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Lunar Limb Observatory

An Incremental Plan for the Utilization, Exploration, and Settlement of the Moon

Paul D. Lowman Jr.

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LIST OF ACRONYMS

BRT	Bradford Robotic Telescope
CCD	Charge-coupled device
COAST	Cambridge Optical Aperture Synthesis Telescope
COBE	Cosmic Background Explorer
CMU	Carnegie Mellon University
ELV	expendable launch vehicle (generic term)
ESA	European Space Agency
EVA	extra-vehicular activity (on Moon or in space)
GRO	Compton Gamma Ray Observatory
GSFC	Goddard Space Flight Center
HST	Hubble Space Telescope
IOTA	Interferometric Optical Telescope Array
IRAS	Infrared Astronomy Satellite
IUE	International Ultraviolet Explorer
JSC	Johnson Space Center
JPL	Jet Propulsion Laboratory
LLO	Lunar Limb Observatory
NPOI	Navy Protoype Optical Interferometer
TLR	telerobotic lunar rover (generic term)

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Abstract

This paper proposes a comprehensive incremental program, **Lunar Limb Observatory (LLO)**, for a return to the Moon, beginning with robotic missions and ending with a permanent lunar settlement. Several recent technological developments make such a program both affordable and scientifically valuable: robotic telescopes, the Internet, light-weight telescopes, shared-autonomy/predictive graphics telerobotic devices, and optical interferometry systems. Reasons for focussing new NASA programs on the Moon include public interest, Moon-based astronomy, renewed lunar exploration, lunar resources (especially helium-3), technological stimulus, accessibility of the Moon (compared to any planet), and dispersal of the human species to counter predictable natural catastrophes, asteroidal or cometary impacts in particular. The proposed Lunar Limb Observatory would be located in the crater Riccioli, with auxiliary robotic telescopes in M. Smythii and at the North and South Poles. The first phase of the program, after site certification, would be a series of 5 Delta-launched telerobotic missions to **Riccioli** (or Grimaldi if Riccioli proves unsuitable), emplacing robotic telescopes and carrying out surface exploration. The next phase would be 7 Delta-launched telerobotic missions, **to M. Smythii** (2 missions), **the South Pole** (3 missions), and the **North Pole** (2 missions), emplacing robotic telescopes to provide continuous all-sky coverage. Lunar base establishment would begin with **two unmanned Shuttle/Titan-Centaur missions to Riccioli**, for shelter emplacement, followed by the first manned return, also using the Shuttle/Titan-Centaur mode. The main LLO at Riccioli would then be permanently or periodically inhabited, for surface exploration, telerobotic rover and telescope operation and maintenance, and support of Earth-based student projects. The LLO would evolve into a permanent human settlement, serving among other functions as a test area and staging base for the exploration, settlement, and terraforming of Mars.

Introduction

The long hiatus in lunar exploration since the Luna 24 mission of 1976 is ending, and a ground swell of interest in returning to the Moon has developed in recent years. The first new lunar data were returned from the Galileo gravity assist fly-bys in 1990 and 1992 (Greeley et al., 1993) and the 1994 Clementine mission (Nozette et al., 1994) made a multispectral survey of the entire Moon. New lunar missions are now planned by the United States and Japan, and privately funded commercial lunar programs are under study in the U.S. The European Space Agency is intensively studying a possible lunar program (Kassing and Novara, 1996). The Lavochkin Association of Russia, in cooperation with International Space Enterprises, has plans for a variety of unmanned lunar missions. Finally, there is strong interest among the post-Apollo generation in what will be, for it, not a "return" to the Moon but a new and exciting enterprise.

When the Apollo Program was proposed in 1961 by President Kennedy, space technology was in its infancy, and essentially everything had to be developed from the beginning. Most of the infrastructure developed for Apollo, and for corresponding Soviet programs, is still available today, and there has been enormous progress in areas to be described. The combination of existing infrastructure, new technology, and our now-extensive knowledge of the lunar surface makes it unnecessary to start all over again in a return to the Moon.

This paper proposes an ambitious but low-cost incremental program for exploration and utilization of the Moon, beginning with robotic missions and culminating with a permanent human settlement. It stresses low cost, speed, low technical risk, public participation, flexibility, and scientific value. It is programmatically compartmentalized, so that failure of a single mission will not have catastrophic effects. It takes advantage of concurrent development, such as space station modules, but uses existing U.S. launch vehicles and requires little in the way of major new systems.

The focus of the plan is an astronomical observatory on the west limb of the Moon that can also serve as a staging base for surface exploration, and specialized robotic auxiliary outposts on the east, north, and south limbs. The working title **Lunar Limb Observatory (LLO)** will be used, although not fully descriptive of the broad nature of the proposed program. The report is essentially a synthesis of many studies done during the last 35 years, as the reference list should make clear, but opinions and recommendations expressed represent the author's views only.

Acknowledgments

This paper is based on the work of hundreds of people, most cited in the reference list. However, I specifically thank David Burns, Jack Burns, Peter Chen, Barbara Christy, Sam Floyd, Ruth Freitag, David Gump, Don Haxton, Jerry Kulcinski, Dave Lavery, Gregg Linebaugh, Bill McLaughlin, Mike Mumma,Stan Ollendorf, Ron Polidan, Charles Price, Mike Simon, and Will Webster for discussions, information, and suggestions, and Herb Frey for his continual support. Visits to the Carnegie Mellon University's Robotics Institute, and discussions with Red Whittaker and his colleagues were invaluable. The late Harlan J. Smith, who dedicated his last years to establishment of a lunar observatory, was a continual source of inspiration. My fictional "Smith Observatory Complex," in the cited Sky and Telescope article, was named after him, and I am gratified that Harlan was able to read the manuscript of "Regards from the Moon" before his death.

Technological Developments Since Apollo

There have been several lines of technological progress since the Apollo lunar missions that collectively make a new lunar program far more achievable, and much less expensive, than generally realized. These can be summarized briefly as follows, roughly in order of importance.

Robotic Telescopes

The most important development with respect to a new lunar program is undoubtedly that of "robotic" telescopes, using the term to include telerobotic or remotely-controlled instruments as well as autonomous ones (Genet and Hayes, 1989; Filippenko, 1992). Several robotic systems are in use, such as the Automated Telescope Facility at the University of Iowa. For illustrative purposes, a brief summary of the system at the University of Bradford in England will be presented.

The Bradford Robotic Telescope (BRT), although a "prototype" (Cox and Baruch, 1996; Baruch, 1994), demonstrates several aspects of robotic telescope systems relevant to their use on the Moon. The BRT itself, a 46 cm Newtonian reflector using a charge-coupled device (CCD) camera, normally operates autonomously, using a computer to scan the sky for suitable weather, and when such exists, to open the roof, aim and focus the telescope, and make the observations following a previously loaded schedule. Alternatively, it can be controlled in real time from the University ten miles away through a Sun work station.

One of the most striking aspects of the BRT is its accessibility. The telescope can be used, in principle, by anyone in the world through the Internet. A Web interface has been written and can be reached through a standard Web browser to submit requests, as described by Cox and Baruch (1996). The actual observations may take considerable time for several reasons, starting with the often-opaque British atmosphere. The Iowa Robotic Observatory previously mentioned similarly can be accessed and controlled through the Internet.

The Bradford Robotic Telescope, though still under development, represents a major advance in astronomy with implications for Moon-based instruments. The telescope itself is basically conventional, with a design obviously dating back to the 17th century, and the weather-sensing system could have been developed many decades ago. The revolutionary aspect of the BRT is its global access, and even more important, its use of the World Wide Web as a command and control system rather than only an information link. Cohen and Churchill (1996) describe the use of the Macintosh computer as a control station, with obvious implications for extraterrestrial telerobotics.

The Internet

The operation of the Bradford and Iowa robotic telescopes calls for more detailed discussion of the Internet and its implications for Moon-based astronomy. Within the last few years the Internet has grown suddenly, as the well-known "Information Superhighway," and is still evolving rapidly. It already has revolutionized global communication with e-mail, permitting easy and low-cost contact with any part of the world. However, as the BRT illustrates, the Internet also permits active control of remote systems. Finally, to close the loop, the Internet then returns the observations (in the now-conventional digital form) to the remote observer. In the most general terms, a BRT user could eventually carry out a major research program without ever having seen the telescope or having set foot in England. Extrapolation of this scenario to the Moon is easy. A corresponding development, so well known as to be easily overlooked, is the exponential growth in the availability of low cost, user-friendly computers. Such computers are now seen to be an essential link, permitting public participation in space exploration.

Light-weight Telescopes

Large telescopes have inherently been heavy objects, because of the weight of the glass mirrors, steel frames, drives, and mounts. For Earth-based systems, this has not been a problem, and in fact massive telescopes can benefit from their great inertia. The situation is obviously quite different for proposed lunar telescopes, and every effort must be made to reduce the system weight. However, even the recently proposed Lunar Ultraviolet Telescope Experiment (LUTE) (McGraw, 1990; McBrayer, 1994), a transit telescope with no moving parts, would have had a mass of 400 kg exclusive of a nuclear power source and the landing vehicle.

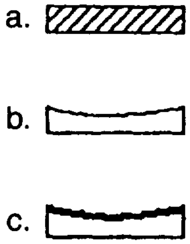
Recent progress in lightweight telescopes is illustrated by the work of P. Chen at Goddard Space Flight Center (Chen, P.C., Oliversen, R.J., Hojaji, H., Romeo, R., Ma, K.B., Lamb, M., and Chu, W.K., A practical, affordable, lunar observatory, submitted to Astrophysical Journal.) Using graphite epoxy to make a frame cuts the weight at once, and the LUTE did make use of this material. However, the main development is production of a graphite-epoxy mirror by replication, i.e., moulding on a precision mandrel, followed by silvering. As shown in Figures 1, 2, and 3, a 42 cm Meinel-type telescope prototype has been built, with a total weight of 1.2 kg for the frame and mirror alone. Similar techniques have been used by the European Space Agency (ESA) for replica optics. The weight savings are illustrated by the comparative areal densities of the Hubble Space Telescope mirror, 180 kg/sq. meter, vs. 2 kg/sq. meter for the ESA mirror.

In addition to the light-weight construction, the Goddard telescope uses other innovative technology oriented toward use on the Moon. Charge-injection devices, rather than charge-coupled devices, are better suited for the radiation environment. The low temperatures achievable on the Moon, either by shielding or by a polar location, permit use of high-temperature superconducting magnets for suspension, without use of cryogenic cooling.

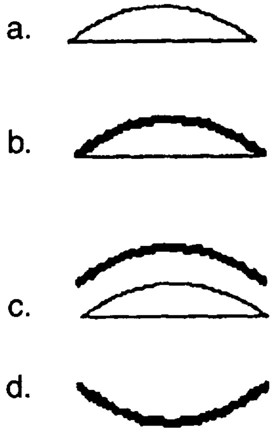
Space Telerobotics

The development of autonomous robots has not been as rapid as once hoped. As pointed out by Lavery (1994), the robotics community set over-ambitious goals for itself, and is now stepping back, so to speak, and concentrating on *tele*robots, devices controlled by human operators. This field, curiously, had for some decades developed separately from that of autonomous robots such as Unimate (Becquet, 1992). However, this schism is now closing, and progress in telerobotics since Apollo has been enormous, with corresponding implications for a new lunar program. The following is a brief summary of highlights in this field.

First, we now have more than two decades of experience with advanced space telerobotics, neglecting for brevity the achievments of early telerobots: Surveyor, Lunokhod, and Viking among others. The Shuttle Remote Manipulator System, or Canadarm, has compiled an impressive list of achievments: launching the Hubble Space Telescope, retrieving satellites, and many others. A more advanced system, the German ROTEX, flown on a Spacelab mission in 1993 (Hirzinger, 1993) was an important demonstration of the "shared autonomy" concept, in which the human operator exercises gross control while the telerobot uses its sensors for fine control (Fig. 4). This "multisensory" technique is not the same as sensor feedback to the human operator, a successful but different method. An incidental but significant aspect of the ROTEX experiment was the 6-second



Traditional Technique
The traditional way of making mirrors is to start with a piece of glass (a.), grind it to shape (b.), then overcoat it with a reflecting surface (c.). This technique is limited by the need for a minimum substrate thickness for grinding and to prevent print-through. Using the lightest material, beryllium, the achievable areal density is about 20 kg/m^2. As an example, areal density of the *Hubble Space Telescope* primary mirror is about 180 kg/m^2.



Replication
In replication a mandrel is first polished to shape (a.). A piece of graphite-epoxy is then applied (b.). After curing the graphite-epoxy takes on the shape of the mandrel (c.). It is then vacuum coated with a reflecting surface (d.).
In the replication the shell is only as thick as it needs to be to maintain optical figure. The European Space Agency's XMM Project has succeeded in making replica optics with areal density < 2 kg/m^2.

Figure 1. Production of ultralightweight telescope mirrors (Peter Chen, Computer Sciences Corporation and Goddard Space Flight Center).

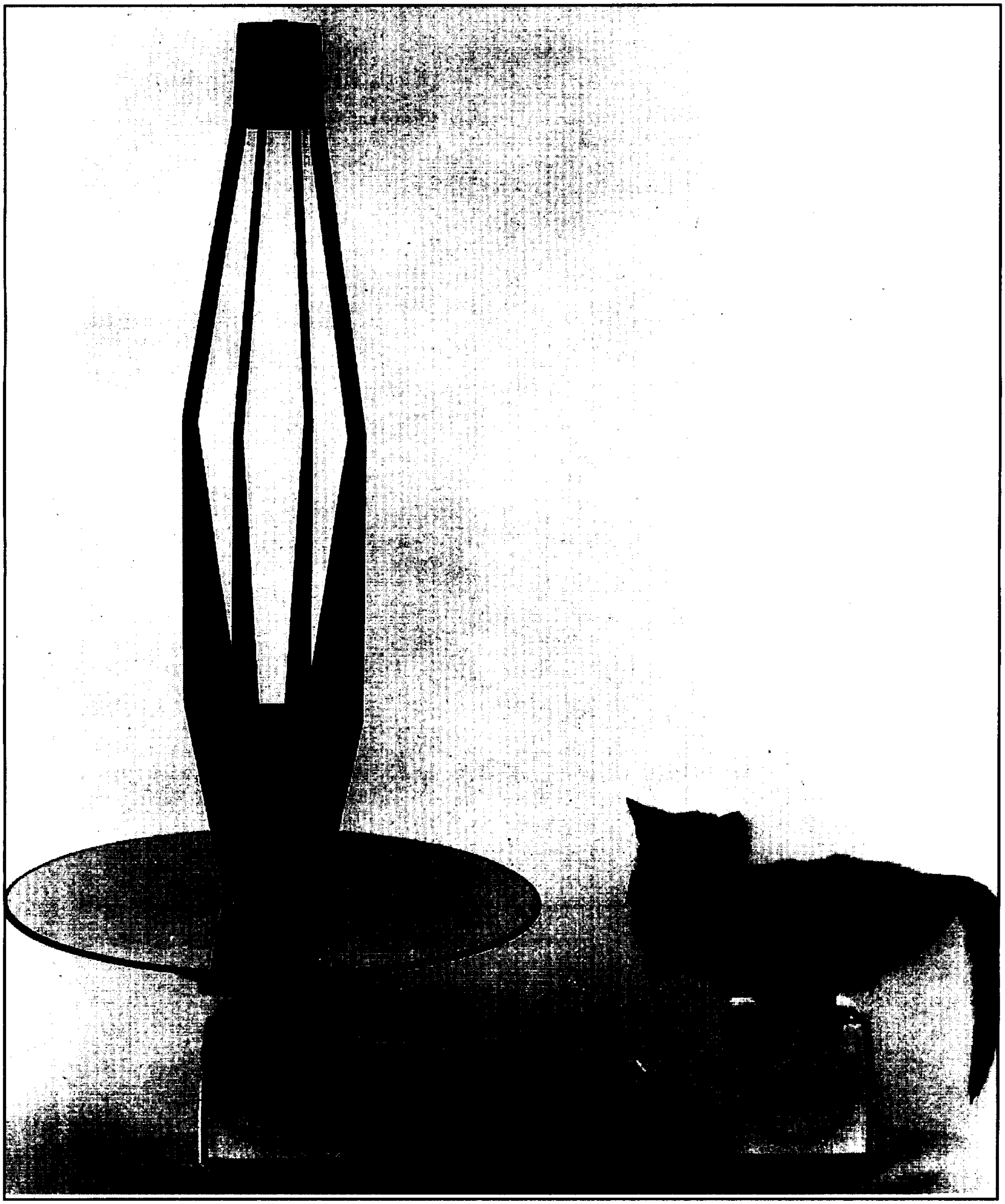


Figure 2. Weight comparison (pounds) of replica mirror and graphite epoxy telescope frame; kitten 7 weeks old when photographed (P. Chen).

Figure 3. Prototype of 42 cm replica mirror telescope, held with one finger by Peter Chen.

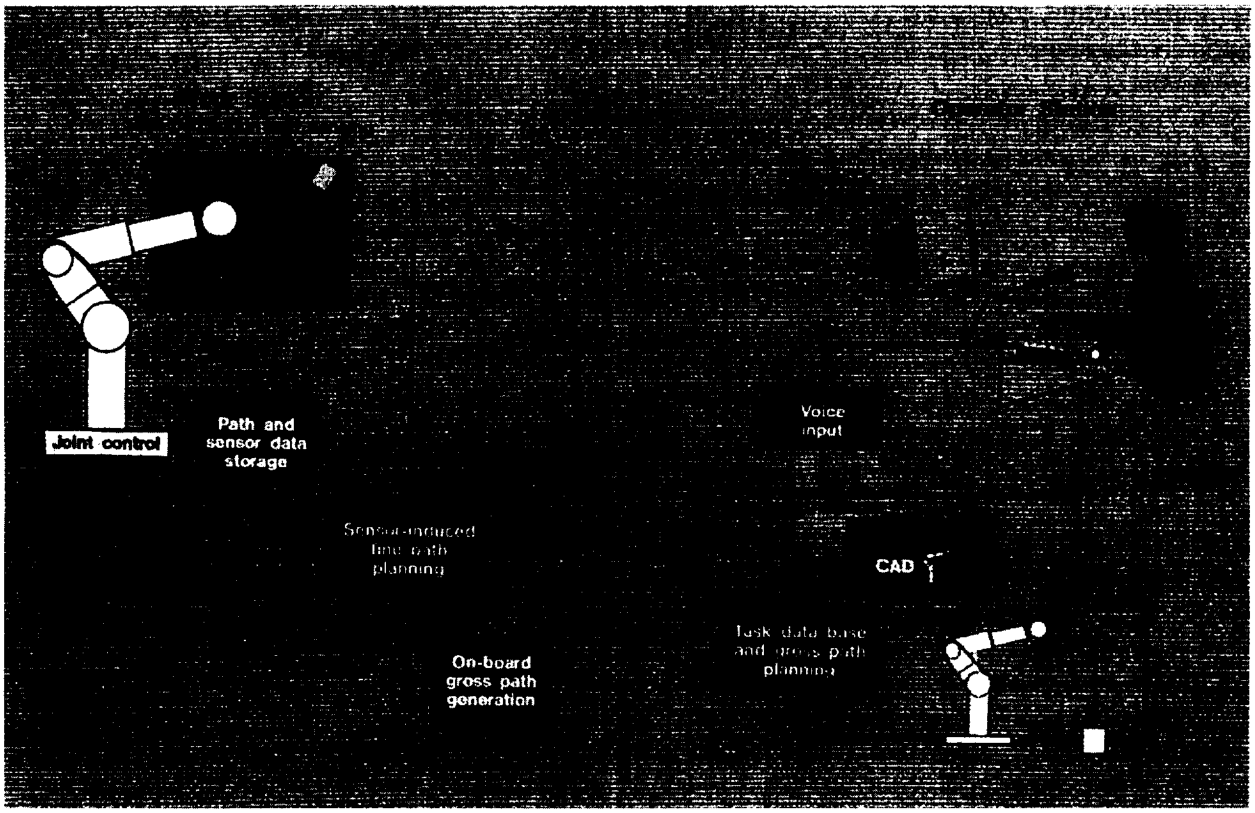


Figure 4. ROTEX control loop; operator does gross path planning, telerobot does sensor-induced fine path planning. (ESA, 1994).

round trip time delay imposed by the communication links, which was overcome by predictive graphics to the degree that a free-floating object could be retrieved by the manipulator.

The NASA Space Telerobotics Program is supporting a wide range of research on the subject (D. Lavery, personal communication) stressing "field" telerobotics: operation in unstructured environments such as a mine, a farm, or a highway (Figure 5). One example of NASA-supported programs is the work at Carnegie Mellon University, whose Dante expeditions into active volcanos have attracted world-wide attention. A recent development is the Australian TELEROBOT, a remotely operated industrial robot (Taylor and Trevylan, 1995) notable for being controllable through the Internet. As of July, 1993, there had been 72,000 requests from 15,000 Web sites around the world.

