role in space; to formulate a bold new agenda to carry America's civilian space enterprise into the 21st century, and to place before the nation a rationale and a program to assure continuing American leadership in space. The commission outlined an agenda and rationale for U.S. space activity over the next 50 years, a set of goals involving science, exploration, and enterprises representing real value to the people on Earth. To accomplish these goals, they recommend national commitments to advancing technology across a broad spectrum to ensure timely availability of critical capabilities; and creating and operating systems and institutions to provide low-cost access to the space frontier. The commission's recommendations can be found in their published report[1].

Subsequent to the NCOS activity, NASA has been conducting long-range planning activities. Several long-range planning teams were formed to outline NASA's direction in carrying out the U.S.'s space activities. Among these were the Civil Space Technology Initiative (CSTI) activity, the Advanced Missions

Working Group (AMWG), the Space Leadership Planning Group (SLPG), and most recently, the "Sally Ride" Committee[2]. From these activities, NASA's Office of Aeronautics and Space Technology (OAST) has outlined a sequence of phases, for planning purposes, characterizing long-range manned exploration of the Solar System. Figure 1 presents these phases and the kinds of activities associated with them. The first phase, beginning now, would be characterized by the construction of the Space Station, OTV, routine LEO/GEO operations, major science and earth-oriented activities, development of lower cost access to space, and, in general, building the basic infrastructure to support the next phases to come. The next "Pathfinder" phase would include Mars site surveys and sample return missions, life science capability development, additional Space Station complex capability, and activities directly precursor to lunar return and manned Mars exploration. The third "Pioneer" phase would be the begining of routine human activities in the Solar System beyond earth. The Pioneer phase may evolve into a continuous human presence or "Pilgrim" phase at the Moon and Mars. Farther into the future there may even be a "Settler" phase characterized by large numbers of people living in self-sustaining planetary settlements. No timelines are shown on Figure 1 associated with these phases, but they would represent several decades in extent. A visionary paper, "A Timeline for Martian Pioneers"[3] by Thomas Paine (former Administrator of NASA and also Chairman of the National Commission on Space) was presented at the Mars II conference in 1984. In this paper, Paine looked ahead ten decades to the possibility of an independent Martian civilization and outlined the necessary prerequisites, such as international peace, cooperation, and national prosperity leading to this possible future.

To develop and conduct the activities outlined in these exploration scenarios, many elements of the basic supporting infrastructure must be developed and integrated into reliable operating systems. One of the critical elements of the supporting infrastructure is communications, and that is the subject of the following sections of this paper.

COMMUNICATIONS REQUIREMENTS AT MARS

The communications requirements of Mars exploration activities will be determined by the type and complexity of those activities, necessary links and connectivity, services to be provided, and particular functions to be performed and characteristics of service desired. The earlier unmanned missions will, of course, be less demanding on systems than later activities. As a human presence emerges in exploration activities, the requirements on communications systems and functions will be greatly increased. The requirements represent the determinant for the types of communications systems to be deployed and the technologies that need to be developed to support these systems. The following suggests some of the requirements that will be involved in Mars exploration activities, and these are summarized in Figure 2.

LINKS

The most obvious communications link required in exploring Mars would be, of course, a link or links between Mars and Earth. In order to maximize communication time per day, communications could be relayed through a Mars orbiter as was done in the Viking program and possibly for the MRSR mission. Earlier missions will use lower altitude elliptical orbit relays, as these will be used for other purposes such as mapping, while later manned surface activity may involve dedicated "areostationary" communication and earth relay satellites. (The term "areostationary" being analogous to "geostationary" when referring to the Earth). For redundancy, direct Earth/Mars link capability will be included.

Communications must be maintained with in-transit spacecraft. Initially, a link would be needed between the spacecraft and Earth and later as a routine human presence develops, communications from Mars with incoming spacecraft will be necessary.

Also, since early activities will likely be conducted at the Martian moons, Phobos and Deimos, links from there with Earth and with later Mars surface bases will be required.

