Lunar Base as a Precursor to Mars Exploration and Settlement

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Abstract

Debates over strategy for human exploration of the solar system focus on whether the next interplanetary travelers ought to go to the Moon or to Mars. The Space Exploration Initiative explicitly calls for a lunar presence, but the "Mars Now" advocates argue for a token effort on the Moon with major emphasis on Mars. A strategy which moves directly to piloted Mars missions incurs serious programmatic risks from (1) our current lack of knowledge on human performance on long-duration deep space missions, (2) our lack of experience designing manned space systems which must remain trouble-free for years without refurbishment, (3) our lack of experience with complex on-orbit operations, and (4) the political instability of the funding process. A well planned program of human exploration of the Moon would provide a context within which to increase our capabilities and experience to levels required for Mars exploration.

Introduction

In his remarks prepared for the Apollo 11 20th Anniversary Celebration at the National Air and Space Museum, President Bush declared:

> "I'm proposing a long-range continuing commitment: First, for the coming decade, for the 1990's, Space Station Freedom…; and next, for the new century, back to the moon, back to the future, and this time, back to stay. And then a journey to another planet, a manned mission to Mars."

By stating these objectives for the next century in space, the President defined a path by which to implement one of the major components of President Reagan's space policy statement of February, 1988: "Establishing a long-range goal to expand human presence and activity beyond Earth orbit into the Solar System".

President Bush chose one of several paths for human exploration of space which had been under study in NASA's Office of Exploration (OExp) since its formation in 1987. The OExp work concentrated on two themes to human exploration of the solar system as outlined by Dr. Sally Ride[1] in her report to the NASA Administrator: (1) outpost on the Moon or (2) piloted missions to Mars. The more vocal advocates of strategic planning for human space exploration had argued forcefully for one or the other of these options as the next "big" initiative in the U.S. space program.

At first glance, it would seem that the President has settled the issue. Following the successful operation of Space Station Freedom, the nation will invest in a permanent lunar presence followed by landings on Mars before the end of the second decade of the 21st Century. However, the less than spectacular initiation of the Space Exploration Initiative has shifted the debate to changes in the emphasis of the objectives. For example, might not an automated observatory on the Moon satisfy the lunar requirement while the program emphasized expeditions to Mars?

One cannot totally generalize the character of the arguments on either side of the case. However, it is true that "Moon First" proponents tend to emphasize the steady buildup of infrastructure and capability in the Earth-Moon system, while "Mars Now" enthusiasts stress the excitement of new discoveries and the inspiration associated with reaching a planet where life might have arisen. Also implicit in "Mars Now" is the belief that the nation (or the world) cannot do both. If a substantial

Table 1. Moon/Mars Comparison[3]

Mission Target	Typical Logistics (LEO) tonnes per departure	Departures/ year	Annual Logistics tonnes/yr	Planet Surface Buildup Rate tonnes/yr
Moon	110	6	660	80
Mars	1500	0.45	675	50

lunar program is undertaken, Mars may not be reached within the lifetime of anyone now extant.

The arguments are usually carried out on a plane that is more philosophical or propagandistic than technical. Statements that, "The Moon is boring," are countered by, "Lunar resources are useful for space development." Nevertheless, all parties do agree that if either program were to be undertaken and were to fail (i.e., be cancelled), then the future of human spaceflight would be in severe jeopardy for the foreseeable future.

I will argue qualitatively in this short paper that commencement now of a program of human exploration of Mars incurs major technical risks that can be mitigated and probably eliminated within a program of human exploration of the Moon. I identify at least four major categories of mission risk which are currently beyond our understanding or our capabilities:

(a) mission failure due to degradation of human performance either physiologically (including death) or psychologically after long duration exposure to the space environment – both in freefall and in reduced gravity – and to the stress of isolation;

(b) mission failure due to equipment or software malfunction because of insufficient testing as an integrated system, inability to guarantee sufficient mean time between failures by analysis, inability to carry as many spare parts as needed, and inability to predict all contingencies before the mission;

(c) critical cost overruns after a failure to meet a launch window when the Earth-to-orbit launch rate cannot be maintained or when in-orbit assembly and checkout proves to be more complicated than believed; or

(d) inability of institutions to maintain public support during long periods of expensive hardware development when no accomplishments are apparent.

Lunar missions face these same difficulties. However, the mission or program parameters in the lunar case fall much closer to our current operational and design experience.