Progress in telerobotic roving vehicles (Figures 6, 7 and 8) for lunar and planetary exploration has been comparably great (Weisbin et al., 1993). There are lunar rovers now in the prototype stage that could be sent to the Moon almost immediately if funding becomes available. The Russian Marsokhod (Kermurjian, 1990) has been successfully used for joint Russian-American trials, as the University of Hawaii "Pele,"in Moon-like terrains. A Mars rover, Sojourner Truth, is planned for launch in December 1996, the first of several. Carnegie Mellon University is developing a commercial lunar rover for LunaCorp that, if successful, will permit theme park attendees to drive the vehicle in real time on a traverse north from Tranquillity Base. A two-phase Delta II-launched lunar rover mission, INTERLUNE-One, proposed by the University of Wisconsin, would have used a 163 kg Macro-rover supplemented by a 10 kg Micro-rover.

Optical Interferometry

Optical interferometry was first used by Michelson many years ago to measure stellar diameters, but it is only recently that ground-based optical arrays have been demonstrated successfully (Shao, 1990). Several systems have been constructed for optical (including infrared) astronomy in the U.S. and Britain, three of which are described in Table 1. The Cambridge system (Figure 9) for example, has produced images with resolution as good as 1 milliarcsecond from a 6 meter baseline array, and it is interesting to note that the array's total cost, for 4 telescopes, was around $1.3 million (Baldwin et al., 1995). The advantages of interferometry

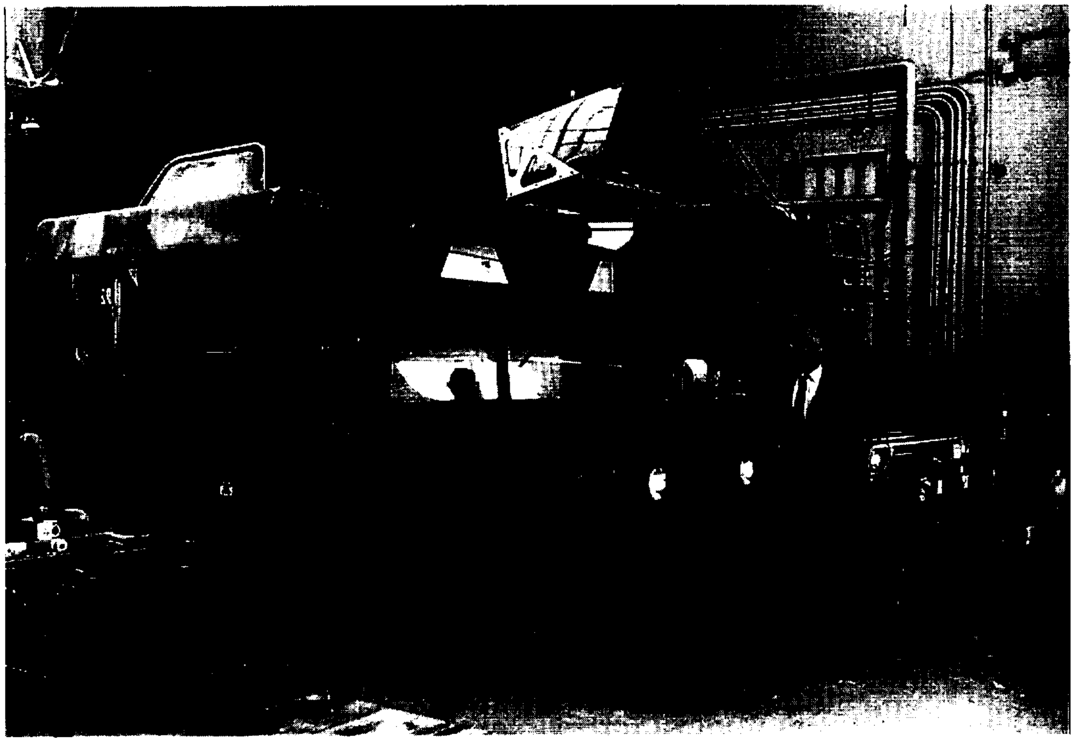


Figure 5. Autonomous robotic vehicles developed by Carnegie Mellon University Robotics Institute, capable of operation on public highways (1994).

Figure 6. Rocky IV, Jet Propulsion Laboratory prototype Mars rover.

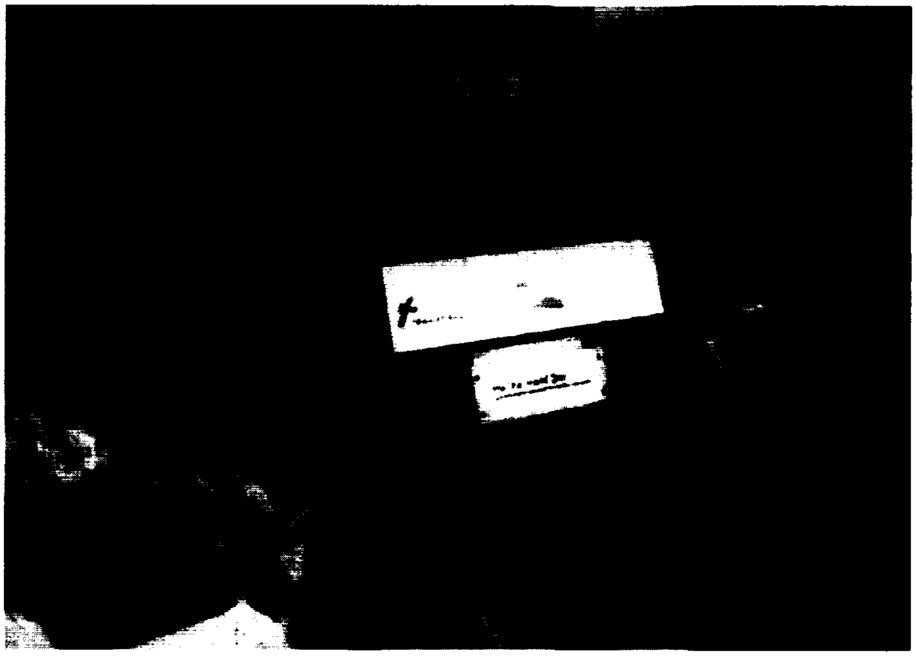


Figure 7. ESA-developed fully autonomous Adam rover (ESA, 1994).

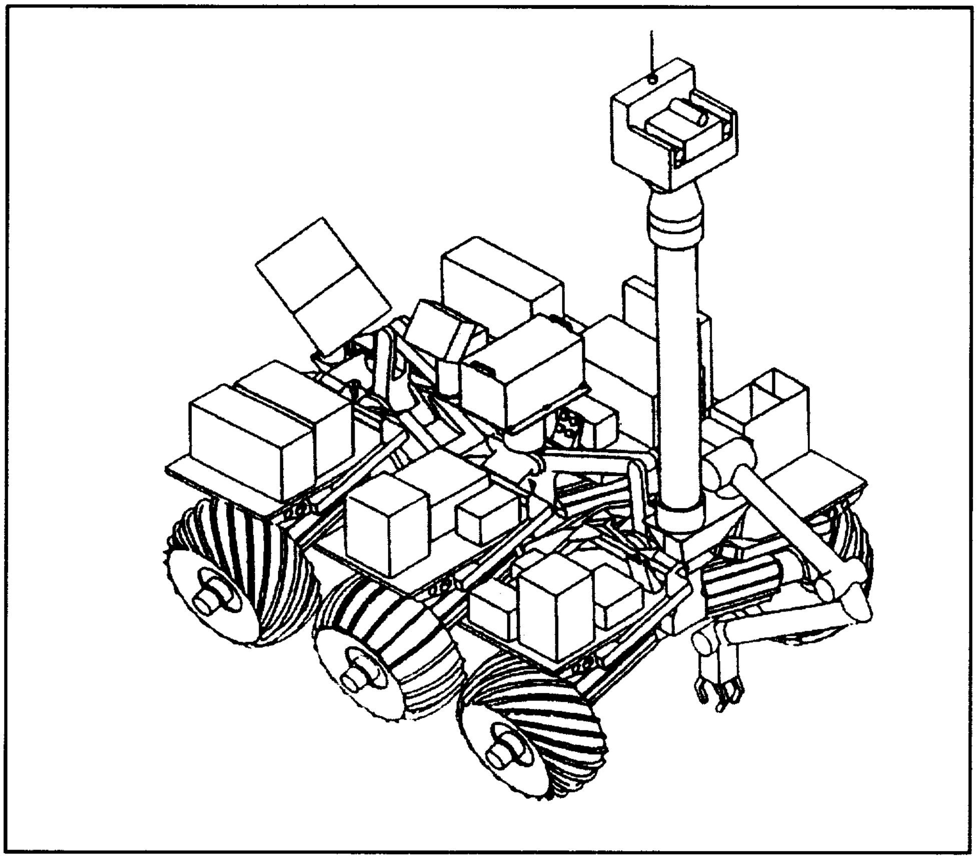


Figure 8. ESA Iares ground demonstrator concept, to test autonomous navigation (ESA, 1994).

Table 1. Optical Interferometric Systems

Cambridge Optical Aperture Synthesis Telescope (COAST)

Four 40 cm fixed horizontal afocal Cassegrain telescopes, located 5 miles W of Cambridge, England. 6.1 m baseline. Produced first true images (of Capella) with ground-based optical system, 1993. (Baldwin et al., 1994)

Infrared - Optical Telescope Array (IOTA)

Two 45 cm telescopes, located near Tucson, Arizona at F.L. Whipple Observatory. Maximum baseline 38 m. Produced 2.2 micrometer measurements of stellar diameters, 1994. (Carleton et al., 1994)

Navy Prototype Optical Interferometer

Four telescopes, located near Flagstaff, Arizona. Maximum astrometric baseline 37.5 m. Imaging portion maximum baseline 435 m. Present (1996) wavelength coverage 450 to 859 nm. First observations made March, 1996. (Benson et al., 1995)

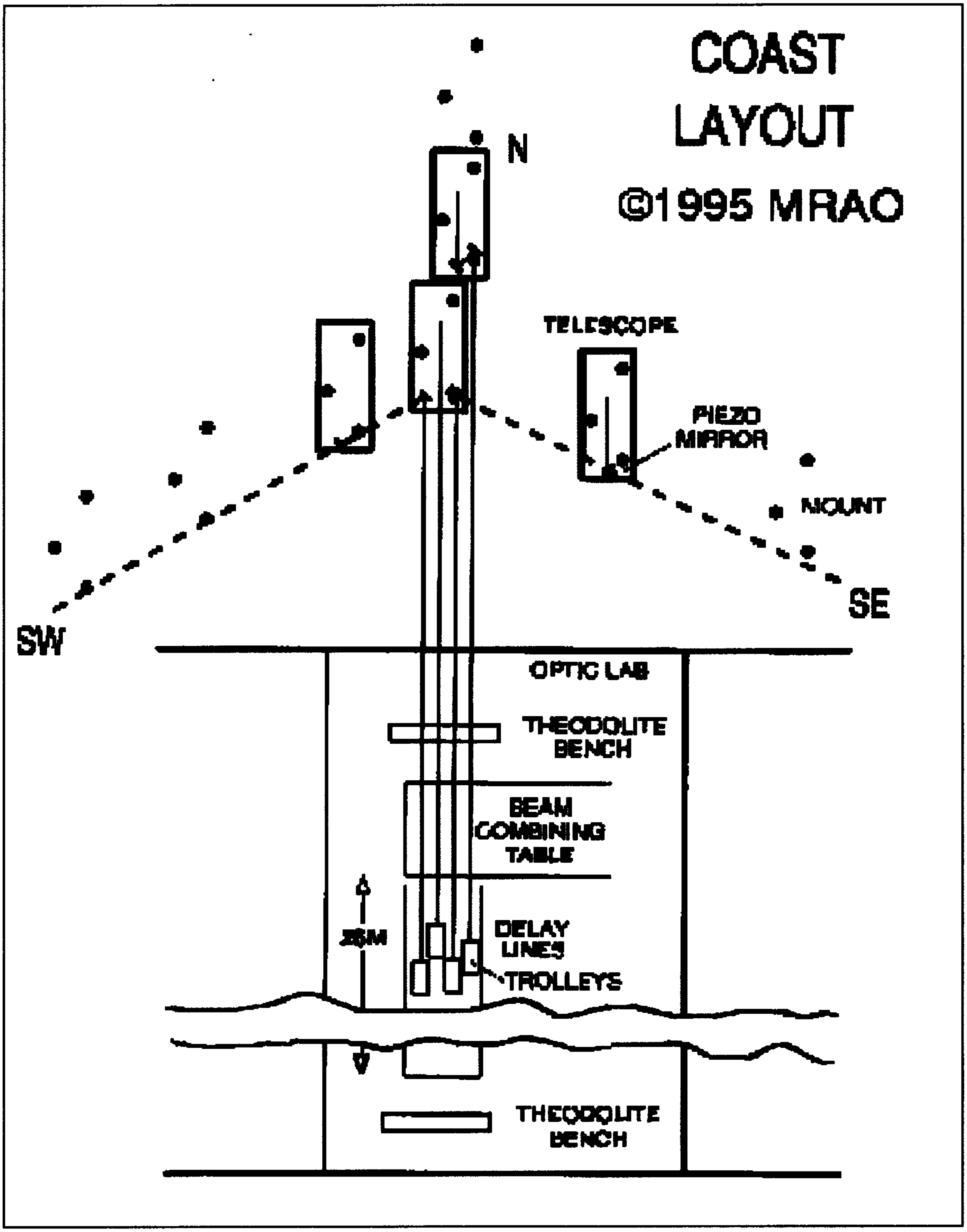


Figure 9. Cambridge Optical Aperture Synthesis Telescope layout, plan view; beam combining system is in an underground building. (Mullard Radio Astronomy Observatory, www manuscript).

for radio astronomy have been recognized for decades, and modern radio astronomy is dominated by this technique. It appears possible that optical interferometry could have similar impact were it not for the problems common to all earth-based systems, namely bad weather and optical opacity at various wavelengths.

The obvious place for optical interferometers is the Moon, as shown by the many conferences and papers advocating lunar optical interferometers.
The advances in telerobotic technology and lightweight telescope materials make such a location even more desirable. This will be discussed in more detail elsewhere in the paper. The point to be made here is that working optical systems are now in use, and their feasibility is no longer in doubt.

The Moon as a Focus of Future NASA Programs

The Apollo Program was assumed by NASA in the early 1960s to be only the beginning of extensive lunar operations, and a lunar base using the Apollo transportation system could have been operating by 1975 had the decision been made to do so (Burgess, 1993). However, the latest NASA strategic plan (1995) lists only a single lunar mission (Lunar Prospector). Given the success of the Apollo Program, and the dozens of unmanned lunar missions, it must be asked if a return to the Moon is justified, compared to other possibilities such as Mars exploration (Paine, 1992). Broader issues in deciding on future programs (Logsdon,1985), cannot be covered here, but the most general answer is that almost every serious study of future NASA programs since the early 1960s has recommended renewed lunar missions and a lunar base. Three such recent studies can be summarized briefly.

The National Commission on Space (1986) included a lunar base as a key element of the "Bridge Between Worlds" (Figure 10), essential to the goal of reaching and colonizing Mars. The Advisory Committee on the Future of the U.S. Space Program (1990) similarly listed "establishment of permanent outposts" on the Moon as necessary preparation for the human exploration of Mars. Finally, the

Synthesis Group (1991) produced the most detailed set of recommendations, four "architectures," every one of which included a renewed lunar program as an essential element ("the most complete test bed for a Mars mission") for reaching the eventual goal of Mars (Figure 11). Each of the studies mentioned included robotic lunar missions, though focussing on extensive manned missions and lunar bases.

There has been a major shift in political climate in the U.S., both parties calling for major budget cuts. Although the NASA budget is small ($13.7 billion outlays for FY 1994, compared with $25.5 billion, for example, for the 1994 Food Stamp Program), the perceived cost of the space program virtually dictates little if any growth. Mention of any mission or spacecraft is almost invariably prefaced by the cost, as in a 1994 Washington Post report of the Italian-American tether experiment: "A $440 million science satellite was lost in space tonight . . . . " (In this particular event, much of the cost was borne by Italy and the experiment was fundamentally successful.)

To counter this development, since 1961, as previously mentioned, there has been enormous progress in space technology, both American and foreign. Several countries now have satellite launching capability. The U.S. flies complex Shuttle missions on a more or less regular basis, and the former Soviet Union has been operating a large space station for 10 years at this writing. Spacecraft have been sent to every planet but Pluto, and one is still in contact with Earth from a distance of several light hours. Correspondingly, our knowledge of the Moon and specifically its surface environment is now infinitely greater than it was in 1961, when fears of free radicals, electrostatically-supported quicksand, and other unknowns amounted to the "here there be dragons" of medieval maps. Apollo was a magnificent achievment (Appendix A), but a new Apollo Program is not needed, especially since our former adversary is now our partner in programs such as the space station.

Turning to specifics, a return to the Moon at some level of effort is justified on several grounds.

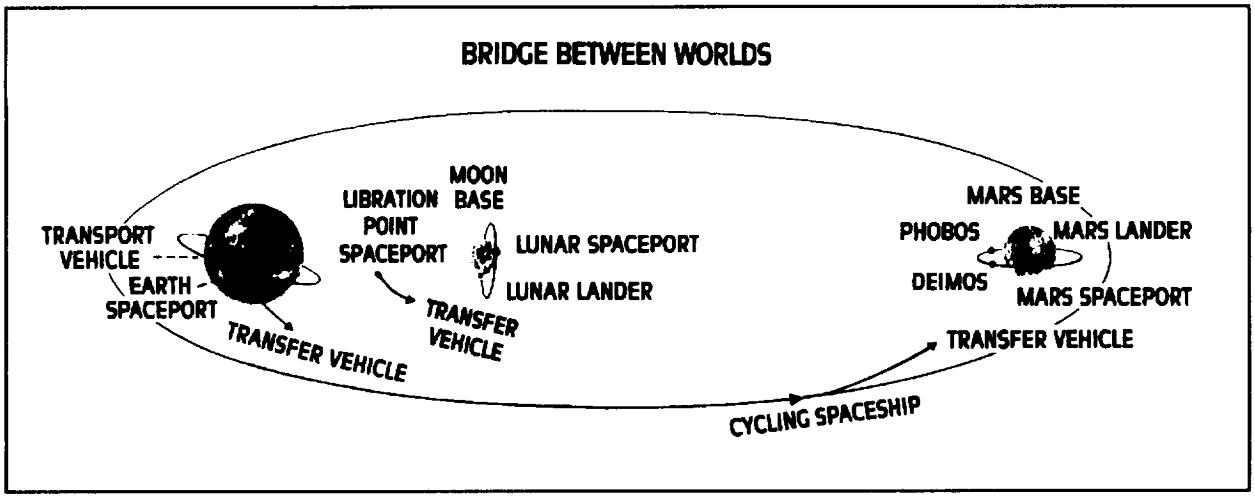


Figure 10. Relationship between lunar and Martian operations, from NCOS report.

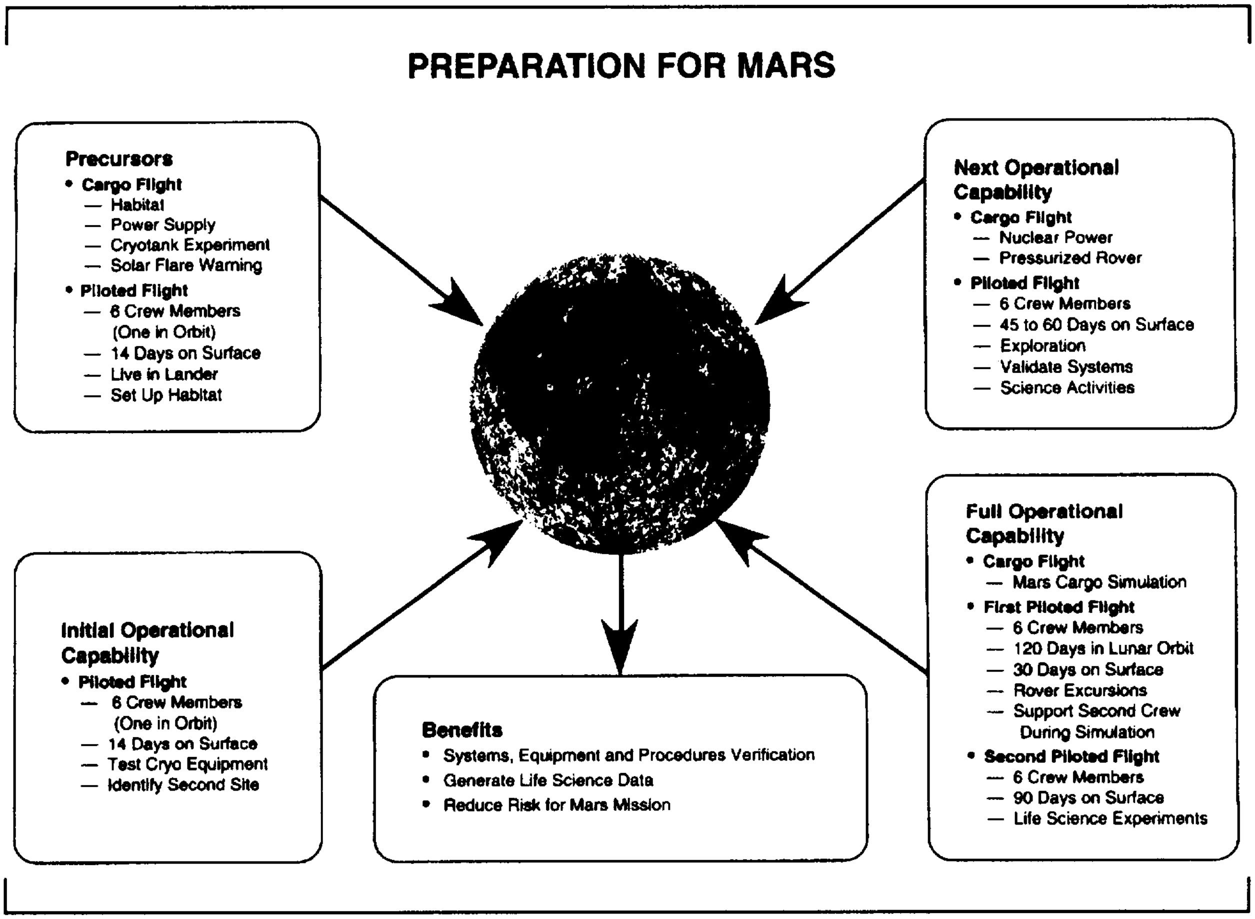


Figure 11. Contribution of lunar operations to Mars program, from Synthesis Group Report (1991).