As multiple exploration sites, outposts, and bases emerge on the Martian surface, there will be a need for communications interconnection.

There will be a need for communications with mobile vehicles and remote exploration activities with the bases and with Earth. Unmanned Martian rovers, balloons, airplanes, manned Martian "jeeps", and other mobile means will require communications with their controlling bases. "Hand-held" or individual means of communications within an immediate exploration site and back to base will be needed.

SERVICES

The services to be provided by communications systems will initially be all data transmission, but later, when manned activities begin, voice and video transmissions will be necessary. High resolution video will be required on the first manned missions to transmit to Earth the first activities of the Martian pioneers. Of course, real time or interactive communications won't be possible due to the time delay caused by the long path length. The transmission time, at the speed of light, varies with the distance between Earth and Mars and varies from a minimum of about 3 minutes to a maximum of about 22 minutes.

FUNCTIONAL REQUIREMENTS

The "functional requirements" of a communications system refers to the nature of the transmissions the system must provide and how it must perform. Examples include such things as type of transmission to be accommodated (voice, video, data), communication capacity to be provided, connectivity required, and standards of services to be adhered to.

In the context of Mars exploration, the earlier missions will send back data streams of up to a few megabits per second (Mbps) while later manned missions involving high resolution video in parallel with other data could represent a need for transmission capacity in the hundreds of Mbps.

Voice and lower speed data transmission among different points on the Martian surface and with Earth will be a fundamental requirement.

Position location and navigation of both manned and unmanned vehicles will be required, and, for some activities, position will need to be known within a few meters.

As the human presence emerges, safety will be an overriding requirement. This dictates that people exploring Mars have the ability to contact their bases at any time and for the Mars expeditions and bases to be in contact with Earth at all times. This also implies that ubiquitous Martian surface coverage will be required, or anywhere that manned activity is likely to be.

COMMUNICATION TECHNOLOGY ASPECTS

Some of the implications for communications technologies involved in manned Mars (and other Solar System) missions are perhaps somewhat different or more stringent than would be required for systems providing similar type functions in a near Earth environment (Figure 3). Because of the human presence, safety is of the utmost concern. The possibility of a failure in a communications system and the cost and time involved in establishing and maintaining it dictates long-lived, ultra-reliable facilities. Fault tolerant and fail soft designs for communication equipment will be required.

The cost of transporting hardware to Mars will put a premium on small, lightweight components with lower power consumption. Likewise, data compression and higher data rates per hertz will be required for conserving power.

Personal communications by explorers on Mars would be greatly enhanced by advanced satellite demodulators enabling access by numerous narrow band channels transmitting independently. Personal communications equipment would also be required to be small, lightweight, reliable, and low power (perhaps on the order of 0.5 watt).

POTENTIAL COMMUNICATION SYSTEM TYPES

Early Systems

Previous and planned missions to Mars typically make use of orbiter/lander combinations in order to make complete surface observations, mapping, etc., and for surface analysis and exploration. The orbiters are also used as communications relays for transmission between the landers and Earth. In order for the orbiters to be used effectively as relays, their orbits must be constrained somewhat beyond that desired for the other orbiter functions. Generally, the orbiters are placed in highly elliptical (e.g., 500x33,429 KM) orbits having 24.5 hour periods (the rotational period of Mars). The orbits are phased such that the zeniths remain in sight of the Mars landers. Using orbiters for communications relays to Earth is somewhat more complex than having direct links, but significantly increases the communications time per day (reduces occultation or blockage time per day when the landers are on the side of Mars away from the Earth)[4,5].