Mission Parameters

Overview

Several different approaches or "architectures" have been proposed for crewed missions to the Moon or to Mars. Therefore, it is difficult to do a thorough comparison without a rather lengthy analysis. I will try to take representative scenarios for each program that illustrate the difference in scale of the respective mission parameters. I will consider the architectures of the type presented in the NASA 90-day Report to the President[2] because they have certain common features that allow comparison. I will assume that the technology to build the transportation systems (propulsion, power, and life support) is equally well understood for either planetary mission.

In both cases, the interplanetary vehicles will be launched from low Earth orbit (LEO) at the 28.5° inclination of Space Station Freedom. In most lunar architectures a spaceport in LEO is used as a transportation node for transshipping cargo and for maintenance of reusable orbit-transfer vehicles. In most Mars mission architectures, the interplanetary vehicles are assembled in LEO. Reusability of these vehicles is problematical, particularly if they use nuclear propulsion and return with a radioactive reactor. I have not factored reusability into the comparison between the two classes of missions because refurbishment of a complex spacecraft on orbit has not been shown definitively to be cost effective.

Table 2. General Characteristics of Mars Mission Profiles[3,4]

Characteristic	Conjunction	Venus Swingby	Opposition	"Sprint"	Nuclear Electric	Exotic Propulsion
Representative transit time (round trip)	30-35 months	20 months	15-16 months	1 year	1 year	60 days
Representative stay time	300-500 days	20-60 days	10-30 days	10-30 days	10-300 days	any desired
Representative ΔV's for transit mission with aerocapture at Mars and at Earth (km / sec)	8.3 - 8.7	10.4-13.0	13.3-23.1	14 in an "easy year" (2003)	20	200-300
Window duration	2-3 months	1-2 months	short	short	many months	always open
Variability with opportunity	slight	modest	high	extreme	usually slight	slight

Table adapted from Woodcock (Ref. 3) with ΔV data taken from Hoffman (Ref. 4), who assumes direct entry on Earth return.

Woodcock[3] has made a comparison of lunar mission modes and Mars mission modes. Tables 1 through 3 are adapted from his paper. The values in the tables are intended to convey the relative magnitudes of important parameters such as Earth to orbit launch rate, crew time in the space environment, mission duration, schedule constraints, and complexity of in-space operations. For example, his two reference models were scaled to produce approximately the same annual launch rate of mass to LEO (Table 1, col. 3). As a result, in a 26-month period, one mission to Mars is launched, while 13 missions could be flown to the Moon during the same period. (For reference, the "aggressive" option in the NASA 90-day Study[2] envisioned two launches to the Moon per year.) The rate of buildup of infrastructure mass on the lunar surface is about 80% greater than the rate on the martian surface. As a result, these two programs do not produce the same scale of planetary surface activities.

Mars Mission Strategies

The least energy for a transfer between Earth and Mars is required when the spacecraft follows a Hohmann ellipse, tangent to the orbit of the Earth and the orbit of Mars. The Earth and Mars align properly for this minimum energy transfer once every 26 months. In the parlance of Mars mission designers, the minimum energy Hohmann transfer is called a "conjunction-class mission". As can be seen from Table 2 (col. 2), the conjunction-class mission has a long round trip time and requires a very long stay on the surface of Mars.

The change in orbital velocity (ΔV) required for the spacecraft to leave LEO for Mars and to enter orbit around Mars is relatively constant from year to year for conjunction-class missions. Slight variations are the result of the eccentricities of the martian and terrestrial orbits about the Sun. The magnitude of the ΔV is directly related to the amount of propellant required onboard the interplanetary vehicle in LEO and therefore related to the mass which must be launched from Earth for the mission.

The trip time to Mars can be reduced at the expense of greater ΔV required at LEO. For a given chemical propulsion system, increases in the ΔV requirement imply that a greater percentage of spacecraft mass in LEO is propellant. Secondly, the amount of the increase is very sensitive to the alignment of the planets and can vary considerably form one opportunity to the next. There does exist a 15-year cycle in the alignments in which the patterns repeat.