Public Participation

The Apollo Program generated enormous interest in its day, not just in the United States but around the world, incomparably more than even the most successful unmanned lunar or planetary programs. Success of the recent movie "Apollo 13" suggests that this interest survives. The phrase "been there, done that" has been applied to the Moon, but it should not be used for the post-Apollo generation (Figure 12), which has *not* "been there." The author lectures frequently to lay audiences, from elementary school classes to professional societies, and has invariably found strong and continuing interest in past and possible future exploration of the Moon. Amateur organizations such as the National Space Society, Students for the Exploration and Development of Space, and the Artemis Society International testify to this interest. (The May 1995 issue of the NSS Ad Astra magazine was devoted to the theme "Return to the Moon and Stay.")

On the most elementary level, the Moon is visible and conspicuous every month, in contrast to most planets. An important aspect of public interest is the Moon's closeness, permitting not only frequent missions at modest cost, but real-time telerobotic operation of roving vehicles and astronomical instruments. Such real-time operation is not feasible for any planet (Burke, 1990) and raises the possibility of *direct public participation* in exploration of the Moon and observations from its surface. The LunaCorp/Carnegie Mellon "entertainment-based lunar excursion" (Katragadda et al., 1994) was responsible for the Dante II excursion into an Alaskan volcano. Students have been able to take part, through the Jason Project, in simulated lunar missions by driving the Marsokhod, and similar student participation could be achieved on the Moon. Students are already using the Hubble Space Telescope (HST), in cooperation with professionals, as part of the "Passport to Knowledge" program. Student and amateur astronomers can benefit much more from the great amount of telescope time provided by instruments on the Moon (Mendell, 1991), which there can operate as long as 14 Earth days with a nearly 100% duty cycle (in contrast to the HST figure of about

Figure 12. Lunar exploration enthusiasts, C.T. Reed Elementary School,Seabrook, Maryland, 1993. Photograph by Melanie Taylor.

30%). Dyson (1994) has pointed out that in astronomy, "... it is the amateurs who ultimately sustain the culture within which the professionals can flourish."

Scientific Value: A Platform for Observation

Space-based astronomy is now in its golden age, with major new discoveries being announced almost at monthly intervals. Fundamental new knowledge of the origin of the universe, its age, and its overall structure have been returned by orbital instruments such as the Cosmic Background Explorer (COBE). The Hubble Space Telescope in particular has fulfilled its promise, and planning has begun for the post-HST period. Successful as these orbiting instruments have been, the advantages of the Moon as an even better site for astronomy have been obvious for decades. The Moon is inherently superior to orbiting platforms in several aspects (Table 2) (Smith, 1990). This superiority has been recognized by at least eight major meetings (Burns, 1990) in the U.S. alone since 1984, and by hundreds of technical papers (Linebaugh, 1990). A 1994 ESA workshop produced a ringing declaration on utilisation of the Moon for astronomy (Fig. 13). The 1991 National Research Council 1990s prioritization study (Bahcall, 1991) recommended lunar astronomy as an initiative for the early 21st century, singling out interferometry as uniquely suitable for the Moon.

An important point in any proposal for "Mission to the Solar System" is that a Moon-based observatory is especially adapted to the study of *planetary* astronomy -- planets, satellites, asteroids, and comets -- as brought out by Mumma (1990), Smith (1990), Cruikshank (1990), and Bruston and Mumma (1994). One reason is that all planets but Mercury have atmospheres, and proper study of them requires long-term synoptic observations, better provided by a lunar telescope than by a telescope in low Earth orbit or even by planet-orbiting spacecraft. A second advantage of the Moon is that it can permit observation of planets and comets with small elongations, i.e., close to the Sun, by use of lightweight shades separated from the telescope (Mumma, 1990). This is important not only for the inner planets but

Table 2. Advantages of Moon-based astronomy, compared to Earth-orbital instruments (from Lowman, 1995)

1. No atmosphere; all radiation (EM and particulate) reaches the lunar surface directly; no background radiation from atmosphere; no radiation belts; unlimited spectral window; no weather.

2. Ground emplacement; distributed instrument network and wide separation essentially eliminate experiment integration problems; simple telescope drives possible (vs. orbital instruments); high reliability from independent instruments; single point failure reduced. Large interferometer arrays practical.

3. No orbital debris problem; micrometeorite flux similar to Earth orbital; no glow effects from collisions with residual atmosphere (vs. LEO).

4. Slow rotation time permits up to 14 days continuous exposure (vs. LEO, frequent eclipse by Earth) from low latitudes sites; polar sites permit exposures of indefinite length for corresponding hemisphere.

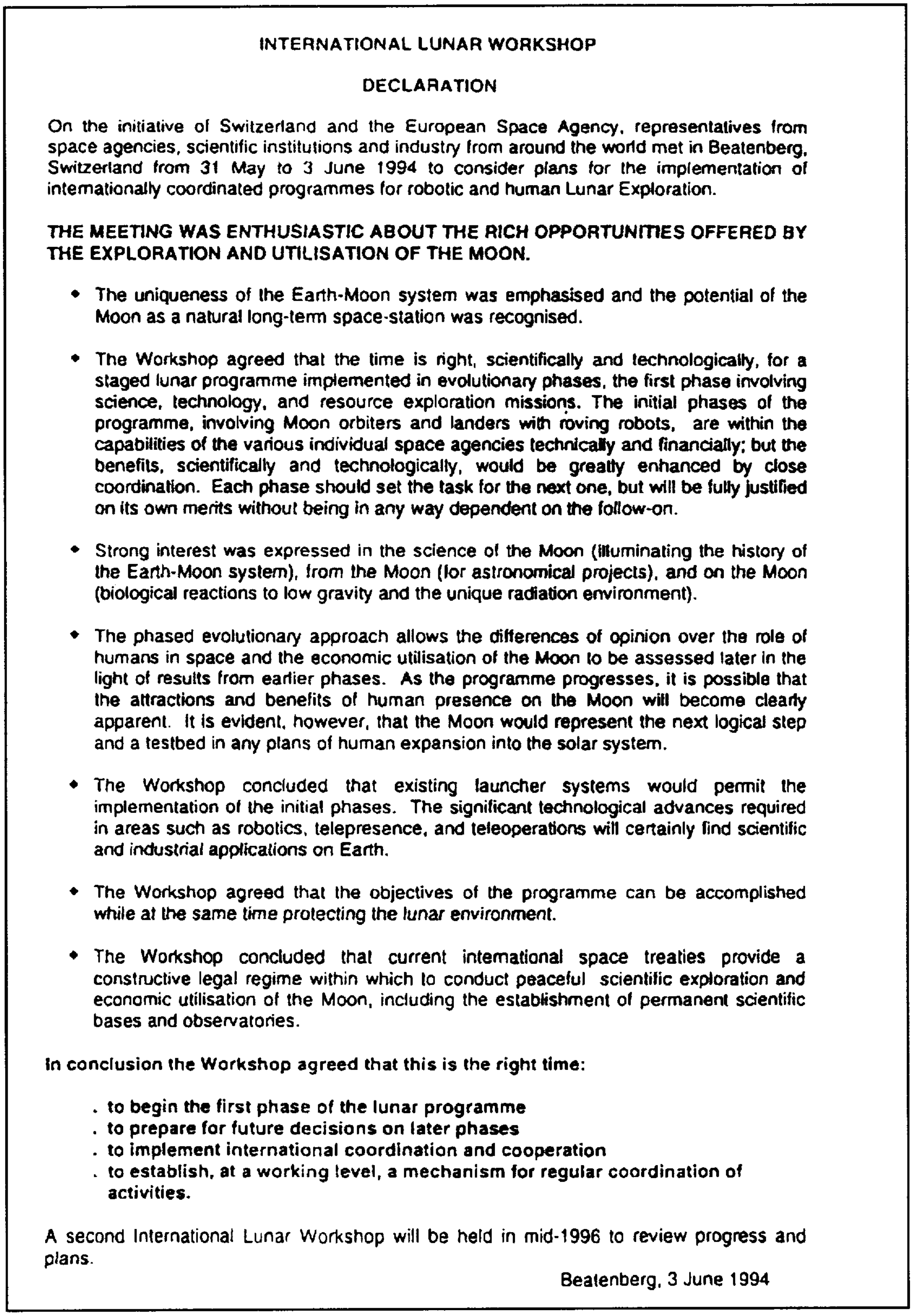
5. Distance from Earth greatly reduces terrestrial source interference (RFI, gamma ray, radar) by inverse square of distance.

6. Far side offers complete radio silence at all frequencies (assuming regulation of radio use); ideal site for SETI, VLF investigations.

7. Near side observatory permits use of Earth as calibration/comparison target for reflectance spectroscopy and other observations.

8. Astronomical study of Earth possible; almost entire hemisphere visible at once including one pole, possibly two.

9. Ultra-long baseline Moon-Earth interferometry possible; extremely high resolution and sensitivity.



INTERNATIONAL LUNAR WORKSHOP

DECLARATION

On the initiative of Switzerland and the European Space Agency, representatives from space agencies, scientific institutions and industry from around the world met in Beatenberg, Switzerland from 31 May to 3 June 1994 to consider plans for the implementation of internationally coordinated programmes for robotic and human Lunar Exploration.

THE MEETING WAS ENTHUSIASTIC ABOUT THE RICH OPPORTUNITIES OFFERED BY THE EXPLORATION AND UTILISATION OF THE MOON.

- The uniqueness of the Earth-Moon system was emphasised and the potential of the Moon as a natural long-term space-station was recognised.
- The Workshop agreed that the time is right, scientifically and technologically, for a staged lunar programme implemented in evolutionary phases, the first phase involving science, technology, and resource exploration missions. The initial phases of the programme, involving Moon orbiters and landers with roving robots, are within the capabilities of the various individual space agencies technically and financially; but the benefits, scientifically and technologically, would be greatly enhanced by close coordination. Each phase should set the task for the next one, but will be fully justified on its own merits without being in any way dependent on the follow-on.
- Strong interest was expressed in the science of the Moon (illuminating the history of the Earth-Moon system), from the Moon (for astronomical projects), and on the Moon (biological reactions to low gravity and the unique radiation environment).
- The phased evolutionary approach allows the differences of opinion over the role of humans in space and the economic utilisation of the Moon to be assessed later in the light of results from earlier phases. As the programme progresses, it is possible that the attractions and benefits of human presence on the Moon will become clearly apparent. It is evident, however, that the Moon would represent the next logical step and a testbed in any plans of human expansion into the solar system.
- The Workshop concluded that existing launcher systems would permit the implementation of the initial phases. The significant technological advances required in areas such as robotics, telepresence, and teleoperations will certainly find scientific and industrial applications on Earth.
- The Workshop agreed that the objectives of the programme can be accomplished while at the same time protecting the lunar environment.
- The Workshop concluded that current international space treaties provide a constructive legal regime within which to conduct peaceful scientific exploration and economic utilisation of the Moon, including the establishment of permanent scientific bases and observatories.

In conclusion the Workshop agreed that this is the right time:

- **to begin the first phase of the lunar programme**
- **to prepare for future decisions on later phases**
- **to implement international coordination and cooperation**
- **to establish, at a working level, a mechanism for regular coordination of activities.**

A second International Lunar Workshop will be held in mid-1996 to review progress and plans.

Beatenberg, 3 June 1994

Figure 13. Declaration of the 1994 ESA International Lunar Workshop on the exploration and utilisation of the Moon. (ESA, 1994).

for Mars, which is available to Earth-based or LEO telescopes for only about 20% of its orbit. Understanding of Martian weather is vital for eventual manned missions, and a dedicated lunar instrument should be a valuable complement to those on or orbiting Mars. For these and other reasons, Bruston and Mumma (1994) conclude that "a lunar observatory should become a central piece of any coherent set of planetary missions...."

As previously mentioned, the Moon's solid surface and lack of atmosphere make it uniquely valuable for optical interferometry. Good summaries of possible lunar interferometric techniques (optical through submillimeter) have been presented by several authors (Burke, 1985, 1990; Burns, 1990; Shao, 1990). An ingenious concept demonstrated by Labeyrie and Mourard (1990) to take advantage of a lunar site is that of an array of automated "walking" telescopes, making possible the elimination of delay lines. The Lunar Study Steering Group of ESA (ESA, 1991) predicted the scientific impact of a lunar interferometer, capable of 100 microarcseconds optically, to be "enormous." Several possible locations for space-based interferometers are evaluated by Burns (1990), in Table 3. The recent discovery of extrasolar planets has triggered a surge of interest in the study of other planetary systems by interferometry. A 75 meter spaceborne infrared interferometer at the distance of Jupiter (to avoid the zodiacal light and provide a cold environment) has been proposed by Angel and Woolf (1996). However, this challenging program would run the risk of technological obsolescence in the 10 to 15 years necessary for its completion. Emplacement by telerobotic methods on the surface of the Moon would be far faster and cheaper, and much higher spatial resolution could be obtained since baselines of several kilometers should be attainable (Figure 14). At a minimum, the proposed orbiting interferometer concept should be tested on the Moon to the extent possible.

The fundamental feasibility of lunar-based astronomy has been demonstrated by various instruments already used on the Moon for UV, X-ray, cosmic ray, and visible light observations from the surface, as well as LF radio astronomy from lunar orbit. The primary obstacle to lunar-based instruments has traditionally been cost, compared to orbiting platforms, an obstacle addressed in

Table 3. Comparison of Different Locations for Space- and Lunar-Based Interferometers (From Burns, 1990)

				Array Location		
Array Characteristic		LEO	Sun Synchr.(0)	GEO	L5 Points	Lunar Surface
Baseline Stability	0-30m	Mod. Diff.	Mod. Easy	Easy	Easy	Intrinsically Very Good
	30-300m	Very Diff.	Difficult	Mod. Diff.	Easy	
	0.3-10km	Impossible	Impossible	Very Diff.	Easy to Diff	
	> 10km	Impossible	Impossible	Impossible	Diff.(1)	
Thermal Stability		Poor	Very Good	Very Good	Very Good	Polar (2):Good Equatorial:Good
Thermal Background		Poor	Very Good	Very Good	Very Good	(11)Lg. Array Poor Sm. Array Good
Radiation Environment (Cosmic, Solar, Van Allen((5)		Good	Poor(4)	Very Poor	Very Poor	Poor
Duration of Total Darkness		0.5 Hr.	0	0	0	336 Hr.
Optical Background		Day: Earth Night: Zodiacal	Zodiacal (6)	Zodiacal	Zodiacal	Day: Moon Night: Zodiacal
Debris And Micrometeorite Risk		Moderate	Low	Low	Low	Lowest
Maintainance, Service And Upgrading (12)		Good	Poor	Poor	Poor	Very Good
Complexity of Science Operations		Very	Moderate	Moderate	Moderate	Simple
Re-Configurability(7)		Limited	Limited	Limited	Flexible	Flexible
Expandability		Poor	Very Poor	Poor	Good	Excellent
# of Reflections(8)	2 to 5	2 to 5	2 to 5	>2	>5	
Science Potential (Angular Resolution)	3 mas	x	x	x	x	x
	0.3 mas		x	x	x	x
	10 μas			x	x	x
	1 μas				x	x
Recommendation	3 mas	√				√
	0.3 mas		√			√
	10 μas				?	√
	<1 μas					√

INTERFEROMETRY FROM THE MOON
(optical, infrared, submillimeter)

- Proof-of-concept prototypes now in use on Earth
- Ground emplacement; telerobotic methods possible
- Stable baselines
- Very long baselines possible (multi-kilometer)
- Easily enlarged; modular approach
- Mobile telescopes without delay lines possible
- Very low temperatures at lunar poles
- Earth-based testing possible
- Failure tolerant (use array as single instruments if necessary?)
- Safe from technological obsolescence
- Wide scientific support (NASA, ESA, Annapolis, NRC, etc.)
- Faster and cheaper than space-borne interferometer

Figure 14. Advantages of lunar-based inteferometry.

this paper. If this can be overcome, lunar-based astronomy can be extraordinarily valuable for study of our solar system and other solar systems, in addition to study of the universe as a whole. It can also be a major stimulus to scientific education by giving students a chance to take part in Moon-based astronomy (Mendell, 1991).

Scientific Value: An Object of Study

The Moon furnishes an end-member in comparative planetology among silicate bodies: large enough to have undergone differentiation and limited tectonic activity, but small enough to preserve a crust formed roughly 4.4 billion years ago (Figures 15 and 16). It has an evidently close but unknown genetic relationship to the Earth; it may have been formed by a giant impact on the primordial Earth, with possible consequences for crustal evolution. It serves as a museum of impact craters, ranging from micron size to larger than Texas, and whose study has revolutionized recognition of impact craters on the Earth. It provides a record of the impact history of the Earth-Moon system from early Archean to the present. The enormous South Pole-Aitken Basin, confirmed by spectral data and laser altimetry from Clementine (Spudis et al., 1994; Zuber et al., 1994) , should tell us much about the lunar crust and deep interior. There are innumerable geologic features on the Moon whose nature and origin are only vaguely understood, since they were not visited during the Apollo missions or any other. A catalog of such features has been compiled by Nash et al. (1989). Even the familiar ray craters of the Tycho-Copernicus family are not fully explored, having been visited at close range only by Surveyor 7. The cause of lunar magnetic anomalies such as Reiner Gamma (Figure 18; Hood et al., 1979) is not understood. A list of unanswered questions from the Lunar Sourcebook (Heiken et al., 1991) is presented in Table 4.

In summary, the Moon still "holds a central place in planetary science" (Spudis and Taylor, 1990), and is well worth futher exploration.

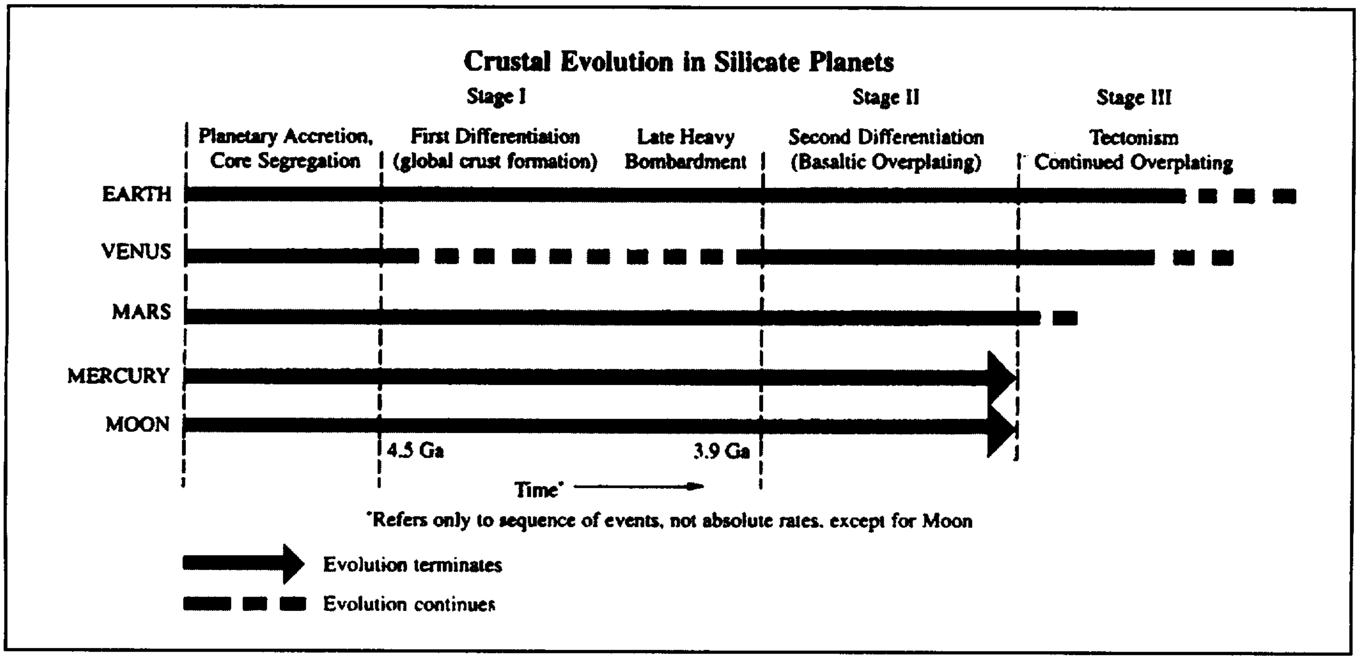


Figure 15. Crustal evolution of Moon and terrestrial planets (Lowman, 1989).