The use of the Martian moons, Phobos and Deimos, for communication relays to Earth and among scattered bases on Mars' surface has been suggested[6]. These moons are in near circular low inclination (less than 2 degrees) orbits about Mars. Their altitudes above the planet are 1.82 and 6.06 Mars radii, respectively. Phobos circles Mars a little over three times a Martian day, but because of Mars' rotation, the moon passes over the same surface locations only about twice per day. Also, because of the lower altitude of Phobos, it is visible from a location on the surface only about 40 percent of the time, and not beyond $\pm$ 69^{0} latitude. Antennas on the surface would either have to track Phobos' movement across the sky or transmit in an omnidirectional mode, a power and frequency wasteful approach. For continuous coverage, two other satellites, spaced 120^{0} in Phobos' orbit, would be needed.

Deimos, the outermost moon, is almost in a Mars synchronous orbit. It has a period of 30 hours compared with the Mars day of 24.5 hours, and considering the rotational velocity of Mars, Deimos passes over the same spot on the surface about every 5.5 Mars days. Because of the relatively slow apparent revolution about Mars, it is in view of a given point on the surface about 2.5 days at a time, but out of sight for 3 days at a time. As in the case with Phobos, Deimos cannot provide coverage to the polar regions from its equatorial orbit. Although less than ideal as communication satellites, Phobos and Deimos may be useful in the early phases of manned Mars exploration as communications relays. For polar coverage, a system of satellites in polar or other highly inclined orbits could be used. Figure 4 outlines some of the systems that might be employed in the early phases of exploration.

The Earth/Mars links would have to transmit increasing amounts of data as exploration activities proliferate, and this requirement could be a major factor in the choice of transmission frequency. The link communications capacity increases with frequency and the current and planned deep space links include S-band (2.5 GHz), X-band (10 GHz), Ka-band (30 GHz), and laser frequencies. The present Deep Space Network (DSN) uses X- and S-band and, recently, segments in Ka-band at 32 and 34 GHz have been allocated for deep space use. A Ka-band system can support data rates of five to ten times the rates supported at X-band for the same antennas and power levels.

For data rates greater than 100 Mbps, lasers should be considered as an alternative to the more conventional microwave links[5]. Lasers can support large data rates with small transmitting/receiving apertures. However, some of the characteristics which make laser communication links attractive also make them difficult to use. The high gain which makes possible small apertures also requires very accurate pointing systems. Atmospheric attenuation, which together with narrow beam width makes unauthorized access to the communication links more difficult, requires a relay system of satellites orbiting the Earth in order to provide dependable communcations with Earth-based stations. A similar situation exists at Mars where a dust storm could block laser communication links. Therefore, it is envisioned that a laser link would be used only for communications between vehicles in Earth and Mars orbit with lower frequency communications to the surfaces.

For present near-term planning a Ka-band system appears attractive for communications between Earth and Mars. A Ka-band system can support moderate data rates, providing dependable communications with the Earth without a data relay system in orbit around the Earth.

Later Systems

As exploration activities on Mars grow in complexity and scope, the communications requirements will grow likewise, dictating more elaborate and complex systems and technology. Figure 5 suggests some systems addressing later communications needs, and Figure 6 depicts these in place about Mars. A system of three "areostationary" satellites spaced equilaterally in Mars' equatorial plane could provide a variety of communication services and form the basis of a network covering 95 percent of Mars' surface. The areostationary concept is analogous to the geostationary communications satellites used for terrestrial communications whereby the satellite appears to be stationary with respect to the planetary surface. These satellites could be interconnected by intersatellite links (ISL), either laser or high frequency microwave, and would constitute a network providing instantaneous and ubiquitous communications from anywhere on the surface, excepting the polar regions, including links to Earth and the Martian moons. The areostationary satellites would be used for various voice, data, and video communications among fixed bases, remote exploration sites, and mobile units, and would include navigation and position location functions. For polar communications, the system could be supplemented by a number of low altitude satellites in various inclined orbits. If a sufficient number of satellites were provided such that four would be in view at any one time, then precision position location, to within a few meters could be provided, much as the current NAVSTAR Global Positioning System (GPS)[7].