Opposition-class trajectories (Table 2, col. 4) take advantage of another form of alignment between the two planets. On either the outbound or inbound leg of the mission, the trajectory passes inside of the orbit of the Earth, crossing the orbit of Venus. The mission travel time in space is not too much different from the conjunction class, but the stay-time on the martian surface is very much less, resulting in a

Table 3. Summary of Lunar Mission Modes[3]

Parameter	Lunar Staging Point			
	Lunar equatorial orbit (100 km)	Lunar polar orbit (100 km)	Moon-Earth L2 or L1 halo orbit	Lunar surface
Lunar surface site access	Near lunar equator only	Any	Any	Any, assuming approach via lunar orbit
Transit time, Earth to staging point	3-5 days	3-5 days	5-8 days	3-5 days
Wait at staging point	Not required	14-28 days (usually 14)	Up to 7 days for lowest ΔV	Not required
Transit time, staging point to lunar surface	~2 hours	~2 hours	3 days	Not applicable
Departure window frequency, SSF orbit	~9 days	55 days	~9 days	~9 days
ΔV (m/sec)				
Earth to staging point	4010	4010	3375 (LGA)	6110
Staging point to surface	2100/2000	2100/2000	2950 /2850	Not applicable
Staging point to Earth	1100	1100	435 (LGA)	3050

LGA = Lunar Gravity Assist

shorter mission duration. Note the wide variation in ΔV requirements. One implication of the variation is that a spacecraft configuration designed for an energetically favorable opportunity may not be able to launch at the next alignment in case of a schedule slip.

For some opposition-class trajectories, the planet Venus is located so that the spacecraft can utilize a gravitational assist on either the outbound or inbound leg. For Venus swingbys, the ΔV requirements are less than for a straight opposition-class mission, but the time spent in transit increases. The total mission duration remains less than that for conjunction-class missions.

The "Split-Sprint" mission strategy was conceived to deal with the increased ΔV (thus increased propellant in LEO) requirements associated with trajectories having decreased flight times. An unmanned mission carrying cargo is sent to Mars on a low-energy trajectory. The cargo mission contains equipment for use on the martian surface. The "Sprint" component of the mission carries the crew on a fast trajectory. The idea is to minimize the payload taken on the piloted mission. In some versions the cargo mission carries the crew lander, leaving it in orbit around Mars, and in some proposals also carries the fuel for the return to Earth. The Split-Sprint strategies demand successful rendezvous between the arriving crew and the prepositioned equipment on the surface and/or in Mars orbit. Depending on how much mission equipment is sent ahead, crew survival could rest on the success of the rendezvous and on the working condition of the unattended equipment.

The problems of large masses being assembled in LEO and long flight times can be mitigated (but not eliminated) with nuclear propulsion systems for the interplanetary vehicle. However, development of the nuclear-dependent technology represents a departure from current transportation system evolution and presents a technical and political risk to the program.

<u>Lunar Mission Strategies</u>

In contrast, the trip time from LEO to the Moon is almost two orders of magnitude less than the trip time to Mars. The mass required in LEO for a lunar mission is approximately one order of magnitude less. The frequency of minimum energy launch opportunities is one order of magnitude greater, reducing the criticality of meeting launch windows. The total duration of mission is quite flexible. Apollo missions lasted about two weeks. At the other end of the spectrum, a crew could be supported on the lunar surface indefinitely using currently available technology.

On the other hand, it is important to note that the scale of operations required to support a lunar surface installation, particularly if it is permanently staffed, can be about the same as the scale to support of a sequence of piloted Mars missions. In addition, a lunar transportation infrastructure could be used easily to simulate the operations and time scales of human exploration of Mars.

Summary

Piloted missions to Mars will involve mission durations and scales of operations far beyond the current experience of the U.S. space program and only approached by the (now troubled) Soviet space program. Brute force technological attacks on these problems involve radical (and therefore expensive) departure from the current directions of technology development and operational philosophy.

A program incorporating a permanent lunar surface base requires modest extrapolation of current technology but will provide an opportunity to develop an efficient operations infrastructure supporting permanent human presence in space.

Major Challenges for Human Exploration of Mars

Human Performance

Deconditioning in Weightlessness. Everyone is familiar with the fact that the human body undergoes certain adaptations when exposed to weightlessness (i.e., zero-g). These changes are most debilitating when the space traveler must readapt to gravity. The most serious known changes include cardiovascular deconditioning, decrease in muscle tone, loss of calcium from bone mass, and suppression of the immune system.

A variety of countermeasures for these conditions have been suggested, but none have been validated by thorough testing. The Soviets have had some success with long periods of daily exercise to maintain cardiovascular capacity and muscle tone, but the monotonous and time-consuming exercise regime affects the efficiency and morale of the crew.