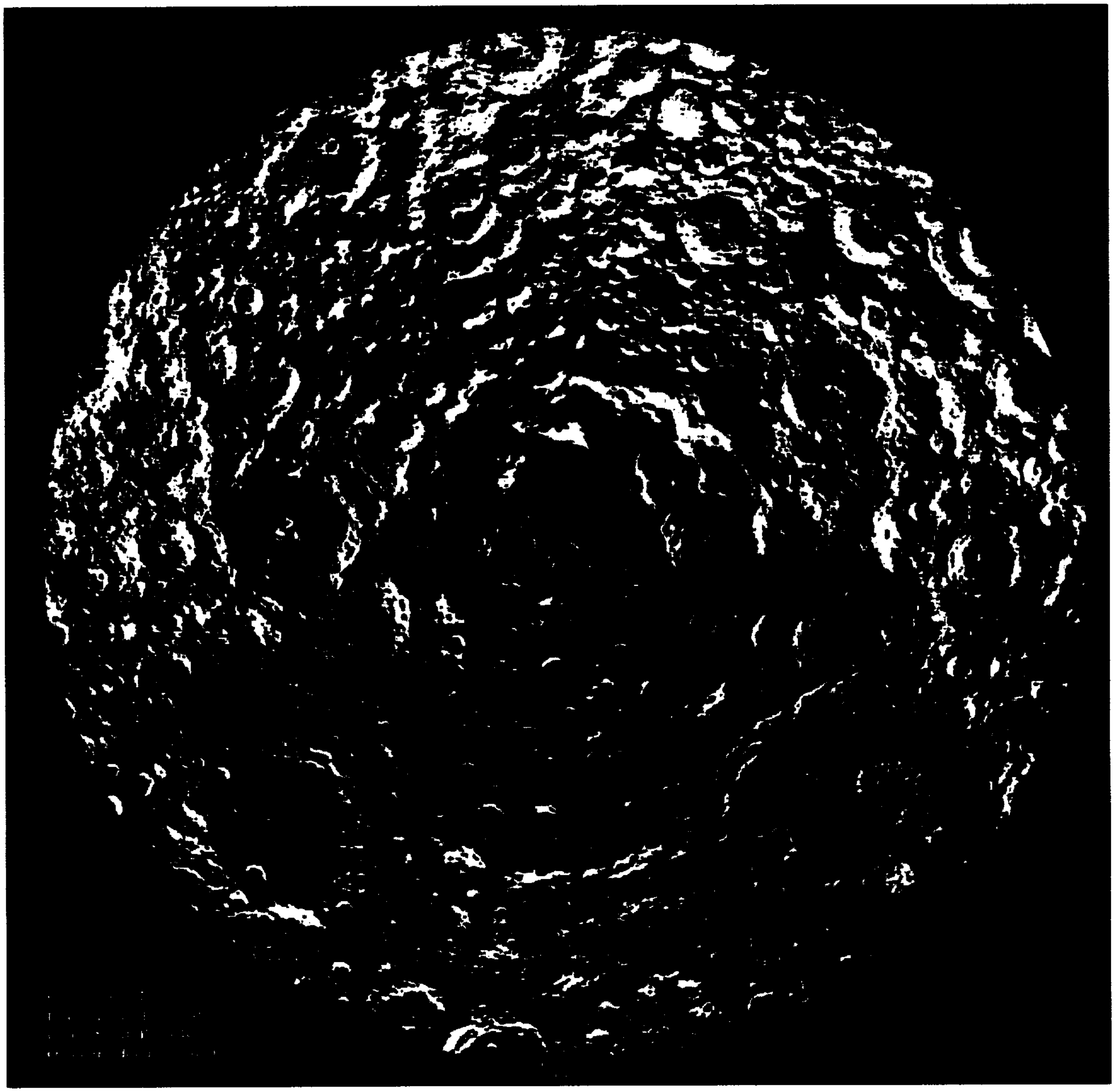


Figure 16. South polar region of Moon; South Pole in shaded region. Area is chiefly highland crust, formed in "first differentiation" (Fig. 15).

Table 4. Unanswered Questions About the Moon

(modified, from Heiken et al., 1991)

1. **Surface history and impact cratering rate**
2. **Mechanisms of impact cratering**
3. **Nature and distribution of impact ejecta from craters and basins**
4. **Lunar regolith and the sun's history**
5. **Thickness, structure, and distribution of the megaregolith**
6. **History and nature of mare and highland volcanism**
7. **Tectonic history of the Moon and individual structures**
8. **The lunar crust and "magma ocean"**
9. **Nature and history of the lunar mantle**
10. **The lunar core: existence, size, composition**
11. **Global properties: moment of inertia, heat flow, paleomagnetism**
12. **Lunar atmosphere: composition, dynamics, modification**
13. **Lunar transient events: Gas release? Impact?**
14. **Bulk composition**
15. **Origin of the Moon**

Lunar Resources

The low surface gravity value of the Moon makes it possible to launch material from the surface into space for roughly 1/22 the energy per unit mass required for a comparable Earth launch, even neglecting air resistance. Consequently, an electric catapult, or "mass-driver" in the Heppenheimer (1985) concept, could send material into Earth-Moon space fairly easily and without the use of reaction mass, i.e., expendable fuel. Accordingly, the use of lunar metals, oxygen, or even bulk soil for space stations or libration-point colonies (O'Neill, 1975) becomes a real possibility. A comprehensive discussion of lunar resource use has been presented by Schmitt (1992).

A potential lunar resource useable even without a mass-driver would be helium-3, whose low neutron flux in fusion reactions makes it extremely attractive if thermonuclear power is achieved. The deuterium-He 3 reaction produces most of its energy as charged particles rather than as neutrons, thus avoiding the problems of radiation damage and disposal of radioactive waste common to other fusion reactions (and of course fission reactors) (Wittenberg et al., 1986; Schmitt, 1994). The helium-3 reaction was not studied seriously for power generation until recently because this isotope is extremely scarce on Earth. However, large amounts of it have been formed in the lunar soil and rock by solar irradiation, and could be easily extracted for export to Earth. This lunar resource might actually make commercial fusion reactors possible by avoiding the radiation problems of other fusion reactions.

Other possibilities for the more remote future include power generation on the Moon for transmission to space stations or even to Earth (Criswell, 1993), although considering present public fear of the radiation ("magnetic fields") emitted by 60 cycle AC current or cellular telephones, we can foresee formidable difficulties in such systems.

Technology Stimulus

Reaching the Moon in the 1960s was obviously an enormous stimulus to space technology, forcing development of launch vehicles, computers, deep space communications, space suits, remote sensing devices, and innumerable other components (Appendix A) . A return to the Moon as outlined in this paper could have similar effects, even though a major program could be carried out with equipment already operational. For example, a broad program of telerobotic rovers, to be described, would generate technology and operational experience applicable not only to other planets but to hostile environments on Earth. Experimental rovers developed by Carnegie Mellon University (CMU), as previously mentioned, have already been used to investigate active volcanos. An autonomous robotic harvester based on planetary rover technology is being developed jointly by CMU and New Holland. Similar developments for mining, construction, forestry, and other industries can be expected.

Eventual establishment and maintenance of a manned lunar settlement would involve regular operation of orbital transfer vehicles. Short as it is, a flight to the Moon is an interplanetary trip, requiring qualitatively the same technology needed for planetary missions, as implied by the phrase "Bridge between Worlds" (Figure 10). An important aspect of such operations is that they could involve not only hardware development but technology for extracting oxygen, the prime component of cryogenic rocket fuels, from lunar rocks. As pointed out by Joosten (1993), initial trials in this field could be carried out with robotic lunar missions.

Accessibility

The dominant advantage of lunar missions over planetary ones is so obvious as to be easily overlooked: the Moon's accessibility. A trip from Washington to Tokyo takes little less time, allowing for airport taxis and recovery from jet lag, than a trip to the Moon. Planetary missions, in contrast, involve one-way travel times of several months, frequently several years (Figure 17), if

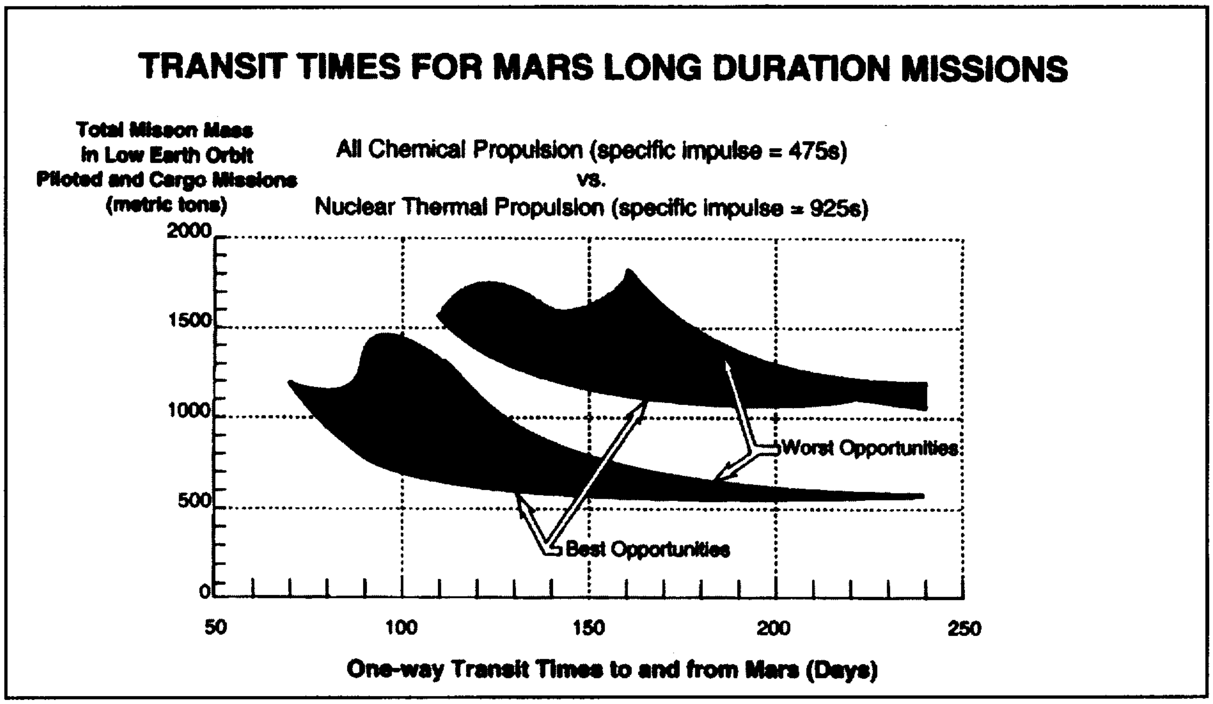


Figure 17. Transit times for Mars missions, chemical vs. nuclear propulsion; from Synthesis Group report, 1991.

Hohmann trajectories are used. Short missions, using nuclear thermal propulsion, can presumably be ruled out in view of public fear of nuclear energy. As important from a programmatic viewpoint is the fact that the launch window for lunar missions is essentially continually open, unlike the roughly 2-year interval between Mars windows. Collectively, the Moon's enormously greater accessibility means that lunar missions can be *orders of magnitude* faster, more frequent, and cheaper (other factors equal) than those focussed on planets. The Moon can be considered as a planet that nature has placed conveniently at our doorstep.

An additional advantage of the Moon's closeness was demonstrated during the Apollo missions, which were televised from the lunar surface as they happened. Lunar surface exploration is made to order for television. Considering the popularity of fictional space exploration, weekly broadcasts from the Moon showing newly explored terrain should be suitable for commercial television Inasmuch as the electronic media in recent years have been consistently hostile to NASA, a regular supply of entertaining and profitable material might be an important product of a return to the Moon. Even today, space events are often used to fill air time on slow news days.

Programmatic Flexibility

There is a certain all-or-nothing aspect (e.g., Mars Observer), and a degree of inflexibility, to planetary programs, dictated by distance, launch windows, and travel time. A lunar program can be inherently more flexible. As will be described, there is a continuum of possible lunar missions, starting with the simplest and the cheapest, for which there will be tangible returns at every stage. This has already been demonstrated in the few post-Apollo lunar missions, such as Clementine. From the viewpoint of budget projections, a lunar program is much more resilient. Pending multiyear assured funding, a dim prospect, we must assume the possibility of budget cuts in the future caused by uncontrollable factors such as natural disasters and wars. This actually happened at the end of the Apollo Program, yet the Apollo technology and hardware could be redirected with dwindling budgets to the Skylab and Apollo-Soyuz programs, both highly productive in their own right (Appendix A). The program to be outlined is *compartmentalized;* even if stopped with establishment of a robotic lunar observatory, it would be scientifically productive. This compartmentalization also will help insure against single mission failure of the Mars Observer type. The LLO Program is Shuttle-independent in all but the penultimate stages, and the much-feared "next Challenger" should not stop the LLO . On a more optimistic note, with public support the proposed program could be open-ended, leading even to a self-supporting and perhaps politically independent lunar commonwealth. One of the main recommendations of the "Augustine committee" was that Mission from Planet Earth be open-ended, "tailored to match the availability of funds." A properly designed lunar program, combining manned and robotic missions (e.g., Duke et al., 1985), can do this.

Immunity to Technological Obsolescence

Somewhat related to programmatic flexibility is the near-certainty that the LLO Program could not be made suddenly obsolete or unnecessary by unexpected scientific or technological developments. A well-known example is the concept of a manned geosynchronous satellite, proposed by Arthur Clarke in 1945 as a communications relay. As Clarke himself has pointed out (1984), he assumed the use of vacuum tube technology, implying the need for human attendants for maintenance. This concept was made obsolete in about 3 years by development of the transistor and later its incorporation in integrated circuits. Other examples abound. The point here is that although individual instruments will generally become obsolete, a Lunar Limb Observatory collectively could never become so. The location and characteristics of the Moon, previously discussed, are unique in the solar system. Even more fundamental is the nature of astronomy: study of the external universe. The static universe of Newton, and until the 1920s even of Einstein, has long since been discarded. Star formation, supernovae, variable stars, and planetary atmospheres are dynamic even on a human time scale. Astronomy can no more be completed than can compilation of weather maps. Most fundamental of all is, of course, the inconceivable *number* of objects to be studied: millions of galaxies, each with comparable numbers of stars. Astronomy from the Moon can be considered a never-ending enterprise, inherently immune to obsolescence.

Dispersal of the Species

There has been no detection of extraterrestrial intelligent life even after some three decades of radio wavelength monitoring, despite the growing evidence that planets are abundant in the universe. One likely explanation, emerging from the terrestrial geologic record, is that intelligent life does not survive very long , either from uncontrollable natural events such as asteroidal impacts or from self-destruction by environmental degradation (Lowman, 1985). The danger from major impacts is now becoming fully realized for several reasons: the continuing discovery of large impact craters on the Earth (see volume edited by Dressler et al., 1994), the asteroid search by Eugene and Carolyn Shoemaker, showing that the Earth is *in* an asteroid belt, and the frightening spectacle of the multiple impacts of comet Shoemaker-Levy 9 on Jupiter. Such events may destroy civilization if not the human species, unless measures are taken to disperse our genetic pool and our accumulated knowledge. The most promising candidate for a dispersal site is unarguably Mars, which is not only marginally habitable now but possibly suitable for terraforming (Zubrin and McKay, 1992). In terms of third millenium technology, this would be hardly more difficult than the centuries-long reclamation of the Netherlands from the North Sea. Establishment of a human settlement on the Moon would be a practicable first step to eventual colonization of Mars or, in the O'Neill (1975) concept, of space itself. A lunar program can be justified in the most fundamental possible terms as the first premium in an insurance policy for the human species.

Summary

The value of the Moon relative to the planets as a focus for future NASA programs can easily be answered by pointing out that the Moon *is* essentially a planet, the closest one to the Earth. It is, and historically has been, the logical starting point for exploration of the solar system, as agreed upon by dozens of studies carried out during the past 35 years (e.g., Duke et al., 1985, and others in Mendell, 1985). The 1994 ESA Declaration (Figure 13) underlines this point. Continued lunar exploration is inherently worthwhile for study of several major scientific problems, and its value as a base for astronomical exploration of the solar system and in fact the universe has been demonstrated beyond reasonable doubt. Most fundamental of all, the Moon represents a convenient and accessible starting point for dispersal of the species beyond the Earth, a measure whose necessity is becoming clear if civilization is to have a long future. A well-planned lunar exploration program could arouse and sustain public interest by frequent robotic surface exploration traverses, and robotic telescope observations, in which members of the public -- students in particular -- could take part themselves. Such a program should be evaluated not as a competitor with planetary and other solar system programs, a problem discussed by Sagan (1989) but as a *fundamental first step* in a renewed program (Schmitt, 1992) or "Mission to the Solar System."

Program Objectives

Specific objectives of the proposed program can be conveniently summarized in roughly chronological order, although these stages will generally overlap.

1. Site Selection

A near side site is chosen for reasons of simplicity, cost, and safety. Preliminary studies (Appendix B) have indicated the suitability of the north east

Orientale Basin, specifically the central peak of the crater Riccioli (Figures 18 and 19). Auxiliary robotic observatory sites are recommended for the east limb, near M. Smythii, and the North and South Poles (Figures 16, 20, and 21). A first objective must be to estimate the surface properties and environment of the Riccioli site and, if necessary, to select a different one for the initial landings.

2. Establishment of a Robotic Lunar Observatory

As outlined in Appendix B, a highly capable robotic or remotely controlled lunar observatory complex could be emplaced with a relatively small number of launches. This instrument complex would be designed for indefinite untended operation, but could serve as the nucleus for an extensive human-tended observatory, the ultimate LLO in the Orientale area. The east limb and polar limb sites would be established after the main LLO.

3. Regional Surface and Subsurface Exploration

The NE Orientale Basin, centered on Riccioli Crater, includes a wide range of geologic features, as discussed in Appendix B. A major objective of the LLO Program is to carry out a series of surface traverses, to investigate the structure of Riccioli and Grimaldi, the Orientale ejecta blanket, and to the extent possible the composition and age of the far side crust. Resource exploration and evaluation would be an important part of this objective.

The Riccioli area is within continuous line of sight from Earth, subject to local terrain obstacles, and remotely controlled lunar rovers and telescopes dedicated to student projects could be supported by the LLO Program. This support would include data relay and transmission to Earth and, if necessary, use of telerobotic lunar rovers (TLR) to aid student vehicles or instruments in difficulty.