Other possibilities for polar region coverage include highly elliptical, highly inclined orbits, such as employed by the Russian "Molniya" communications satellites for coverage of high latitudes. These orbits are configured such that the apogees occur over the desired region of coverage at the most appropriate time of day. The high ellipticity and relatively high apogee ensures the satellite to be in view during most of the orbital period. Because of the apparent movement though, the ground stations must mechanically track the satellites to keep the antennas pointed at them.

Advanced phased array antennas having the beams electronically steered rather than mechanically, would probably be more appropriate for a Mars application. If steerable beam antennas were to become suitably practical, then perhaps two systems of equilaterally spaced synchronous altitude satellites, inclined ± 45 degrees, respectively, to the equatorial plane could be employed. This could provide virtually all services required and cover the entire planet. Another possibility for polar coverage would be to have satellites placed above both poles and interconnected with the satellites in the equatorial planes via ISL, thus forming a network for complete Martian surface coverage and connectivity. These "pole sitter" satellites would have to be held in place by continous thrust since they are not in orbits about Mars, but rather are subject to both the gravitational attractions of Mars and the Sun. The satellites would basically be in orbits about the Sun, some distance above or below the North and South Mars poles and would have to resist both the Sun's attraction attempting to pull them across Mars' orbital plane and Mars' gravitational attraction. The distance from Mars would have to be such that a small enough thrust could be employed to make the fuel consumption practical. For this application, a very high specific impulse thruster such as an ion engine would be desirable. Since ion engine thrust is measured in millipounds, the distance from Mars must be quite great to employ this low thrust level--on the order of one million miles. Actually, for the pole-sitter concept, there exists a distance from the planet where the sum of the planet's and the Sun's gravitational attractions are a minimum. For the case of Mars, this distance is 1.275 million miles. By way of example, a 3.5 millipound ion thruster, with a specific impulse of 3000 seconds, could support a 1000-pound satellite at this distance for 10 years with a propellant expenditure of a little over 300 pounds. Since the distance of the pole-sitter satellite is so large compared with the equatorial communications satellites, the link characteristics would be markedly different. The equipment required for interfacing with the two systems might, therefore, be incompatible making the pole-sitter concept unattractive. This concept should be examined in more depth for possible advantages.

Communications links with Earth will be highly redundant, capable of being relayed through both the communications and other satellites in orbit about Mars, from the moons, and from the bases on the surface. Although real-time interactive communications with Earth will not be possible because of the long signal delay (varies between 3 and 22 minutes one-way), the availability of an Earth link must exist at all times. There exists an Earth/Mars occultation by the Sun lasting for up to three weeks that occurs periodically (on the order of a little over a year) that would cause communications blackout, were not a way found around it. The concept of a "Trojan" satellite relay system, having relay satellites placed at the Earth/Sun libration points has been proposed[8] as a way of avoiding the periodic occultation (the term "Trojan" coming from the so-called asteroids in similar positions in the Jupiter/Sun system). The Earth-Sun libration points are located at positions leading and following the Earth $\pm$ 60 degrees, respectively, from the Sun (Figure 7). They would be one astronomical unit (1 AU) from the Earth and would add 6 minutes or 27 percent to the otherwise maximum signal time delay. The Trojan satellites would only need be used during the occultation periods, since the direct Earth/Mars path length is always shorter, but they would be necessary and could support other planetary missions. The primary links themselves would most likely be high capacity laser links in this later time period.

INITIATIVES REQUIRED

The solar system exploration goals and operations suggested by the NCOS will drive communications requirements beyond that which can be met by the current NASA R&T program in communications. To support these future exploration activities, a variety of focused R&T programs should be initiated. Studies should be initiated that will identify the variety of likely exploration activities and their supporting requirements in sufficient depth to define alternative system concepts and architectures for accomplishing these missions. These studies will identify the more appropriate and enabling technology areas and provide direction for the R&T programs. Although probably not much can be said about specific technology requirements far into the future, work initiated now will build the generic technology base needed, and will certainly be directly applicable to missions at least two or three decades away, and will ensure that it's available when needed.