Artificial gravity is often put forward a fallback solution. The entire spacecraft is rotated so that the crew experiences a constant "downward" acceleration simulating gravity. It is generally assumed that coriolis effects will fall below the threshold of human perception if the spacecraft is rotated at a slow rate. It is unknown whether simulation of full terrestrial gravity is required or whether the small residual coriolis forces will cause some disorientation in crew members. No data from a space-based facility exists, and the space life science research community is split over the validity of the artificial gravity "solution".

Spacecraft designers believe that the engineering problems associated with a rotating manned vehicle are soluble with appropriate testing on orbit. Everyone agrees that such a spacecraft will be more massive than a nonrotating craft, but not all agree on how much more massive. Control of a rotating craft will be a challenge.

Deconditioning is a critical issue for Mars missions because the crew will undergo high transient accelerations during descent to the martian surface. Depending on the physiological condition of the crew, these accelerations could be life-threatening. Once on the surface of Mars, the crew must recover without external medical support and must perform a series of demanding tasks. The time required for recovery is particularly important if the surface stay is short as in opposition-class missions. No one knows whether exposure to a gravity field lower than the Earth's will reverse the deconditioning induced by space travel. Without more research on these issues the performance of the crew on the surface of Mars cannot be guaranteed.

Deconditioning under Low Gravity. No one knows whether the types of deconditioning discussed above will be manifested in low gravity as well as in the weightless condition. In other words, if the crew arrives on Mars in good shape, what will their condition be after spending a long time under martian gravity? "Artificial gravity" cannot be provided on the surface. The rates of change and the final levels of the effects observed on orbit may be linear with level of gravity exposure or they may be triggered only below some threshold of exposure. The Apollo missions to the Moon were too short to produce observable differences between the condition of the astronauts who went to the surface and the condition of the astronauts who stayed in orbit.

Psychological Stress. Psychiatrists and psychologists agree that piloted missions to Mars may well give rise to behavioral aberrations among the crew seen on Earth in conditions of stress and isolation over long periods of time. The probability of occurrence and the level of any such anomalous behavior will depend not only on the crew members individually but also on the group dynamics among the crew and between the crew and mission control on Earth. In general, the probability of behavior extreme enough to threaten the mission will decrease with an increase in the size of the crew. However, the expense of sending large payloads to Mars limits the crew size to four or less in most scenarios. At the present time, no known techniques for crew selection are adequate to guarantee psychological stability on a voyage to Mars. Soviet experience suggests that a crew should train together for many years.

Reliability and Lifetime of Complex Systems

The Mars mission interplanetary spacecraft will be the most complex ever constructed, and the lives of the crew will depend on its reliable performance for periods of a year to three years. The life support, propulsion, power, computer, and communication systems must perform without fail for a period of time longer than that required from any previous manned spacecraft. The mission duration will be two orders of magnitude greater than current Space Shuttle missions, and resupply will be impossible.

Although reliability of subsystems will be part of the design and testing philosophy, redundancy through backup systems and spare parts will also be important. However, the constraints on mass launched from LEO will place limitations on the degree of redundancy available to designers. Estimates of the mass of necessary spare parts, extrapolated from failure rates aboard the Shuttle, give numbers which are prohibitively large. Therefore, testing and quality control will be paramount.

Particularly important will be testing of the integrated flight system under conditions similar to the actual mission for periods of time similar to (and preferably much greater than) the actual mission. Integrated flight testing is truly critical if the flight system is the first of its kind. Unfortunately, if history is a guide, budget pressures will cause program management to search for substitutions for full-up flight testing. After all, most of the expense of a mission to Mars resides in launch and operations, two categories of expense for a flight test whose magnitude would be similar to that of an actual mission. In addition, consider the motivation of a crew which would spend two or three years in orbit pretending to go to Mars.

Experience with the Hubble Space Telescope is illustrative of the problem. A full quality assurance organization was in place but was ineffective in preventing a fundamental error in the construction of the observatory in the absence of integrated testing.

Another problem is inability of careful analysis to predict every contingency. Once again, we can point to the jitter in the solar arrays of the Hubble when it passes from the Earth's shadow into sunlight. The Galileo mission is threatened by a stuck antenna, caused by degradation in a lubricant after delays in launch unanticipated by the original designers. Consider the remarks from the German manufacturer of tube amplifiers which failed aboard the recent French TDF direct broadcast satellite:

> "It appears that tubes in orbit behave worse than tubes on the ground despite vacuum testing and other simulation. We have no explanation for this. It could the radiation environment of space, or increased heat from the solar collectors. It shows we have no sure way of simulating the space environment."[5]

Yet, satellite communications is always treated as the most mature of space technologies.