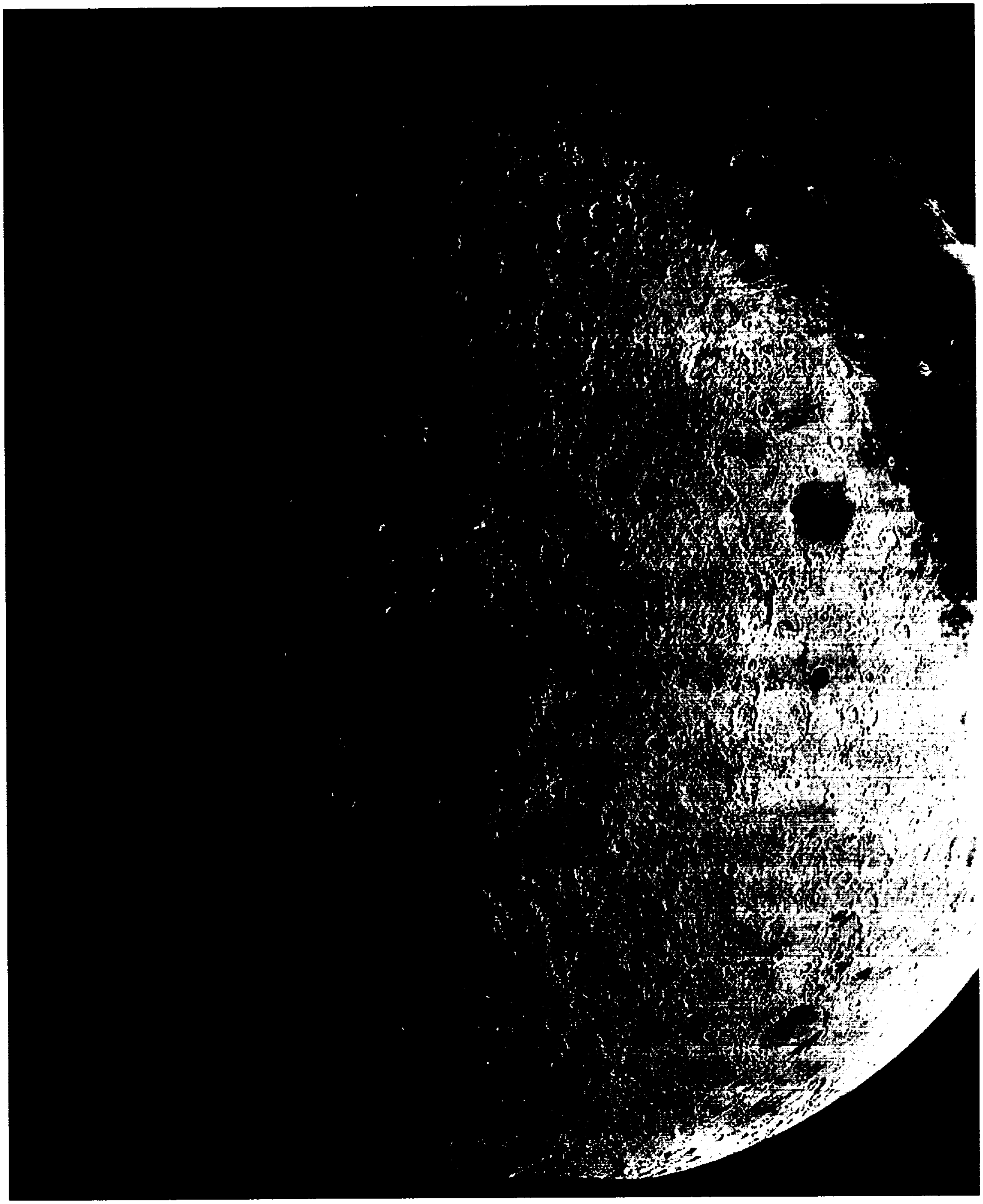


Figure 18. Orientale Basin; north at top, Earth to right. Lunar Orbiter photo. Left arrow points to Riccioli; one at extreme right, to Reiner Gamma.

Figure 19. Riccioli Crater (upper right). Single framelets 12 km wide. Lunar Orbiter photo.

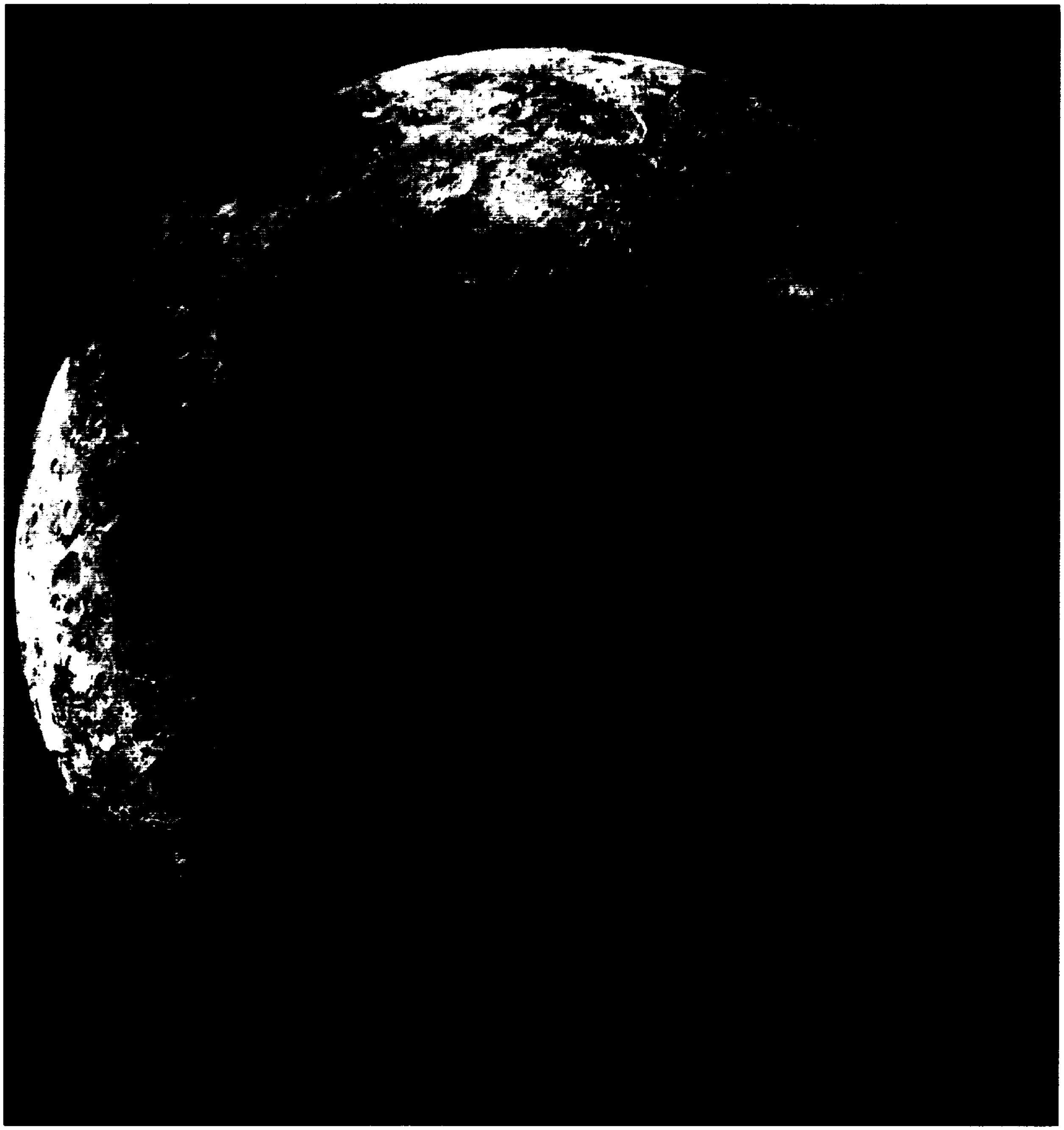


Figure 20. East limb of Moon; north at top, earth to left. Mare Smythii left center. Apollo 16 metric camera photo.

Figure 21. North polar region of Moon; arrow head on North Pole, in crater Peary. Mare Serenitatis bottom center. Lunar Orbiter photo.

4. Exploration Technology Research and Development

An early phase of robotic lunar operations could be automated oxygen extraction, as proposed by Joosten (1993), on at least a pilot plant basis. In addition, the lunar surface would provide a natural proving ground for vehicles, instruments, power supplies, and other components of an eventual manned Mars program. There are obviously environmental differences, such as the presence of a Martian atmosphere and the stronger surface gravity on Mars. However, operation of TLRs and robotic telescopes on the Moon would be invaluable preparation for use of similar devices on Mars.

5. Establishment of a Manned Base

This objective would be a major accomplishment itself if achieved, but is considered in this paper as a precursor to a permanent human settlement on the Moon. It would involve the first post-Apollo manned lunar missions, and could be accomplished in one proposed concept with existing launch vehicles and minor modifications of Apollo vehicles. Conceptual plans for Saturn-based modular lunar bases were developed in the 1960s (Johnson and Leonard, 1985), and modernized versions of such bases using space station modules or inflatable structures should be feasible.

6. Establishment of a Permanent Lunar Settlement

Building on the initial manned base, it should be possible within 20 years, i.e., by 2016, to construct a nearly autonomous settlement with a permanent (or if necessary for health reasons, periodically rotated) population. The feasibility of this objective will depend largely on success in several specific subobjectives, such as development of closed ecology life support systems and achievment of economic viability through lunar exports of energy or material to Earth or near-Earth space. It is stressed that this permanent settlement is not proposed as the final program, but as a step to the colonization of Mars.

Program Description

The Lunar Limb Observatory Program can best be described by stages corresponding to objectives as just summarized. It will be obvious that this description is a qualitative outline of detailed studies that would have to be done if all or part of this program were to be carried out. Furthermore, the later stages of the LLO would depend heavily on the results of earlier ones, and hence can not in principle be described at this point.

Stage 1: Site Selection and Certification

All previous studies of post-Apollo lunar programs assumed the need for a precursor orbital reconnaissance, unless future landings were to be at an Apollo site. However, the Clementine mission has probably produced good enough imagery , when used in combination with Lunar Orbiter, Apollo, and Galileo data, to permit fairly firm site selection.

This stage has already begun, starting with a 1990 site selection workshop at Johnson Space Center. This workshop (Morrison, 1990) considered six candidate sites for future manned lunar missions. It was assumed that lunar-based astronomy would be a major function of such missions, and that only one site could be selected. Given this constraint, and assuming the requirement of seeing the entire celestial sphere, only two general areas were recommended: M. Smythii (Spudis et al., 1989) and Riccioli (Appendix B). Contrary to popular belief, a far side site is not needed for astronomy, with the exception of very low frequency radio astronomy (Burns et al., 1989) and high-sensitivity searches for extraterrestrial intelligence (SETI). A near side site is overwhelmingly favored for several reasons. Communications, command links, and data transmission are greatly simplified, with no lunar communications satellite required. The feasibility of direct rover-Earth communications without even a lunar surface relay has been shown by Bapna et al. (1995). A final basic argument for near side missions is that this side is already fairly well-known, and can be further studied from Earth.

For reasons summarized in Appendix B, the central peak of Riccioli (Figure 19) is recommended here as the first choice for the main LLO, subject to further investigation. However, assuming that the ultimate objective of Moon-based astronomy is the ability to observe any celestial object at any time, or for any desired continuous time, small specialized robotic observatories at the east and polar (N and S) limbs should be established.

Site investigation should have the following main steps:

(a) **Detailed analysis of available data**: study of Lunar Orbiter, Apollo, Clementine, and Galileo imagery; reduction of already-acquired Arecibo radar data. Study of data from Lunar Prospector when available, concentrating on the Orientale Basin area.

(b) **Earth-based studies of Riccioli area**, by radar and reflectance spectroscopy.

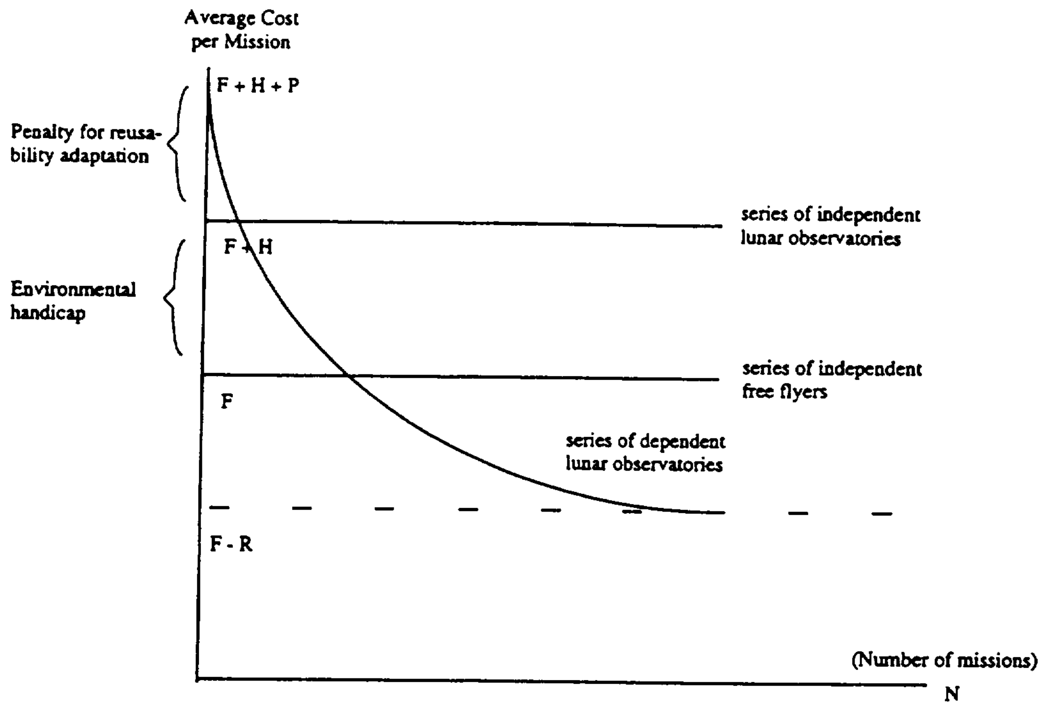
(c) If desirable, specialized study of Riccioli area with Earth-based telescopes.

(d) **Study of available coverage, and that from Lunar Prospector, of auxiliary sites**: M. Smythii, N and S poles.

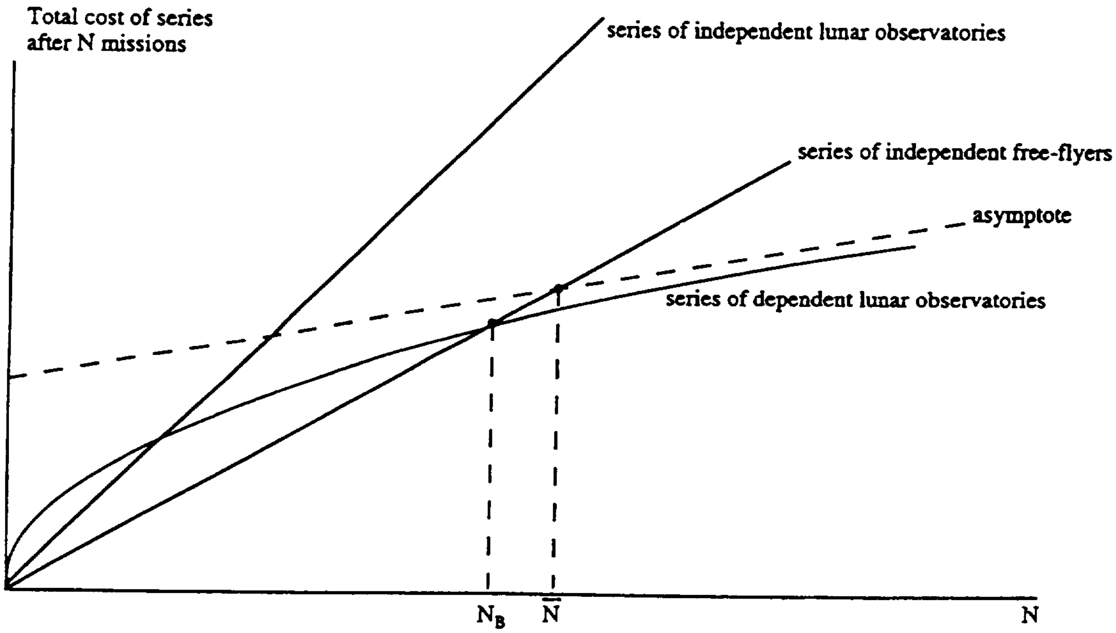
The final site certification will be accomplished by actual landings and surface examination at the various locations, Riccioli in particular.

Stage 2: Emplacement of a Robotic Lunar Observatory

Assuming no unexpected findings from Stage 1, the first flight missions would be started, with the objective of establishing a versatile robotic observatory complex in the Riccioli area, the LLO proper. An initial series of 5 missions to a single site is proposed, using an expendable launch vehicle. The strategy of multiple missions to a single site, a form of "reusability" in the term proposed by McLaughlin (1996), should lead to major improvements in economy, efficiency, and scientific performance (Figure 22). The Surveyor missions used the Atlas-



If assets from previous lunar observatories can be (partially) reused by subsequent observatories, the cost per investigation will decrease. The curves are idealized in many ways including, for convenience, representation of the reusable case by a smooth curve rather than a chain of step functions. The horizontal asymptote accounts for the facts that there are always costs associated with a mission and that emplaced assets eventually break down or become obsolete.



Integration of the curves of Figure 1. The point N_B is the "break-even" number; if N_B or more partially reusable missions are flown, the total cost for the series will be less than for a similar series of independent free flyers. See equation (8) for $\overline{N}$.

Figure 22. Cost benefits per mission and total costs from "reusability" approach for lunar observatories (McLaughlin, 1996).

Centaur. However, a Delta II can put 1200 kg into an escape trajectory, and was proposed for the Johnson Space Center Common Lunar Lander,the University of Wisconsin INTERLUNE-One, and the University of Hawaii Pele. The Delta II is therefore proposed for initial LLO missions. The discussion will assume the use of American equipment, but international participation should be welcomed. Russian launch vehicles and landers, as proposed by International Space Enterprises in cooperation with the Lavochkin Association, could carry out a comprehensive robotic lunar program.

Mission 1: Telerobotic lunar rover (TLR-1) to the Riccioli mare area. Examples of the sort of vehicle needed are shown in Fig. 23, 24, 25, and 26 although a manipulator would be required if the rover is to emplace instruments. A similar concept, designed specifically for lunar exploration, has been outlined by Taylor and Spudis (1990). Objectives are to carry out surface investigations of terrain trafficability and workability, to certify the site for the LLO. A landing beacon (radar transponder) would be emplaced at the most suitable site for return landings. A small test telescope of the 1 meter class comparable to the Dedicated Astronomical Research Telescope (DART) proposed by Sykes et al. (1990) would be emplaced. As previously discussed, use of lightweight materials should permit instruments of this size to be built with weights under 40 kg. After these operations, the TLR would be used for surface exploration as long as possible. Solar power is assumed for the TLR, which should be designed for modular replacement of malfunctioning parts either by another TLR or eventually by LLO personnel.

Mission 2: Second TLR to the Riccioli mare site. Objectives are to begin emplacement of the instrument complex, possibly starting with telescope pairs to test the optical interferometer concept (e.g., Burke, 1990; Cutts and Swanson, 1990). Alternatively, mobile telescopes with the same function, as proposed by Labeyrie and Mourard (1990), would be landed. Following these operations, TLR-2 would extend the surface investigations begun by TLR-1. A wide range of analytical instruments is available, for physical, chemical, and geophysical traverse studies, such as those proposed for INTERLUNE-One (Table 6). The selection of rover payloads would be beyond the scope of this paper. However, it is worth stressing that progress in microelectronics and related technology permits use of far more capable and versatile instrument complements for surface investigation than carried by the landers and rovers of the 1960s and 70s.

Mission 3: Third TLR to Riccioli mare site. Objectives are to continue emplacement of instrument complex. Likely candidate payloads for TLR-3 are additional optical interferometer elements. Following these operations, TLR would continue surface investigations. By this time, the Riccioli area should be fairly well known, and longer range traverses, such as east to the Marius Hills and Aristarchus Plateau, could be undertaken.

Mission 4: Fourth TLR to Riccioli mare site. Additional instruments would be emplaced. Likely candidate payloads for TLR-4 would be elements of a submillimeter interferometer array (Cutts and Swanson, 1990). At this stage, maintenance or modification of previously-emplaced instruments or TLRs might be needed, and the manipulator on TLR-4 could be used for this function. Afterward, further long-range exploration could be carried out. A possible activity would be the start of westward traverses toward the limb and eventually the far side, carrying out initial exploration of the Orientale Basin deposits (Spudis et al., 1984) and beginning emplacement of a chain of radio relay towers for communication with TLRs beyond line of sight with Earth.