Mars exploration probably does not impose communications requirements unique to itself, but rather shares similar requirements with other advanced solar system exploration that may differ from those in the near-Earth environment. More emphasis will be placed on safety, reliability, mass reduction, and cost. These will be primary drivers on technology development for deep space missions and the initial studies should identify technologies providing the biggest payoffs in these areas. Some of the initiatives and technology developments that should be or are being pursued to support NASA planetary goals are noted in Figure 8.

Laser and high frequency communications technologies for deep space links need to be pursued. Goddard Space Flight Center and Lewis Research Center are two NASA field centers in particular that are engaged in laser and Ka-band radiofrequency developments, respectively, for space applications. The Jet Propulsion Laboratory (JPL), who manages the DSN for NASA, is also sponsoring Ka-band technology for DSN upgrading.

The development of advanced high level of integration solid-state electronic devices, such as Monolithic Microwave Integrated Circuits (MMIC's) in antenna applications would have great application and impact on weight and power requirements and mission flexibility. The present need here is to develop a low cost, high yield, uniform quality production capability for these devices and the capability to integrate them into large-scale system designs.

Advanced antenna technology will be needed, based on either solid state MMIC devices or advanced traveling wave tube technology. Optical beam forming techniques, employing optical fibers instead of metallic waveguides will greatly simplify size, weight, and complexity of antenna beam forming for multiple, spot and hopping beam applications. In conjunction with this, optoelectronic device technology for conversion of electronic signals to/from optical for signal switching will need to be developed.

Bulk demodulators for demodulating many signals simultaneously rather than separately, along with advanced modulation and coding techniques, will greatly reduce the consumption, power, and weight of the associated systems. These will be particularly useful in communications with personnel and mobile unit-type communications where, typically, a separate single device is devoted to each user channel.

Ultra-small electron beam devices (traveling wave tubes) for applications as amplifiers, frequency sources, use in personal communications, and as elements of phased array antennas will be beneficial in applications where weight and power are at a premium. Besides communications, such tubes promise to provide a source of electromagnetic power in the 30 to 300 GHz range for use as local oscillators in remote sensing and low power radar applications of value to Lunar and Mars exploration.

CURRENT ACTIVITIES

A number of communications technology activities having value for future planetary exploration are underway in the NASA communications program. Mentioned earlier were laser and Ka-band activities at Goddard Space Flight Center, JPL, and Lewis Research Center. In particular, Lewis Research Center, a lead NASA center for communications technology development, is building the Advanced Communications Technology Satellite (ACTS) to prove the operational viability of a wide variety of advanced communications subsystems. ACTS is pioneering the application of Ka-band technology integrated with advanced beam forming antennas, including multiple fixed and scanning beam capability, on-board switching, baseband signal processing, and intersatellite link technology. The U.S. Air Force/MIT's Lincoln Labs and NASA's Goddard Space Flight Center are developing laser packages to be flown on ACTS that will be used for experiments with laser transmission to ground stations, aircraft, and the Shuttle.

Other activities at Lewis include technology thrusts in the areas of MMIC solid state technology and ultrasmall highly efficient electron beam technology. MMIC technology employing gallium arsenide and more advanced heterostructure materials, leading to devices with higher switching speeds, faster signal processing, and other attributes is being explored. Paralleling the solid state device developments are efforts in the advancement of traveling wave tube (TWT) technology, at both high and low power levels. Lewis has efforts in advanced tube technology at 60 GHz and 8.4 GHz for intersatellite link and X-band DSN applications. The Ka-band ACTS technology will also be directly applicable to deep space link applications. Low power (on the order of 0.5 watt) ultra-small highly efficient TWT technology having potential for the applications mentioned above is also being developed.

Lewis has developed and demonstrated a digital video compression technique for vastly reducing the bit rate required for transmission of full motion broadcast quality video, while retaining virtually full picture quality. Because of the high bandwidths and power required in video transmission, techniques of this nature will be particularly valuable in future manned deep space activities.

Superconductivity is another area being explored at Lewis and other NASA centers for the potential it holds in many areas including communications.