In a large, complex program, a manager somewhere will take a shortcut under pressure from budget and / or schedule. The consequences of his / her action will not always be obvious to program management. As a result, the reliability of the product will be overestimated. And management always expresses a very human tendency to believe good news. The net result of these phenomena can be illustrated by the change in the official estimates of the reliability of the Shuttle before and after the Challenger tragedy.

In short, do not rely on a product that has not been tested in its working environment, whether it is a new car, a complex piece of software, or a spaceship.

Reliability and Resilience of Earth-to-Orbit Launch Operations

In most Mars mission architectures, the interplanetary vehicle is constructed in Earth orbit. The vehicle is generally more massive than Space Station Freedom by a factor of five or more. Most of the mass is propellant in the case of chemical propulsion systems. In most cases, the vehicle is also larger than Space Station Freedom. Therefore, we can look to the difficulties being encountered in planning the assembly and operation of Freedom and qualitatively extrapolate to assess the magnitude of the task of assembling the Mars vehicle.

No one proposing orbital assembly of an interplanetary vehicle believes it can be done without using a heavy lift launch vehicle. New systems being proposed now for the U.S. have payload capacities of 50 to 100 tonnes to LEO. The larger vehicles are preferable. In any case, the assembly operation will require at least 10 to 15 launches of cargo and crew over the 26-month interval between launch windows. Most of the cargo launches will occur over a relatively brief interval just before the launch opportunity, carrying propellant to orbit.

These rather general considerations make it clear that the mission to Mars will require levels of launch operations and of on-orbit operations far beyond our current experience. Please note that this is not a problem with hardware; the required number of launchers can be designed and built. Rather, this is a problem of meeting a constrained schedule with a management system and a work force whose first job is this demanding operation. The learning curve cannot be steep enough. The launch to Mars would challenge a team experienced in tightly scheduled launch operations and complex in-space assembly.

Political Viability

Going into the U.S. Fiscal Year 1992, the Space Exploration Initiative has not been funded by the Congress for even planning studies. I believe that there are several reasons for this, one of which is the poor performance (in the eyes of the Congress) of the Space Station Freedom program. Almost seven years after approval and after spending an average of almost a billion dollars per year, the fundamental purpose of the station is still being debated and the design has undergone recent radical changes.

If Space Station Freedom requires approximately ten years before launch of the first hardware element, one might ask what interval of apparent inactivity would transpire between approval and launch of the much more challenging piloted mission to Mars. Large scale publicly funded programs are subject to continuous critical scrutiny by technically unsophisticated observers who want simple answers to simple (and often simplistic) questions. Tangible performance is demanded over time frames determined by political time constants (two to four years in the U.S.).

If an institution wishes to be supported by public funds for a project with a duration of many political time constants, then that institution must be sophisticated enough plan visible milestones, comprehensible by the public, at intervals appropriate to the funding review process. Historically, NASA has been reasonably successful at maintaining funding of decade-long programs in the face of an annual budget review. The vast majority of those programs are understood by all to have a finite duration. After a satellite has been launched and operated for a given period, it either fails or is shut off. Neither NASA nor the Congress are yet comfortable with programs that are open-ended, such as the Shuttle or Space Station or human settlement of the solar system.

In summary, the U.S. space program has not yet adapted to the modern reality that approval of a goal by a President cannot guarantee ten or twenty years of sustained funding. The thirty-year time frames for human exploration of Mars cannot be supported until the role of the space program is well integrated into the national agenda and the exploration of space is no longer regarded as a subsidy of the aerospace industry. To accomplish this, the space program must show concern for, and address, national needs (visible contributions to technology, science, environmental studies, education, inspiration of youth, etc.) while maintaining a thoughtful and challenging agenda of human exploration of space in which the public can feel a partnership.

Human Exploration of the Moon

The medical, technical, operational, and institutional challenges detailed in the previous section in the context of human exploration of Mars are also applicable to human exploration of the Moon. The difference is that in no case must our degree of knowledge or capability be advanced to a much higher level in order to perform the exploration safely and scientifically. In fact, lunar exploration provides an ideal context within which to advance our technology to the level required for planning Mars exploration.