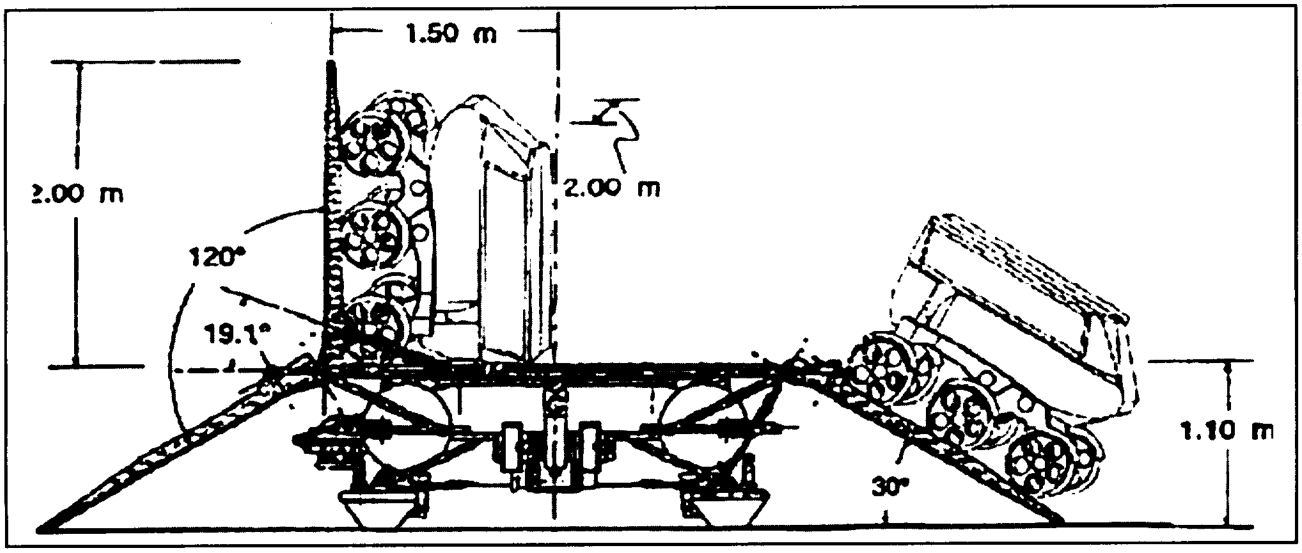


Figure 23. Lander module, designed by Robotics Institute, Carnegie Mellon University (Katragadda et al., 1995)

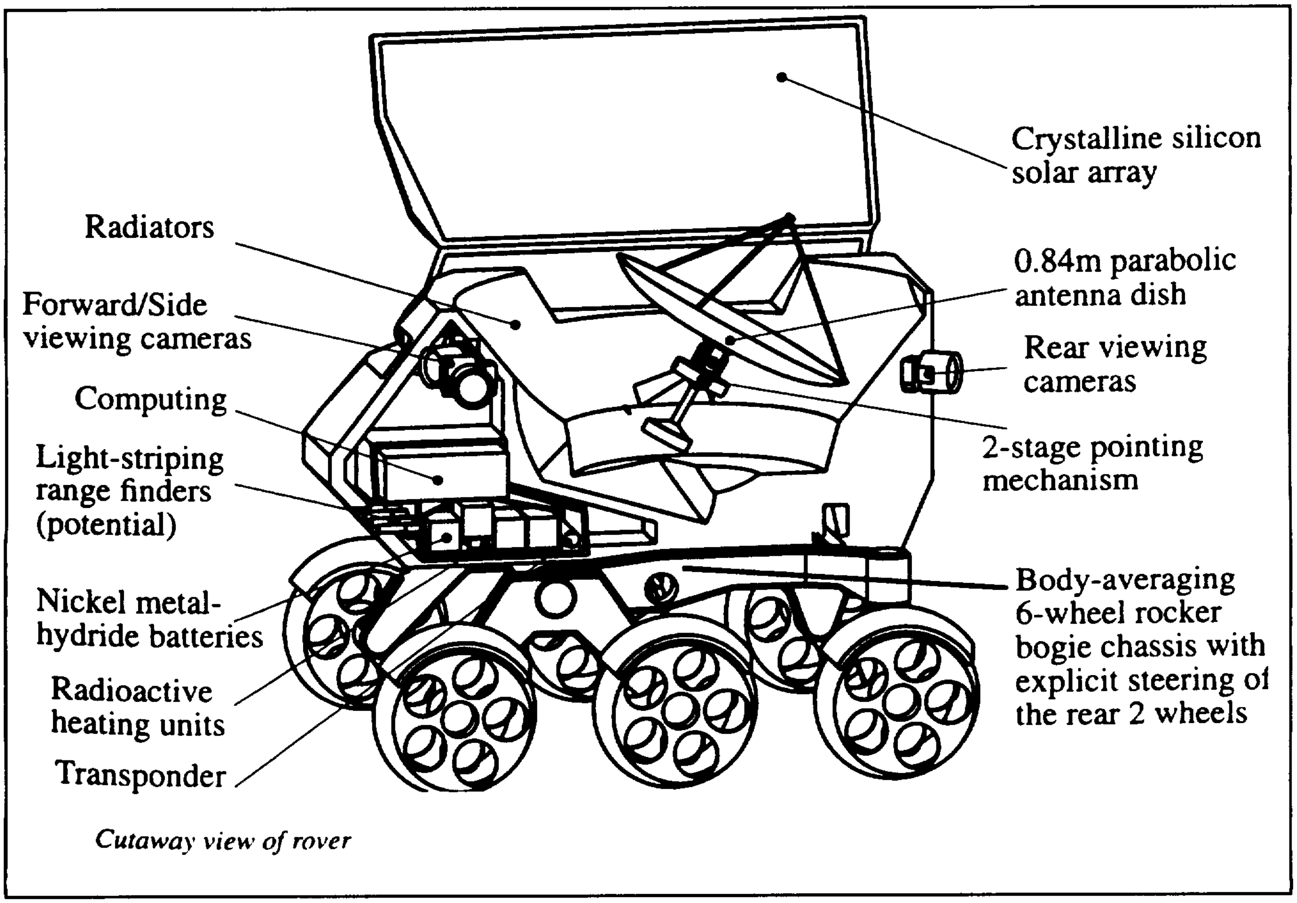


Figure 24. Telerobotic lunar rover designed by Robotics Institute, Carnegie Mellon University (Katragadda et al., 1995).

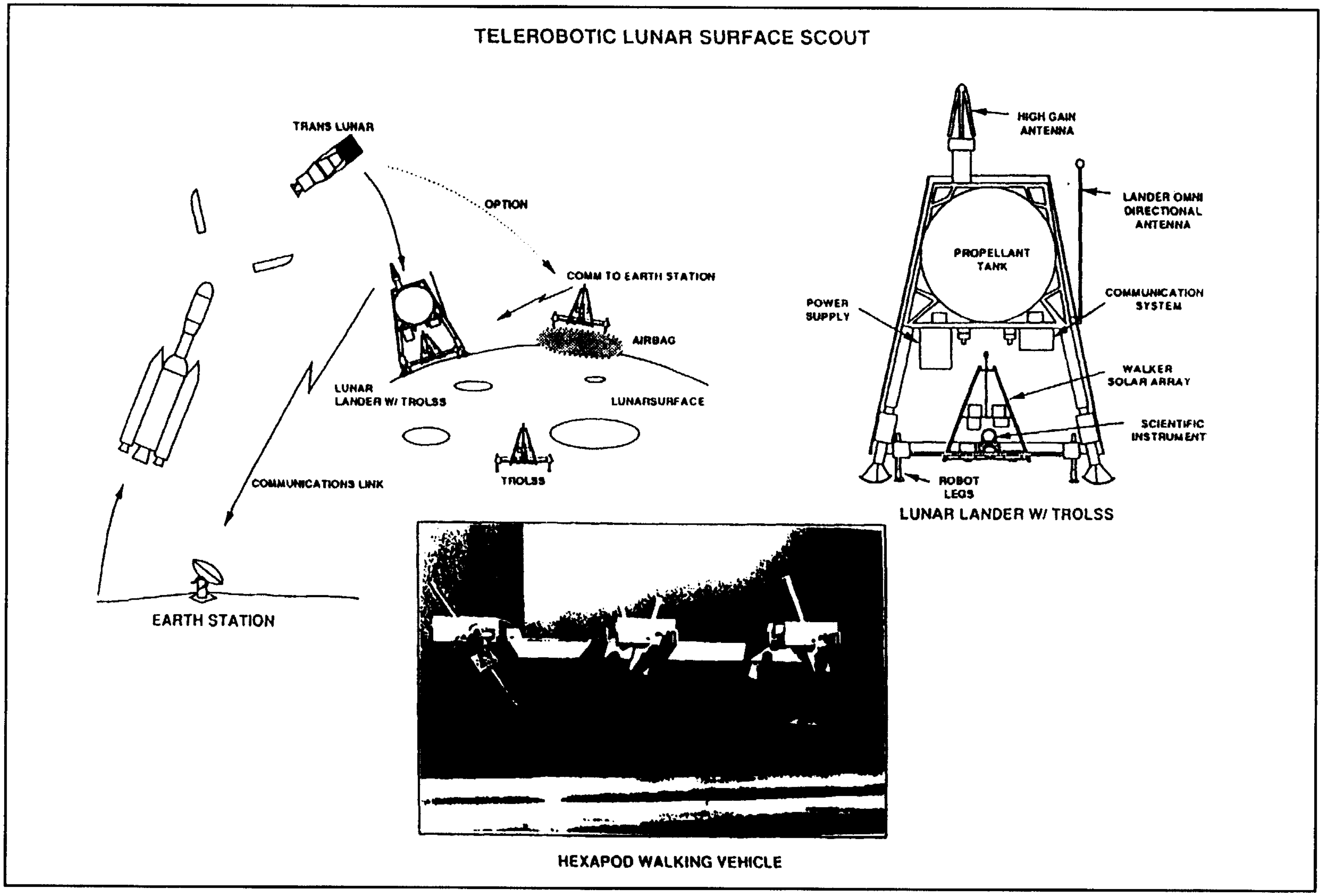
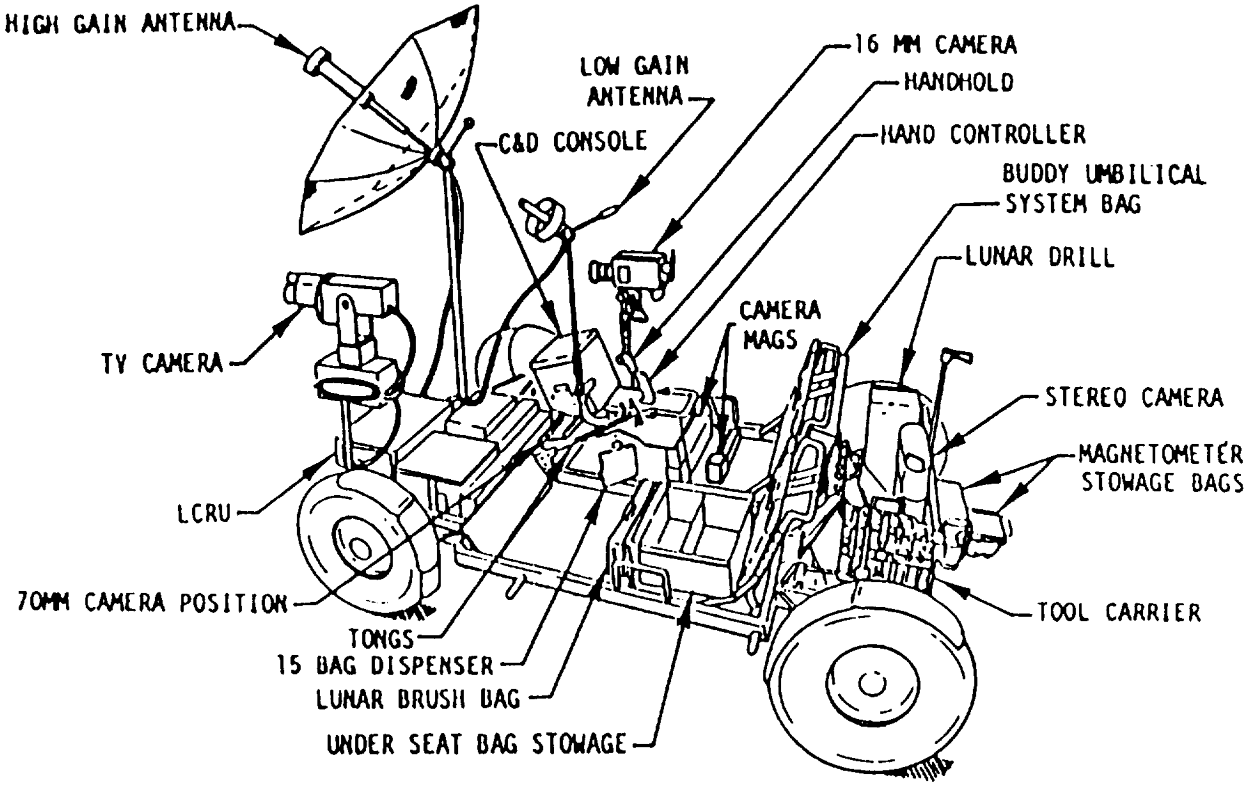


Figure 25. Telerobotic Lunar Surface Scout. from presentation to Lunar Exploration Science Working Group, S. Ollendorf, 1991. Hexapod walking vehicle built by Case Western Research University.



SUGGESTED MODIFICATIONS TO LUNAR ROVER FOR CONVERSION TO REMOTE CONTROL

Remove:
- **Seats**
- **Lunar Drill**
- **Tool Carrier**
- **Hand Controller**
- **70mm Camera Position**

Add:
- **Solar cell array**
- **Remote control attachments**
- **Traverse science instruments:**
  - **e.g, GRS, XRF, TV**
- **Emplaced science instruments**
  - **e.g., seismometers**
- **Manipulator arm**

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Figure 26. Possible modifications to Boeing Lunar Rover, for conversion to telerobotic operation.

Table 6. Proposed Science Payload, INTERLUNE-One

(Fusion Technology Institute, University of Wisconsin)

Surface and Atmospheric Properties Study

Volatiles Extraction System: extraction of solar wind volatiles from the lunar regolith

Ion Mass Spectrometer: analysis of solar wind volatiles and major elements of the regolith, and analysis of the lunar atmosphere

Surface (R) Wave Analyzer: analysis of regolith structure and physical properties

Imaging/Spectroscopy Systems: multispectral and stereo examination of the regolith; imaging of horizon glow

Backscatter Mossbauer Spectrometer: analysis of regolith maturity and iron mineralogy

Laser Ablator: in situ analysis of regolith composition

Dust and Micrometeoroid Detectors: analysis of regolith formation and dust transport

Moon-based Observations

UV-Visible Spectrum Telescope: astronomical study of solar system, stellar, and galactic phenomena; analysis of horizon glow, dust deposition

Cosmic Ray Telescope: monitoring of cosmic ray flux and albedo

Mission 5: Fifth TLR to Riccioli mare site. Additional instruments TBD would be emplaced, after which more surface traverses toward the west limb and possibly beyond would be carried out. Additional RF relay towers would be emplaced.

Summary

By the end of this five launch program, a versatile robotic lunar observatory complex should be functioning. The strategy of this program is to build up a network of mutually supporting instruments, and a motor pool, so to speak, of TLRs, by returning again and again to one site. The infrastructure for future operations would also be under construction: landing beacons or other navigational aids, the beginning of a chain or net of radio relays for command and communication to the far side, and even minor road preparation. The effectiveness of this strategy should increase exponentially with the number of landings because of the synergistic effect. At the same time, intensive exploration of an area with examples of all major types of lunar structure and lithology (Appendix B) should permit construction of a detailed and accurate model of the lunar crust and its evolution, comparable to the Canadian Lithoprobe transects. The detailed sequence of operations laid out here is obviously tentative and subject to major alteration, but would go a long way toward utilizing the Moon as a base for observation and as an object of exploration. Even if the program were to be stopped after Mission 5, it would represent a major achievment. However, it is intended as only the beginning.

Stage 3: Opposite Limb Missions

A single equatorial observatory site can observe a given celestial object for no more than 14 days at a time, and at least one auxiliary site on the eastern limb is necessary. Furthermore, polar sites permit unlimited observing times for the corresponding celestial hemispheres, analogous to South Pole sites on Earth but not limited by daylight to half the year.

For programmatic continuity and economy, the same mission mode, based on the Delta II , would be used. A series of seven launches would be carried out, as follows.

Mission 6 and 7: This phase would begin with two TLRs landed in or near Mare Smythii (Figure 20), the other site picked as most promising for lunar astronomy by the 1990 JSC study (Morrison, 1990). The first landing, TLR-6, would carry a landing beacon, a single telescope of the 1-meter DART type, and a wide range of geochemical and geophysical instruments. Its first function would be to emplace the beacon and telescope, thus laying the foundation for future missions to this site. TLR-6 would then begin surface exploration of Mare Smythii, shown by P. D. Spudis to be of geologic interest as one of the oldest mare basins. TLR-7 would land at the same site, homing in on the beacon, and carry out similar functions. However, an underlying objective of Mission 7 would be to back up Mission 6, in case of total failure or problems encountered once on the surface.

Missions 7, 8, and 9: The South Pole of the Moon is at present under intense study because of the unconfirmed finding by Clementine of possible ice deposits in the surprisingly large permanently shaded area (Figure 16). This area is topographically rugged and more challenging to land in than the maria. Consequently, three missions are considered the minimum to accomplish the objectives. These are, first, to emplace astronomical instruments near the south pole, to take advantage of the unlimited exposure times for the south celestial sphere and the low temperatures in shaded craters (Burke, 1985). Candidate instruments might include a DART or a thermal infrared telescope. Because of the topography and latitude of the area, emplacement of radio relay towers for transmission of data from the TLRs and emplaced instruments to Earth may be necessary. After emplacement of the instruments and relays, the TLRs would be dedicated to surface exploration.

Missions 10 and 11: The lunar North Pole (Figure 21) shares general astronomical characteristics with the south pole, providing permanently shaded areas (though much less than the South Pole) and access to the celestial hemisphere for unlimited times. Advantages of a north polar site for a base have been discussed by Burke (1985). The relief appears significantly less than around the south pole, expressing the greater proportion of mare basalts. Accordingly, two TLR landings are recommended. They would carry out basically the same functions as the South Pole TLRs 7, 8, and 9, beginning surface exploration of indefinite duration after emplacing instruments, relays, and the like.

Summary

The seven missions of Stage 3 are inherently more risky than those to the main LLO site at Riccioli. Those to the poles will be visiting parts of the Moon barely visible from Earth and not covered by the Apollo orbital surveys, unlike Mare Smythii. The south polar regions are pure highland terrain, and their unique characteristic -- large shaded areas -- presents obvious problems of thermal control, solar power availability, and communications with Earth. However, if the problems can be overcome, by the end of Phase 3 we will have emplaced basic instruments at widely separated sites that collectively will permit us to observe any celestial object at any time, and to observe most objects with unlimited exposure times. What the surface exploration traverses will discover, especially at the south pole, is essentially unknown. The equatorial parts of the Moon are largely familiar terrain, easily observed from Earth. The poles, in contrast, are true unknown territory, and should be even more exciting to explore.

Stage 4: Lunar Base Establishment

This phase will be the long-awaited return to the Moon by humans, which has been advocated as we have seen by every serious study of post-Apollo programs. It was proposed in 1989 by President Bush that we go back to the Moon, "this time to stay," a proposal leading to the unfulfilled Space Exploration Initiative (SEI) of the early 1990s. Reasons for expiration of the SEI will not be discussed here (see Pike, 1993) but it should be pointed out that a resumption of manned lunar missions will emphatically not be Apollo II, so to speak. (Since women routinely fly on NASA space missions, euphemisms for "manned" will not be used.)

A valuable report, Exploring the Moon and Mars, was published by the late Office of Technology Assessment in 1991. Useful though it was, this report grouped the Moon and Mars, giving the unconscious impression that a return to the Moon would be an extremely ambitious and expensive undertaking. The term "Apollo II" would be similarly misleading; the lunar base phase outlined here might cost less than Apollo if allowance is made for inflation. The reasons for this are that the Apollo costs included construction of launch facilities and new space centers, expansion of the NASA tracking network, and, of course, development of an entire new technology -- launch vehicles, spacecraft, life support systems, and much more. We still have all these things, or at least the knowledge to build them. A new Apollo Program is simply not needed, as brought out at the 1993 Low-Cost Lunar Access meeting . A conservative cost estimate by Sellers and Keaton (1985) put the cost of a permanent lunar base at $100 billion over 25 years, compared with $80 billion over 11 years for the Apollo Program (in 1984 dollars; see Appendix A for the actual cost). A further comparison is the 1994 cost of the federal Food Stamp Program, $25.5 billion (The World Almanac, 1996).

Turning to specifics, it has been shown by Bialla (1993) that a return to the Moon, putting crews on the surface for up to 3 weeks, would be possible with a 7 year program. The basis for this plan is maximum use of existing or slightly modified launch vehicles and spacecraft, as outlined in Figures 27 and 28, in particular, the Shuttle and a Titan-Centaur combination. The basic mission mode is a dual launch, with the Shuttle carrying the astronauts, lunar excursion vehicle, and payload. After rendezvous and docking with the Centaur, the Centaur is used for trans-lunar injection. Bialla presented a sample manifest for early missions (Figure 29), showing the strategy of using the system for landing unmanned payloads first, followed by crew landings. Other approaches are of course possible; Joosten (1993), for example, has suggested use of a Shuttle-derived launch vehicle in combination with Russian vehicles. Carnegie Mellon University proposed a Proton vehicle for their unmanned LunaCorp program, as has International Space Enterprises. Comprehensive phased programs have been outlined by Schmitt. (1992) and Davis (1993).

Bialla's general approach could be applied to the LLO as follows. The sequential numbers are continued to emphasize the incremental but unified nature of the LLO program.