CONCLUSIONS

Long-range goals for the U.S. space program are currently being established. Planning activities are getting underway to determine how best to accomplish those goals. Specific mission concepts arising from the planning activities will provide the focus for the needed technology developments.

Communications is an essential part of the exploration infrastructure and will be vital when humans become involved in deep space missions. Although advances in communications technology will continue to occur independently of deep space goals, deep space exploration imposes some unique technology requirements that must be specifically addressed. Certain technology characteristics that will be needed for foreseen missions over the next two decades can be identified now. Many of these required technologies are not now available, and the necessary development programs should be initiated in order to provide a timely choice of options when required.

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CSTI	<u>ROUTINE EARTH-SPACE ORBITAL OPERATIONS AND ACTIVITIES</u> • ROUTINE LEO OPERATIONS • ROUTINE GEO OCCUPATIONS • MAJOR DEEP SPACE PROBES • MAJOR SPACE OBSERVATORIES • LARGE PLANETARY MISSIONS • EVOLUTIONARY S/S • SHUTTLE 1 AND 2 • HEAVY CARGO • OTV • LARGE TRANSFER STAGES	
PATHFINDER	<u>TRANSITION TO HUMAN PLANETARY PRESENCE</u> • PRELIMINARY SITE SURVEYS • SAMPLE RETURN MISSIONS • PILOT PLANT DEVELOPMENT • LIFE SCIENCE FACILITY • SORTIES • EVOLUTIONARY S/S • ADDITIONAL SPACEPORTS • OTV WITH LUNAR CAPABILITY • ADDITIONAL S/S OR DETACHED MODULES	
PIONEER	<u>ROUTINE HUMAN OCCUPATION</u> • LUNAR RETURN • LUNAR BASED SCIENCE • LUNAR RESOURCE PRODUCTION • LUNAR UTILITY • LUNAR-BASED LAUNCHES • LUNAR OUTPOST • LUNAR FERRY • LUNAR POWER PLANT • LUNAR PROCESSING • LUNAR ORBITAL FACILITY • SPACEPORT	 • MARS SORTIES • MARS SCIENCE AND OPERATIONS • MARS RESOURCE PRODUCTION • PHOBOS ACTIVITIES: SCIENCE AND RESOURCE ASSESSMENT • MARS DESCENT/ASCENT • MARS SURFACE VEHICLE • MARS POWER PLANT • PILOT PROCESSING PLANTS
PILGRIM	<u>CONTINUOUS HUMAN OCCUPATION</u> • LUNAR • MARS	
SETTLER	<u>SETTLEMENTS</u> • LUNAR BASE • MARS OUTPOST • MARS BASES AND EXTENSIVE SURFACE ACTIVITY	

Figure 1 Exploration Phases Outlined by the Office of Aeronautics and Space Technology (NASA)

LINKS

- MARS/EARTH
- MARS/IN-TRANSIT SPACECRAFT
- MARS/PHOBOS AND DEIMOS
- AMONG MARS BASES & OUTPOSTS
- UNMANNED ROVERS & REMOTE ACTIVITIES
- MOVING VEHICLES

FUNCTIONAL REQUIREMENTS

- HIGH DATA RATE TRANSFER (VIDEO AND DATA)
- VOICE AND LOWER SPEED DATA
- NAVIGATION/PRECISION POSITION LOCATION
- UBIQUITOUS SURFACE COVERAGE
- CONTINUOUS TIME COVERAGE