The Apollo missions demonstrate that no problem exists for adaptation to low gravity for short times. Modern lunar exploration would extend stay time on the lunar surface to months and would monitor crew performance. Coupled with long duration in weightlessness in Earth orbit, data could be efficiently accumulated to predict the regimes of human performance on a Mars mission. Cumulative effects of galactic cosmic rays and solar particle events on the crews could be measured. Psychological issues raised by long duration in isolation could also be studied.

The predecessors of interplanetary spacecraft would accumulate operational time in an Earth-Moon transportation system. Data would be accumulated on integrated system reliability, maintenance rates, and degradation of performance in the deep space environment. Lunar surface life support systems could evolve into their martian counterparts. Operational experience on a planetary surface would be obtained. Power, transportation, communication, construction, and resource utilization can all be elements of a lunar base.

A heavy lift launch vehicle is a natural element of a lunar program. Initial demands on performance and launch rate are not as high as in a Mars program. These conditions provide a natural training ground for operations personnel and management and a chance to incorporate evolutionary improvements in the first model of the launch vehicle. Maintaining, refueling and refurbishing orbit-transfer vehicles on orbit provides the experience from which to build a professional and competent operations team for future assembly of Mars spacecraft.

Dealing with the institutional barriers to human space exploration requires a different kind of innovation which is not automatically supplied by lunar exploration. However, because the Moon is close to the Earth and because it is possible to launch small payloads there with relatively small rockets, the opportunity arises to involve many students in the exploration experience using robotics, telepresence, and the national high speed data networks now in place. Students in classes could accumulate data from instruments on the Moon and even direct some of those instruments.[6] An intelligently designed program could provide for real (if not direct) interaction between the scientists of tomorrow and the lunar explorers of today. A publicly visible participation in the exploration experience for people across the nation would go far to keep the funding alive.

The question still remains whether a lunar program of exploration would preclude exploration of Mars. The formulation of such a question makes several assumptions.

First it assumes that our technology and our institutions will not evolve and that space exploration will stay as relatively expensive as it is now. Such a prophecy will be self-fulfilling if space utilization remains the low volume, elitist activity that it is today. Eventually society will produce a breakthrough technology that will open the space frontier, but the status quo can be maintained for a long time as long as space exploration is the captive function of a single institution. The more widely distributed the participation in space exploration, the more quickly innovation and iconoclastic thinking will invade the system.

Secondly, the question assumes that the generation after ours will view exploration of Mars with the same attitude that we do. It assumes that exploring the Moon will so exhaust the nation that no one will have the energy to think about the planets beyond. Such thinking flies in the face of history. Opening a frontier does not induce inertia. On the contrary, access to the frontier inspires creativity and destroys old ways of thinking in the generation that is raised on its threshold.

My answer is that human exploration of the Moon will accelerate human exploration of Mars.

Conclusions

While an immediate program to land humans on Mars is technically feasible, the large advances in operational and technical capability required present a significant risk for program failure. An immediate commitment to piloted missions to Mars runs the risk of revisiting the fate of Apollo, where a crash program created by the political system was cancelled by the same system when the effort seemed no longer relevant.

In the process of human exploration of the solar system, the establishment of a permanent presence on the Moon is not a diversion or an impediment. It is a necessary step in the steady progress of technology, operational experience, and the understanding of human capabilities in space. A lunar program provides an opportunity to build up space capability in an evolutionary and orderly way and to broaden the participation of the educational system in the excitement of space exploration.

References

1. Ride, Sally K. (1987) *Leadership and America's Future in Space.* A report to the Administrator of NASA, 63pp.

2. Cohen, Aaron (1989) *Report of 90-Day Study on Human Exploration of the Moon and Mars.* NASA Johnson Space Center, 143pp.

3. Woodcock, Gordon (1988) *Modular Evolutionary System Architectures for Exploration Missions.* Paper delivered at the Second Symposium on Lunar Bases and Space Activities of the 21st Century, Houston, TX, April, 1988

4. Hoffman, Stephen J. (1991) Mission Design for Piloted Mars Missions. Lecture delivered at the International Space University, Toulouse, France, July, 1991. Based on work done in support of NASA / JSC Lunar and Mars Exploration Program Office.

5. de Selding, Peter (1991) Amplifiers Blamed for TDF-2 Failure. News Item in Space News, Vol. 2, No. 5, p. 9, February 18-24, 1991.

6. Mendell, W. W. (1991) A Proposal for an Early SEI Milestone: A Simple Automated Lunar Surface Telescope with an Emphasis on Educational Objectives. Paper accepted for Space92 Conference, Denver, Colorado, May 31 - June 4, 1992.