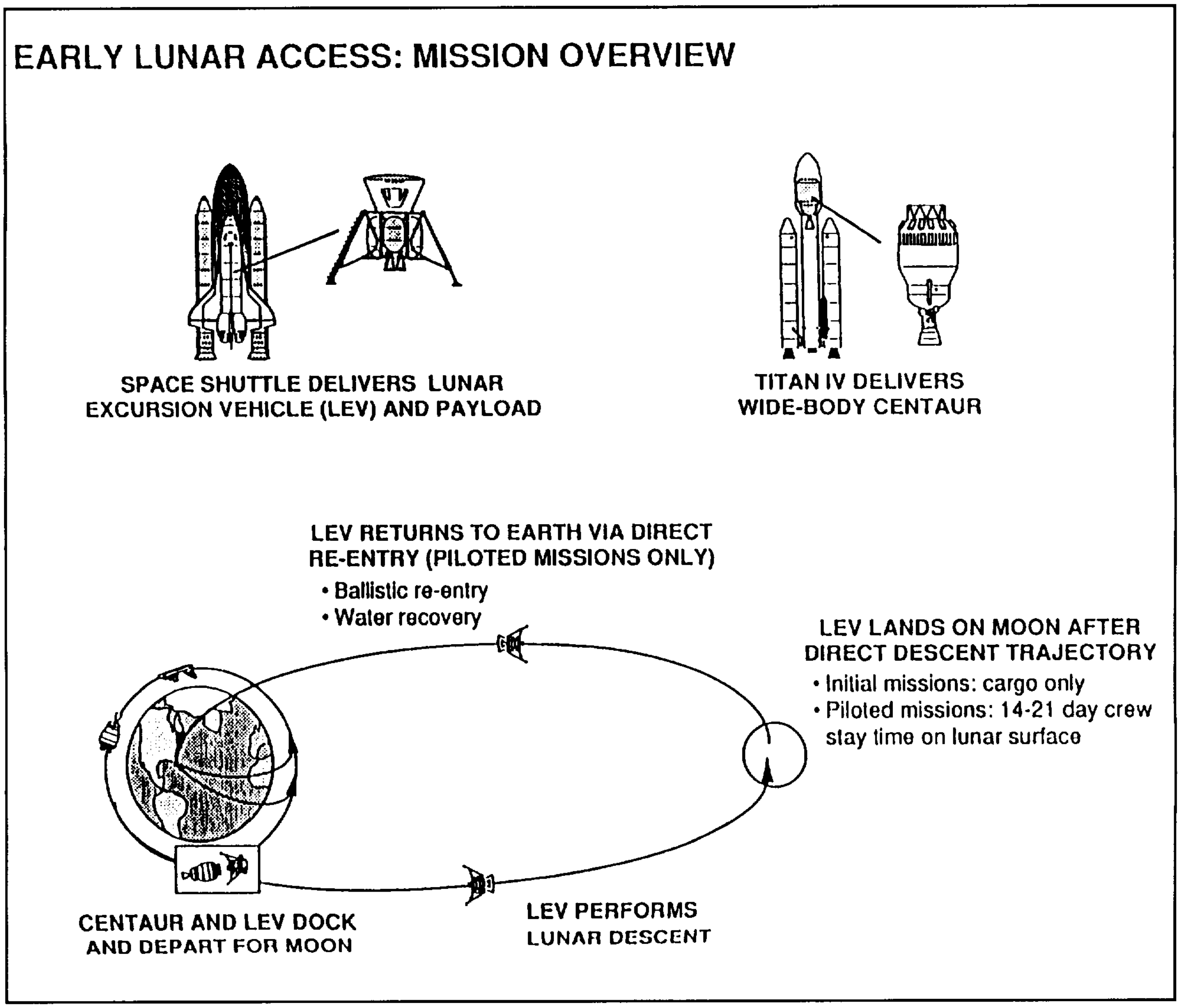


Figure 27. Mission overview, Shuttle/Titan-Centaur concept; from Bialla (1993).

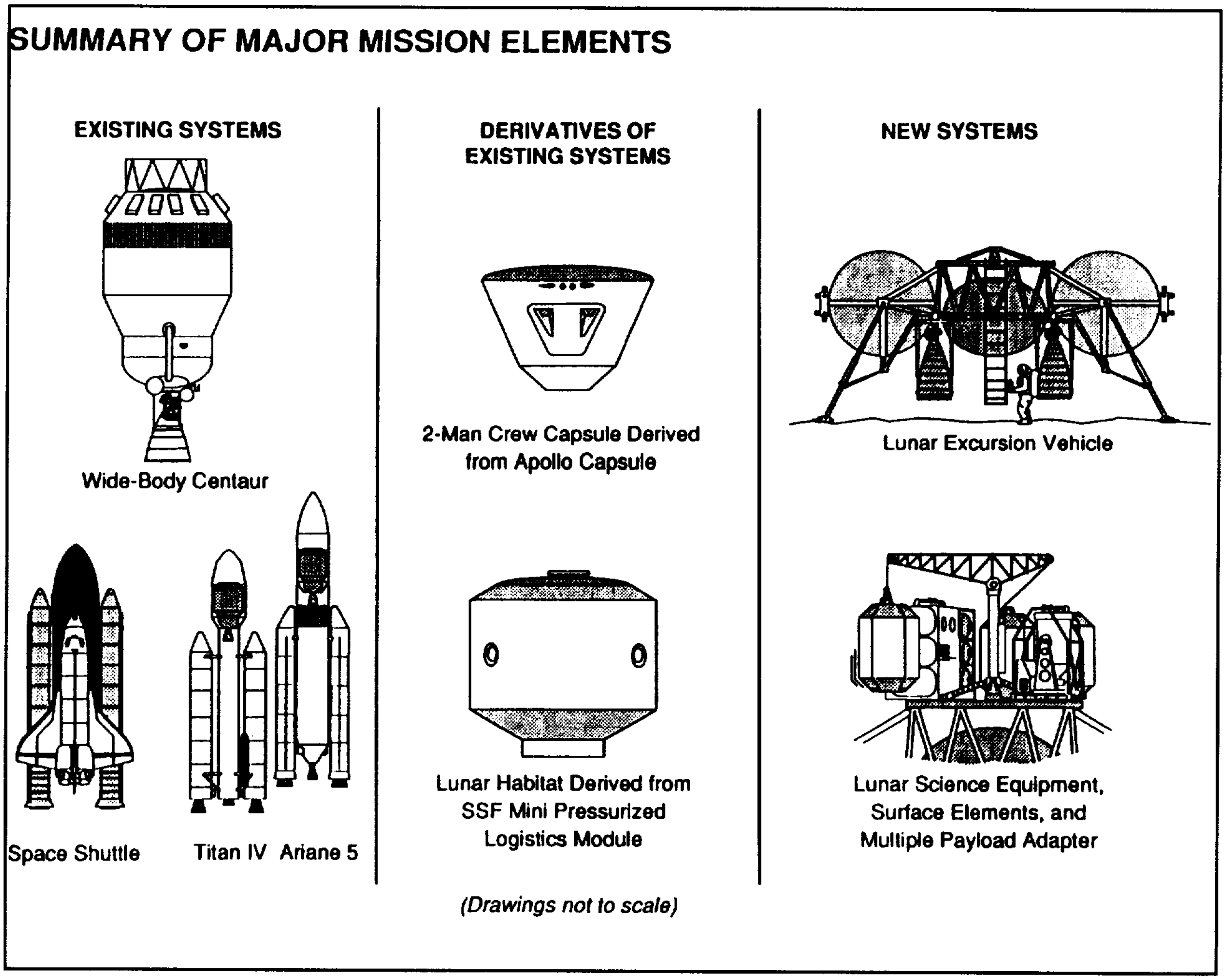
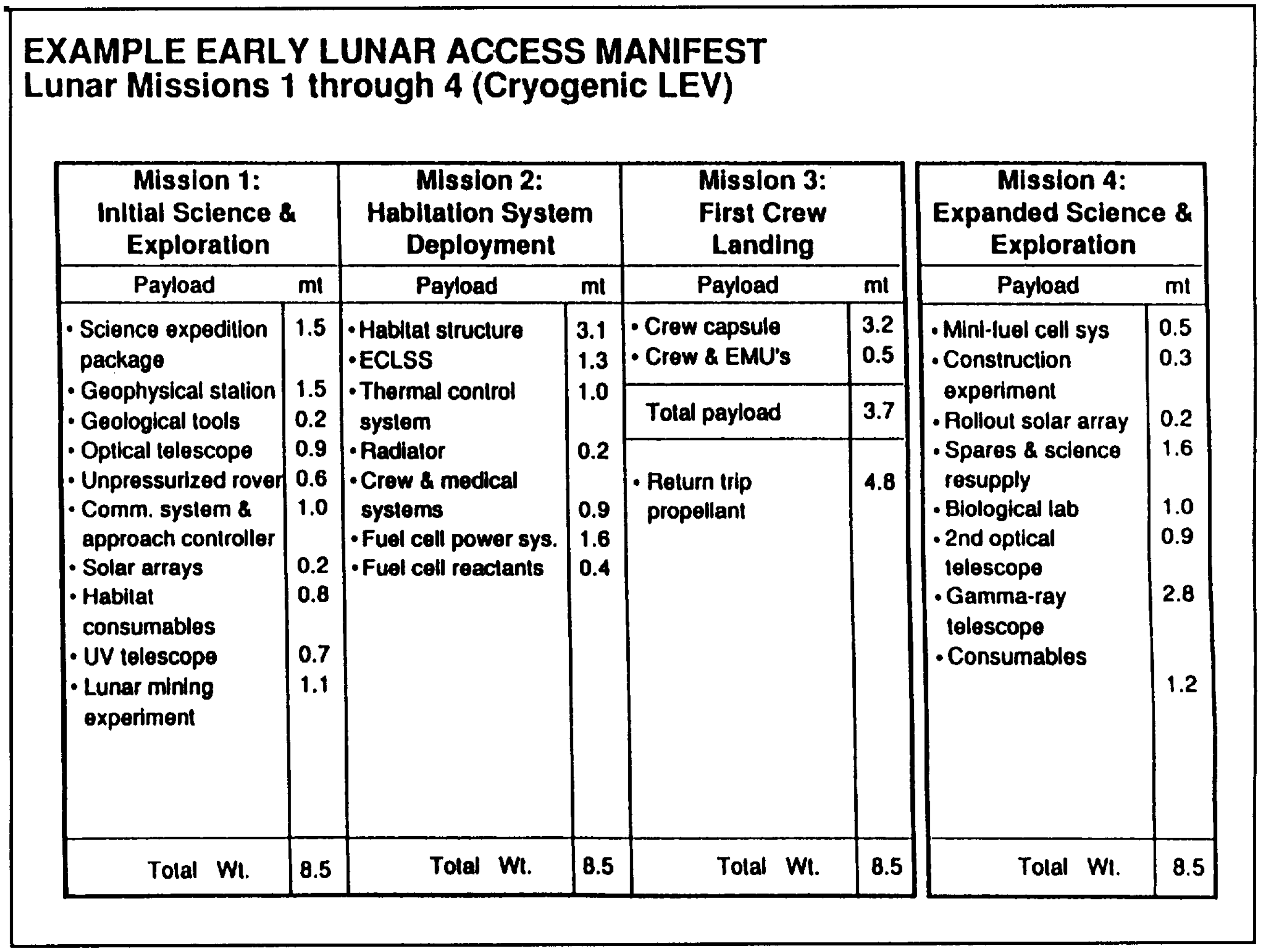


Figure 28. Major mission elements, Shuttle/Titan-Centaur concept; from Bialla (1993).



EXAMPLE EARLY LUNAR ACCESS MANIFEST
Lunar Missions 1 through 4 (Cryogenic LEV)

Mission 1: Initial Science & Exploration		Mission 2: Habitation System Deployment		Mission 3: First Crew Landing		Mission 4: Expanded Science & Exploration	
Payload	mt	Payload	mt	Payload	mt	Payload	mt
• Science expedition package	1.5	• Habitat structure	3.1	• Crew capsule	3.2	• Mini-fuel cell sys	0.5
• Geophysical station	1.5	• ECLSS	1.3	• Crew & EMU's	0.5	• Construction experiment	0.3
• Geological tools	0.2	• Thermal control system	1.0	Total payload	3.7	• Rollout solar array	0.2
• Optical telescope	0.9	• Radiator	0.2	• Return trip propellant	4.8	• Spares & science resupply	1.6
• Unpressurized rover	0.6	• Crew & medical systems	0.9			• Biological lab	1.0
• Comm. system & approach controller	1.0	• Fuel cell power sys.	1.6			• 2nd optical telescope	0.9
• Solar arrays	0.2	• Fuel cell reactants	0.4			• Gamma-ray telescope	2.8
• Habitat consumables	0.8					• Consumables	1.2
• UV telescope	0.7						
• Lunar mining experiment	1.1						
Total Wt.	8.5	Total Wt.	8.5	Total Wt.	8.5	Total Wt.	8.5

Figure 29. Sample mission manifests, first four missions; from Bialla (1993).

Mission 12: The first mission in Phase 4 would be an unmanned cargo/shelter payload, landed with transponder guidance at the site selected in Riccioli, presumably on the mare fill. A small version of the "construction shack" proposed by Alred et al. (1989) might be suitable: simply a large integral pressurized cabin with airlock on the lander, which would stay on the Moon. Alternatively, a modified Space Station module might used, a concept dating back to at least the 1970s (Lowman, 1985). Space Station modules are man-rated pressure vessels, and those under construction for the international Space Station are designed with floor/wall/ceiling layouts, unlike the Skylab Multiple Docking Adapter. They should be easily adapted to use on the lunar surface. Still another possibility would be an inflatable shelter, using lunar soil for radiation and meteoroid shielding, as proposed by Alred et al. (1989). Relatively little of the first payload would be science-focussed, since an array of telescopes and instrumented TLRs would already be operating at the LLO site.

Mission 13: The next Stage 4 mission would correspond to the second one in Figure 29, an unmanned payload landed as close as possible to the Mission 13 payload at Riccioli. The actual payload of Mission 13 would depend on the success of the previous mission, detailed plans for the LLO, and other factors that at this point are unknown. However, one specific item should be definitely included, a man-rated unpressurized roving vehicle similar to the Apollo LRV. An interesting possibility would be a dual-mode vehicle, capable of being driven by remote control from the LLO or from Earth, and used as a TLR when the LLO is unoccupied. The Apollo LRV design, weighing only a few hundred pounds, might be modified for telerobotic use (Fig. 26). As a fall-back position, Mission 13 could simply be a duplicate backup for Mission 12 in the event of its failure.

Mission 14: This first manned landing since Apollo 17, despite its historic significance, should be a fairly routine operation: a tested mission mode and spacecraft; a well-known site with ground navigation aids; and a shelter, consumables, and other items ready for use. Although the previously-landed shelter, if not an integral part of the lander, could in principle be deployed robotically, presence of the crew would help ensure its success. It has been demonstrated repeatedly, on dozens of manned missions, that physical manipulation of structures under low or zero gravity is well suited to human ability, and the first landed crew might play a major part in emplacing their shelter. The stay time, 2 to 3 weeks, of Mission 14 would probably be largely taken up in shelter deployment, inspection of previously-emplaced telescopes, collection of rock and soil samples from the TLRs for return to Earth, and similar operations essentially precursory to full base operations.

Mission 15: Assuming success of the first manned return mission, Mission 15 would mark the beginning of regular (though not necessarily continuous) occupation of the lunar base. It can reasonably be asked, given the presumed effectiveness of the robotic telescopes and TLRs, just what essential functions would be left for the base personnel. The following are possible activities.

Surface exploration and sample collection in the vicinity of the LLO. This activity, essentially similar to the Apollo mission EVAs, takes advantage of human vision, real-time judgement, mobility, and manipulative ability. The achievments of the Apollo astronauts, only one of whom was a professional geologist, demonstrated beyond doubt that the human role on planetary surfaces is unique. Petrographic, chemical, and even radiometric analysis of samples at the LLO might increase the effectiveness of surface exploration. Nothing of this sort was feasible for Apollo, because of the short time available. However, LLO occupation and the speed of modern automated analytical methods might make on-the-spot analysis attractive.

TLR operation from the LLO. As suggested by Lowman (1992a), most lunar exploration from a permanent lunar base would be done remotely, with obvious benefits in safety, cost, and efficiency. The possibility of remote control with no time lag at all should significantly increase the effectiveness and versatility of the TLRs. The radio relays previously emplaced, or possibly optical links, should make it possible to carry out TLR operations far from the LLO. The use of telepresence and virtual reality should make it possible to combine uniquely human capabilities -- vision, manipulation, mobility -- with those of robots.

Geophysical instrument emplacement and operation. This category includes activities carried out on Apollo missions, such as drilling and emplacement of heat flow probes, active seismology, gravity wave instrument emplacement, and seismometer emplacment (Strangway, 1985). Such activities could be carried out robotically, but for mechanically complex operations, human assistance is clearly preferable.

Astronomical instrument emplacement, repair, and adjustment. This activity corresponds to the geophysical intrument emplacement previously mentioned, and the arguments for it are the same. One foreseeable operation for which human ability would be well suited is erection of large but light-weight occulting screens for certain of the instruments, such as infrared telescopes or microwave radio telescopes. Comparable activities have been carried out many times in orbit and even to some degree on the Moon (e.g., erection of the Apollo S-band antennas). Antenna and solar panel deployment on unmanned spacecraft has rarely failed, but even one such failure can have major consequences.

Support of student TLR and robotic telescope operations. The presence of trained support personnal at the lunar base should be a major help in vicarious exploration of the Moon and astronomy from the Moon by students. The basic idea is that students themselves could build TLRs and small telescopes, to be carried to the LLO, emplaced, and operated by the students from Earth. It is obvious that student-built hardware would not have the reliability and technical level of professional hardware, but if the LLO staff were able to give direct assistance to the homebuilt equipment it would be most helpful. This assistance might be as elementary as righting an overturned rover, or emplacing a student's telescope.

Technology Research and Development. This would be an extremely broad category of activity. It might include oxygen or He-3 extraction, emplacement of energy collection/transmission equipment, testing of Mars rovers, life support research, and biological experimentation. One possible example of the last-named would be maintenance and study of a small animal colony, with the objective of finding the long-term or multi-generation effects of the lunar environment. A corresponding activity would be lunar farming, perhaps under inflatable greenhouses. The psychological benefits of gardening are well-known, as demonstrated by Soviet space station experience (Oberg and Oberg, 1986), and this activity might be considered recreation as much as research.

Guided Tours of the Moon. To maintain public interest in the LLO, base personnel should be expected to spend an occasional few hours "in the barrel," to use the old Apollo phrase, making TV broadcasts to Earth. These should be much more than news-reading, so to speak, and should include activities such as televised field trips on a lunar rover. Given the success of CNN broadcasts of congressional activities, consideration should be given to having real-time unrehearsed broadcasts of surface exploration sent directly to Earth, complete with heavy breathing and occasional profanity. Such activities should be considered a minimal requirement, given the possible participation of the public itself in lunar exploration as proposed by LunaCorp.

Summary

This paper will not pursue Stage 4 beyond Mission 15. By this time, assuming no major failures, we should have established an effective, safe, and reasonably comfortable lunar base, which could serve as a control and repair center for operation of the extensive network of robotic telescopes and TLRs. Continual occupation of the base would be desirable but not mandatory, just as Skylab was powered down between missions. The lunar environment is a stable one, as shown by the years of operation of the Apollo geophysical instruments (including the laser retroreflectors). The Surveyor 3 spacecraft survived 31 months on the surface with essentially no deterioration. An obvious advantage of Moon-based instruments is that, unlike orbiting ones, they will not go anywhere when not in use. Shelter modules should undergo much less degradation when unoccupied than do comparable shelters in the Antarctic, where wind-blown snow collapses structures in a few years. Given sufficient public support and funding, operation and expansion of the LLO could continue indefinitely, gradually evolving into Phase 5.

Stage 5: Establishment of a Permanent Human Settlement

This phase would of course be the ultimate goal of operations on the Moon, and would represent a major step for the human species, not just NASA or the United States. The timing and size of such a settlement would obviously depend on many factors quite unknown at this time. The economic ones may dominate; although many countries subsidize permanent settlements in Antarctica, economic self-sufficiency is probably necessary for permanent colonization of the Moon. The unhappy experience of Newfoundland serves as a warning; it became necessary for the government to, in effect, close down many small coastal villages, whose isolation and low income made them an insupportable burden. A more encouraging Canadian example is that of Sudbury, Ontario. This city, located on the edge of a supposed terrestrial mare basin (Lowman, 1992b), was originally developed as a one-industry mining town, subject to the customary boom-and-bust cycle (Wallace and Thomson, 1993). Sudbury in recent decades has successfully diversified its economy, stressing tourism. Inasmuch as the terrain is often described by Sudburians as "like the Moon," this example is especially apt.

Relatively few serious studies of the economics of lunar settlement have been published. However, recent presentations by Schmitt (1992, 1994) have summarized income sources and financing for a lunar settlement. Collection of helium-3 is particularly promising, contingent on achievment of controlled nuclear fusion. The present oversupply of oil can not continue indefinitely, and the possibility of anthropogenic global warming argues against major expansion of fossil fuel use in general. These considerations support the use of lunar helium-3, or even the satellite solar power system (whose practicality would depend on use of lunar materials). A theme park, based on telerobotic lunar rovers, has been proposed by David Gump's LunaCorp and, if successful, suggests comparable income sources in the future. When Earth-Moon transportation becomes routine and efficient, tourism should be a major source of income for the settlement. Commercial tourism has been carried out in the Antarctic for some years, yet there are still men alive who remember the days of dog-sled exploration. Less than 20 years after Lindbergh's spartan flight from New York to Paris in 1927, four-engine aircraft were carrying thousands of people a year across the Atlantic in luxury. Given these historical facts, it would be a mistake to consider lunar tourism a program for the distant future.