SERVICES

- VOICE
- DATA
- VIDEO

Figure 2. Communications Requirements at Mars

- SAFETY IMPLICATIONS OF FAILURE OF COMMUNICATIONS SYSTEM AND COST AND TIME REQUIRED TO ESTABLISH AND MAINTAIN IT DICTATES LONG LIVED, ULTRA-RELIABLE FACILITIES.
- FAULT TOLERANT AND FAIL SOFT DESIGNS FOR COMMUNICATIONS EQUIPMENT.
- COST OF TRANSPORTING HARDWARE TO MARS WILL PUT PREMIUM ON SMALL, LIGHTWEIGHT COMPONENTS WITH LOWER POWER CONSUMPTION.
- DATA COMPRESSION AND HIGHER DATA RATES PER HERTZ TO COMMUNICATE OVER LONG DISTANCES IN REAL TIME WHILE CONSERVING POWER.
- ADVANCED SATELLITE DEMODULATORS TO ENABLE ACCESS BY NUMEROUS NARROW BAND CHANNELS USED IN PERSONAL PORTABLE COMMUNICATIONS.
- SMALL, LIGHTWEIGHT, RELIABLE AND LOWER POWER (PERHAPS .5 WATT) PERSONAL PORTABLE COMMUNICATORS.

Figure 3. Technology Aspects

INITIAL

- ORBITER/LANDER
- ORBITER RELAY TO EARTH
- USE OF PHOBOS/DEIMOS
- PASSIVE SYSTEM IN LOW ORBIT; "ECHO" TYPE INFLATABLE REFLECTIVE STRUCTURE

Figure 4. Potential Early Communication System Types

LATER

- SYSTEM OF EQUILATERALLY SPACED "AREOSTATIONARY" SATELLITES
  - MULTIPLE SERVICE PROVISIONS
  - INTERSATELLITE LINK CONNECTIVITY
  - 95 PERCENT CONTINUOUS SURFACE COVERAGE
  - EARTH RELAY
- SYSTEM OF LOW ORBITING MULTIPLE SATELLITES/ORBIT INCLINATIONS FOR PRECISION POSITION DETERMINATION
- HIGH INCLINATION SATELLITES OR "POLE-SITTER" FOR POLAR COVERAGE

Figure 5. Potential Later Communication System Types

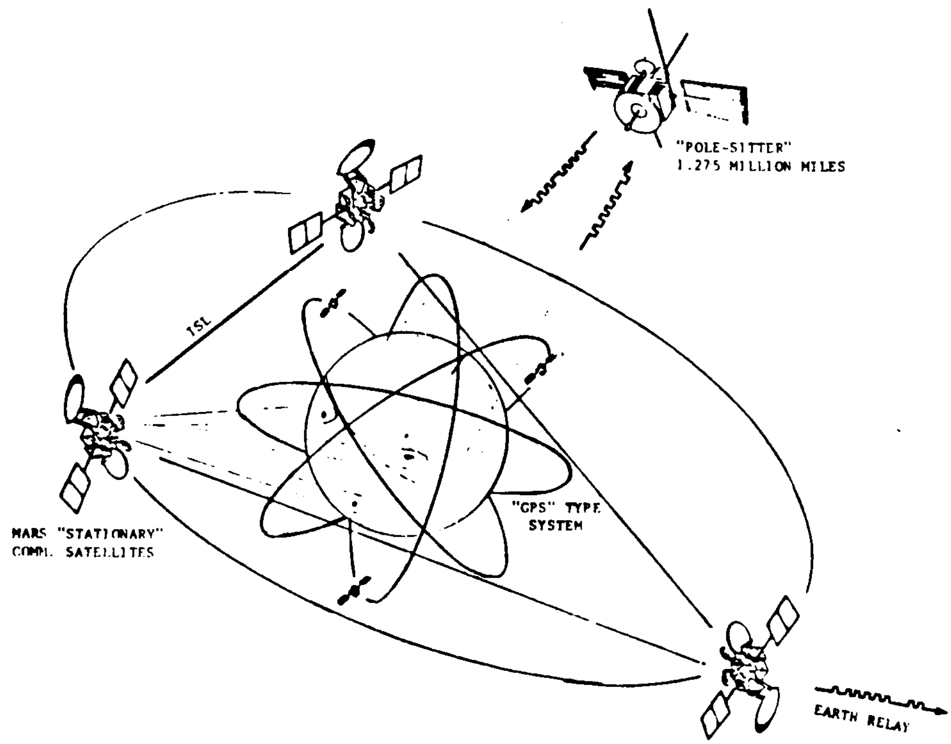

Figure 6. Candidate Communications Systems for Later Mars Exploration

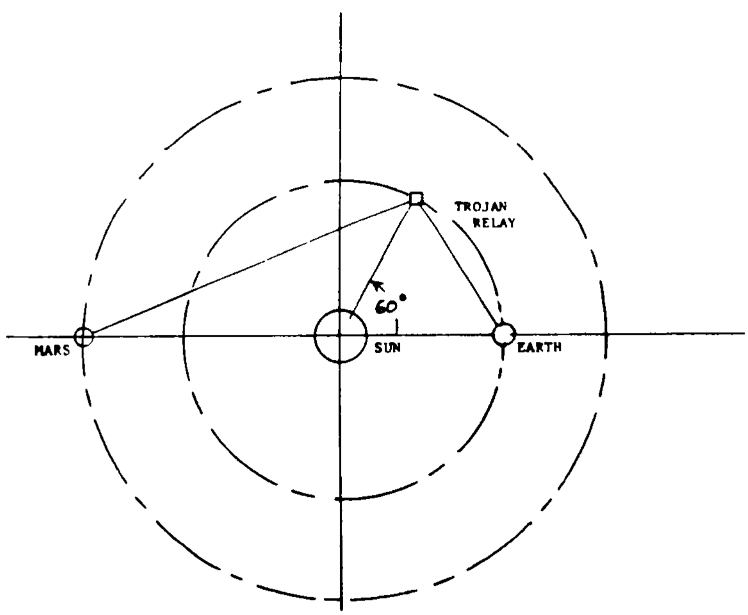

Figure 7. Trojan Relay Satellite to Eliminate Communication Occultation of Mars by the Sun

- INITIATE STUDIES
  - SYSTEM CONCEPTS AND ARCHITECTURES
  - TECHNOLOGY DEFINITION
  - ASSESS IMPACT OF ADVANCED COMM. TECHNOLOGY ON SAFETY AND COST OF MARS EXPLORATION
- PURSUE TECHNOLOGY DEVELOPMENT
  - LASER AND HIGH FREQUENCY OF COMMUNICATIONS
  - LOW COST, HIGH YIELD, UNIFORMITY OF MMIC DEVICES
  - ADVANCED ANTENNAS:
    - MULTIPLE BEAM FORMING, PARABOLIC AND PHASED ARRAY
    - OPTICAL BEAM FORMING
  - OPTOELECTRONIC SATELLITE SWITCH
  - SATELLITE BULK DEMODULATORS
  - ADVANCED MODULATION AND CODING TECHNIQUES
  - ULTRA SMALL TRAVELING WAVE TUBES

Figure 8. Initiatives Required

- ACTS/LASERCOM
  - MULTIBEAM ANTENNAS
  - SCANNING BEAMS
  - LASER LINKS
- MONOLITHIC MICROWAVE INTEGRATED CIRCUIT (MMIC) TECHNOLOGY
  - GaAs
  - HETEROSTRUCTURE (InGaAs + AlGaAs)
- TRAVELING WAVE TUBES (TWT'S)
  - HIGH POWER TWT'S (60 GHz + 8.4 GHz)
  - ULTRA SMALL HIGHLY EFFFICIENT TWT'S
- VIDEOCOMPRESSION
- SUPERCONDUCTIVITY

Figure 9. NASA Related Activities and Current Technology Development

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16. Abstract

As Mars exploration grows in complexity with time, the corresponding communications needs will grow in variety and complexity also. From initial Earth/Mars links, further needs will arise for complete surface connectivity for the provision of navigation, position location, and voice, data, and video communications services among multiple Mars bases and remote exploration sites. This paper addresses the likely required communications functions over the first few decades of Martian exploration and postulates systems for providing these services. Required technologies are identified and development requirements indicated.

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