Summary and Conclusions

A return to the Moon is strongly supported by considerations of value, speed, feasibility, failure tolerance, and economy. The proposed program is austere and conservative , but one that could be expanded if funding permits. It can begin with relatively low cost unmanned missions, emplacing a network of robotic telescopes by means of telerobotic rovers that would then be used for remotely controlled lunar exploration. Even these initial stages of the proposed program would pay off in scientific, educational, and public interest values. However, they could be integrated into a return of humans to the Moon and establishment of a manned lunar base. Existing launch vehicles and upper stages could be used with minor modifications, and the program might cost less, during 20 years, than $100 billion in 1996 dollars. (For comparison: the FY 1995 federal budget was roughly $1.5 *trillion*.)

The benefits of a return to the Moon are familiar ones, including science, education, and technology. But the most fundamental result bears on the long-term survival of the human species, namely the beginning of our dispersal beyond the Earth, known to be vulnerable to major impacts and other uncontrollable external factors. Mars is of course a far more attractive goal for such dispersal, but the Moon is agreed to represent an essential interim stage for the settlement of Mars (Duke, 1988). A renewed lunar program is an initial step to become "a multi-planet species" (Sagan, 1992), and to insure that the Earth will not become "both cradle and grave" for humanity (Clarke, 1993).

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T PLUS TWENTY FIVE YEARS: A DEFENSE OF THE APOLLO PROGRAM

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This paper reviews the results of the Apollo Program, defined as including the Gemini, Lunar Orbiter, Skylab and Apollo Soyuz Test Project as well as the lunar landing missions. It is shown that Apollo contributed to the end of the Cold War as a demonstration of the superiority of democracy, and to improved international relations in general. The scientific return from the Apollo Program included new fundamental knowledge of the Moon, Sun and Earth. The Moon has been found to be a habitable planet with many potential uses, notably lunar-based astronomy. Remote sensing and specifically the Landsat Program were given great impetus by the Gemini 70 mm colour photographs of the Earth. Technology transfer in areas of computers and microelectronics is traceable to the Apollo Program in that its demands greatly stimulated progress in these fields. A general surge of technological progress (including data handling) can also be traced to technology transfer from Apollo. The total cost for the 14 year Apollo Program as defined here was roughly $30 billion dollars, about half as much as the 1975 appropriation for the Department of Health, Education and Welfare.

1. INTRODUCTION

The last Apollo mission to the Moon was flown in 1972, capping a ten year effort that was criticised during the decade as a "mad effort to win a stunt race," [1] a "moon-doggle," [2] and equally harsh terms. Similar evaluations are heard today; Rogers [3], for example, argues that "the civil space area has demonstrably failed to provide a satisfactory direct economic return on the expenditure of over half a trillion dollars (sic)". Inasmuch as new programmes of space exploration, including a return to the Moon, have been proposed, it is worthwhile to present a defence of the Apollo Program in the light of the 20 years since the last lunar landing, of Apollo 17. This paper is the case for the affirmative: that Apollo was worth its cost. It will be restricted to the Apollo Program (as defined shortly) and its results, rather than covering the benefits of American civil space programmes as a whole.

Because an entire generation has grown up since the last Apollo lunar landing, some basic definitions will be helpful. "Apollo Program" has come to mean essentially flags and footprints, a series of lunar landings that returned Moon rocks and some spectacular deep space photos of the Earth. However, the formal Apollo Program was only the central element of a broader effort that included the Gemini, Lunar Orbiter, Skylab and Apollo-Soyuz Test Programs. The Gemini Program, in which the first true American manned spacecraft were developed (with propulsion, rendezvous radar and extravehicular capability), was solely preparation for the Apollo missions. The Lunar Orbiter Program, in which five unmanned photographic reconnaissance spacecraft were put into lunar orbit, was intended for Apollo landing site selection. After the six Apollo lunar missions, a converted Saturn SIVB stage was used for the first American space station, Skylab, with the Apollo Command and Service Modules (CSM) used for crew launch and return. The Apollo Soyuz Test Project (ASTP) involved rendezvous and docking of an Apollo CSM with a Soviet Soyuz, in 1975. These four programmes, well summarised in Collins's "Liftoff", [4] can thus be seen as an integrated series of missions, leading to or derived from the Apollo lunar programme. I will therefore group them in the following discussions, including their costs as part of the total bill for Apollo.

This "total bill" should be presented at once, forming as it did much of the basis for criticism of the programme. In very round numbers, the total cost of Apollo (itself $25 billion) and the four accompanying programmes listed was about $30 billion. The total of all NASA budgets, 1959 through 1975, for all expenditures (including Apollo), was $58 billion. For comparison, the budget for the Department of Health, Education and Welfare in 1975 alone was $59.9 billion (not including Social Security, which would almost double the total), and for the Defense Department, $87.5 billion [5]. No allowance has been made here for the modest inflation of the time. However, a simple comparison from the same year may be instructive: the 1975 expenditures for the Food Stamp Program alone were $5.0 billion, compared with the 1975 NASA budget of $3.3 billion.

The question was persistently asked about Apollo: "Why not spend that much money to help people?". The "case for the affirmative" begins here: we did.

The "bill" having presented, what did we get for the roughly $30 billion spent for the 5 programmes considered here as "Apollo"? Bearing in mind that the fundamental rationale for the Apollo Program was political, rather than scientific, I will start with its effects on the Cold War.

2. THE END OF THE COLD WAR

The most stunning political development of the 20th century will almost certainly prove to have been the collapse of communism in the Soviet Union and eastern Europe. This event put an end to the 45 year cold war, a war which in 1962 came close to the nuclear flash point.

It would be absurd to attribute these developments to the Apollo Program. Nevertheless, there is more than a casual connection between them, one clearer than it was in 1975 when I labelled the race to the Moon "a test of democracy" [6]. As early as 1970, an open letter [7] to the Soviet government was sent by three leading liberals headed by the late Andrei Sakharov. The letter summarised Soviet failures and shortcomings, specifically citing the fact that "the first men to land on the Moon were Americans". Furthermore, they said, the USSR was behind the US economically, scientifically and technically, lagging "infinitely" behind in computer technology. They then called for "democratisation" of the USSR, for greater freedom of information, expression of opinions and other changes.

The Apollo Program was thus viewed even in 1970, by the Soviets, as a demonstration of the superiority of democracy and its technology. But we now know, with the revelation that the USSR tried and failed, disastrously, to get to the Moon, just how overwhelming this demonstration must have been to the highest levels of the Soviet government. The factors leading to the ascendancy of Mikhail Gorbachev and to "glasnost" will not be fully known for some time, if ever. The most general cause appears to have been the simple failure of communism to provide a reasonable living standard for the Soviet people. Other failures have also surfaced since the dissolution of the Soviet Union, including environmental damage beyond anything in the western world: polluted air and water, near-destruction of the Aral Sea, nuclear accidents of which Chernobyl was only the most spectacular. Even Soviet military technology, once feared the world over, has proven inferior to that of the United States in every direct encounter, most recently the Gulf War of 1991. The Apollo Program's success gave an early demonstration that Soviet technological inferiority was general, as seen by the Soviets themselves.

In December, 1957, Andrei Gromyko told the Supreme Soviet that "The situation today is different from what it was even a few months ago. The Soviet Earth satellites have improved the political climate on our planet" [8]. Nikita Kruschev's subsequent "rocket-rattling", fed by Soviet space achievements such as Yuri Gagarin's 1961 orbital flight, culminated in the 1962 Cuban missile crisis, the closest the world has ever come to nuclear war. In the three decades since, the well-known clock on the Bulletin of the Atomic Scientists has slowly and sporadically been turned back and freedom has finally come to the former Soviet Union. Certainly some credit for this must be given to the Apollo Program, a flagship demonstration, in Russian eyes, of the superiority of democracy.

3. INTERNATIONAL RELATIONS

A glance through the world's newspaper headlines from July 20, 1969, will show that the Apollo 11 lunar landing had a global impact rarely, if ever, matched in modern history. Even countries mired in poverty and disease, or locked firmly behind the Iron Curtain, shared the excitement. I can only repeat my 1975 [6] suggestion: "Surely this shared experience, this step toward world consciousness, can be considered an achievement, if a temporary one, of the Apollo Program".

It is now generally forgotten, at least by the public, that in many ways the Apollo Program was an international one. The NASA tracking network of the day had stations around the world; a photographic cliche showed a microwave antenna with the appropriate exotic animal in the foreground. The countries in which the stations were located felt a real sense of participation in the Mercury, Gemini, Apollo and Skylab missions.

The results from the Apollo Program, as broadly defined here, were shared with the entire world. The terrain and weather photographs from the Gemini and Apollo Earth-orbital flights, for example, were made available without restriction to anyone, setting a precedent since followed for Landsat images. The lunar sample analysis programme was a classic of international scientific cooperation. For the later missions, the total number of principal investigators, most heading large teams, was 189, of whom 55 were foreign [10]. This global participation was incidentally possible primarily because of the great amount of lunar rock and soil - some 850 pounds - brought back by the Apollo astronauts, contrasted to the half pound returned by Soviet unmanned missions. Results of the Skylab solar physics observations were also disseminated to scientists around the world.

It is obvious that satellite communications links and weather satellite pictures have done much to unify the world. But the Apollo Program contributed to this unification as well, a significant achievement for a time when the United States was mired in the Viet Nam war and the two global power blocs had growing nuclear arsenals aimed at each other.

4. THE SCIENTIFIC RETURN

Twenty years permit us to evaluate more clearly the scientific results of the Apollo Program as defined here. The indirect or second-generation results in particular are now much more apparent.

Turning first to the Moon, we must remember that the Apollo lunar missions were much more than rock-collecting trips. They were complex expeditions (Table 1) that carried out extensive orbital remote sensing, geophysical investigations, geologic mapping and sampling, and finally emplacement of nuclear-powered instruments that functioned for years until budget cuts forced their termination. The results from these missions already fill many library shelves and the data and samples are still being analysed. To summarise them is difficult; the reader is urged to consult texts by Glass [9], Taylor [10] and other references [11,12]. The great scientific superiority of the Apollo missions to unmanned missions is well-covered by Taylor.

The most immediate result of the Apollo missions, and their precursor Lunar Orbiter photography, was a solid understanding of the structure, composition, age and geologic evolution of the Moon, an understanding better in many respects than that of the Earth. The Moon is now known to have formed about 4.5 billion years ago, and to have been extensively melted and differentiated early in its history, forming a global crust now visible as the lunar highlands. The last stages of the Moon's accretion formed the oldest craters of these highlands. There were several major impacts about half a billion years or so after the Moon's formation that produced the mare basins. These basins, and other areas, were flooded over the next several hundred million years by the basalts now forming the maria: Imbrium, Serenitatis, Nubium and others (fig. 1).

This early period, the first few hundred million years after formation, is extremely obscure on the Earth, rocks and structures from that time having been destroyed, metamorphosed, or hidden many kilometres under later rocks. The Moon thus gave us our first good look at a primordial planet.

This was essentially the end of the Moon's internal evolution, but sporadic impacts of comets or meteoroids continue to this day as they do on the Earth. However,the seismic and remote sensing investigations of the Apollo missions indicate that although the Moon is externally inactive, the deep interior is still hot and emitting gas of unknown composition from a few sites such as Aristarchus.

The most general significance of these findings is that we now understand fairly well the evolution of an end member in a series that includes Mercury, Mars, Venus and the Earth. This series is one of increasing size, internal activity, and crustal evolution (fig. 2). Mars, for example, can be understood as geologically intermediate between the Moon and the Earth. We can now interpret terrestrial geology in a planetary context, viewing the Earth as the most highly evolved of a series beginning with the Moon [13]. Simple comparison with the

TABLE 1: *Scientific Accomplishments of the Apollo Program.*

- Carried out in situ geological and geophysical exploration at six landing sites.
- Returned 385 kilogrammes of rock and soil samples from six landing sites.
- Emplaced six geophysical instrument stations that carried out measurements of seismicity, heat flow, crustal properties, local fields and particles, and other phenomena.
- Carried out orbital remote sensing experiments, collecting data on crustal composition, magnetic fields, gas emission, topography, subsurface structure, and other properties.
- Obtained extensive photographic coverage of the Moon with metric, panoramic, multispectral, and hand-held cameras during six landing and three non-landing missions.
- Carried out extensive visual observations from lunar orbit.
- Visited and retrieved parts from Surveyor III, permitting evaluation of the effects of 31 month's exposure to lunar surface conditions.
- Carried out extensive orbital photography of the Earth with hand-held and hard-mounted multispectral cameras, providing verification of Landsat multispectral concept.
- Emplaced laser retroreflectors at several points on the lunar surface, permitting precision measurement of lunar motions with an accuracy of several centimetres.
- Emplaced first telescope on the Moon, obtaining ultraviolet photographs of the Earth and various celestial objects.
- Obtained samples of the Sun by collecting solar wind-implanted ions with surface-emplaced aluminium foil.
- Carried out astronomical photography from lunar orbit.
- Carried out cosmic ray and space physics experiments on lunar surface, in lunar orbit, and in Earth-Moon space.

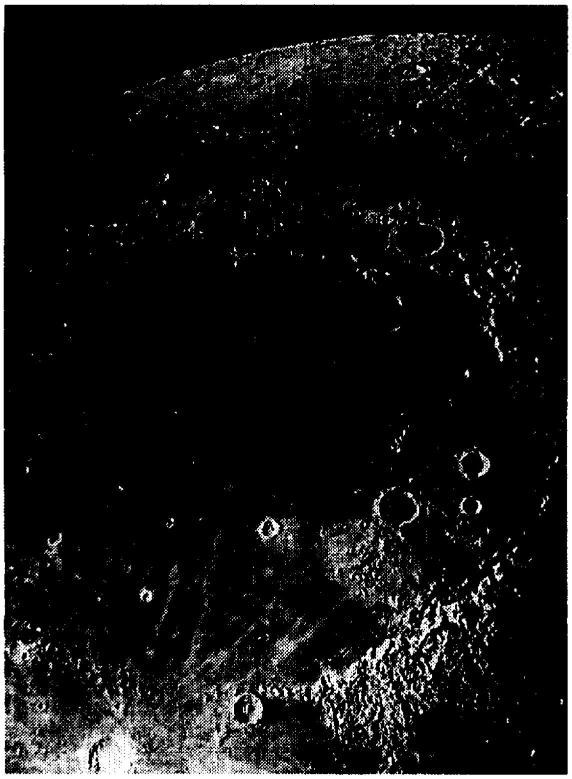


Fig. 1 Mare Imbrium as photographed by the Mt Wilson 100 inch telescope. Major stages of the Moon's crustal evolution as expressed in this area include the first differentiation (the northern highlands), the late heavy bombardment (the Imbrium Basin), and the second differentiation (the basalt flows that make up Mare Imbrium). Ray craters such as Copernicus (lower left) are later, external events.

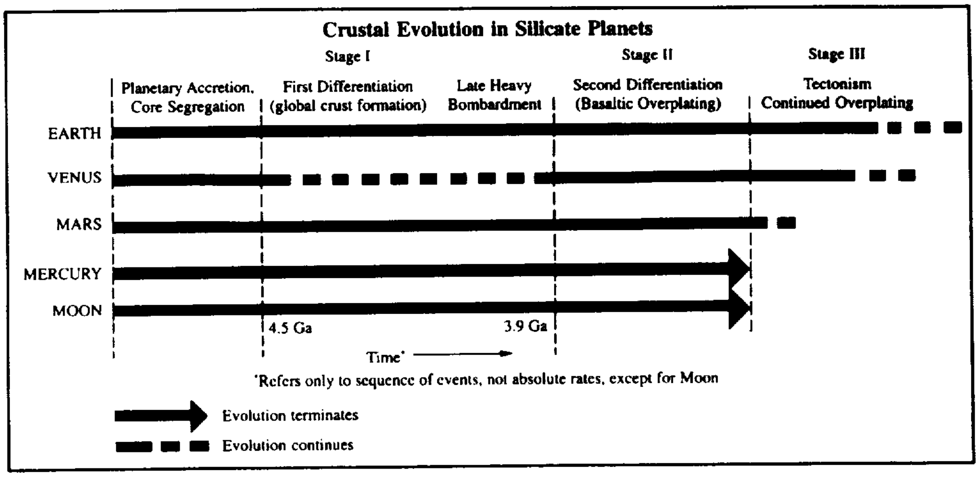
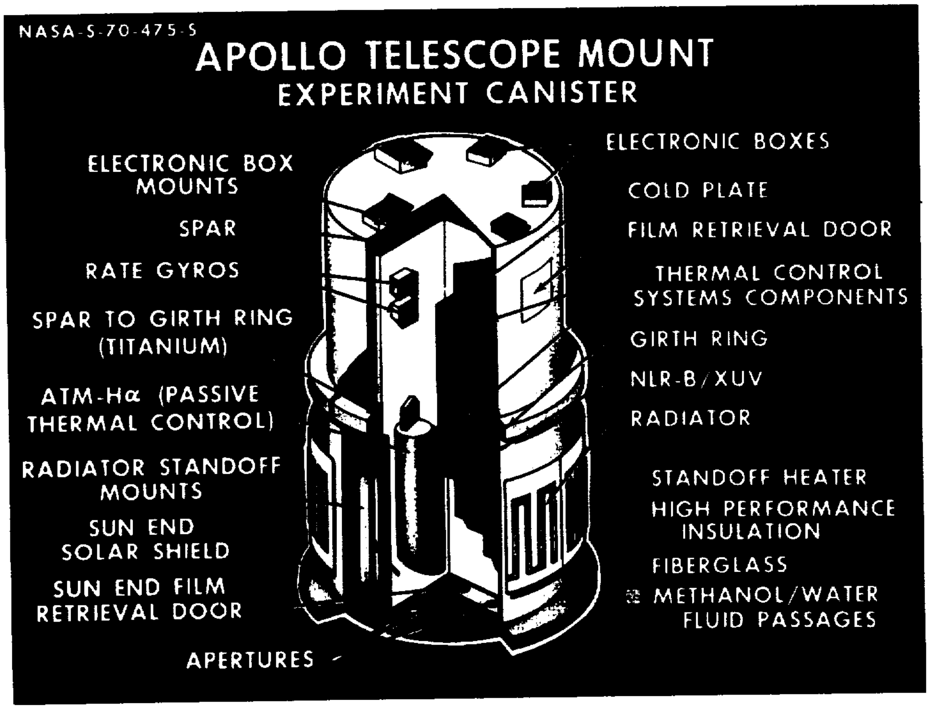


Fig. 2 Comparative crustal evolution in silicate planets, as function of increasing mass. Dashed line for Stage I, Venus, also implies no direct evidence of this stage because of basaltic overplating that covered early crust.

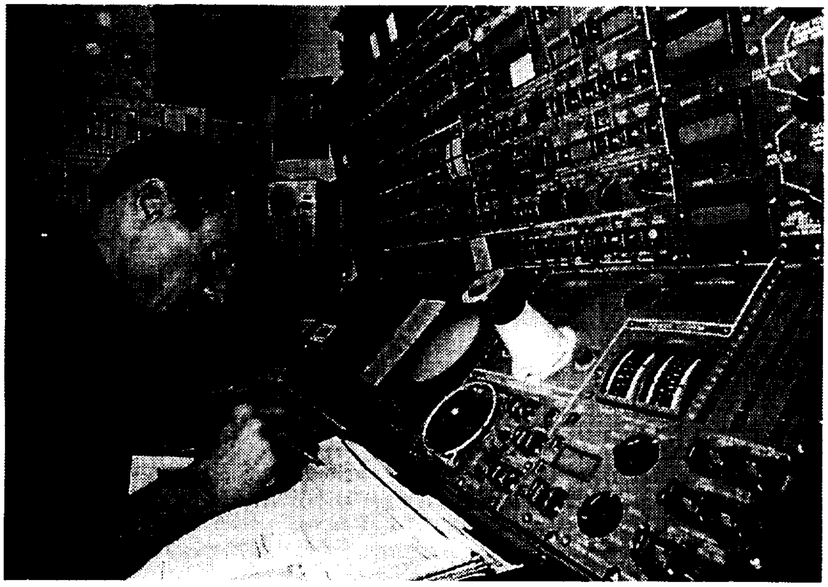
Moon itself offers interesting insights to terrestrial geology. For example, the Moon evidently lost all its water, at least from the outer few hundred kilometres, early in its history, and thus furnishes a control in comparative planetology with this important variable removed. It has since been inferred that the abundance of granite on Earth results [10] from the effect of water in igneous processes, a petrologic interpretation directly derived from the Apollo Program.

A further and extremely important result of the Apollo sample analyses is a reasonably firm lunar time scale, whose construction was possibly only with the extensive sampling programmes permitted by six lunar landings. This absolute time scale in turn permits calibration of the cratering time scale, admittedly with considerable uncertainty. It has also cleared up some cosmochemical mysteries, such as the origin of the SNC meteorites. These objects, essentially extraterrestrial igneous rocks, have ages of about 1.5 billion years. Our knowledge of the Moon's evolution shows that this is far too low an age for lunar rocks, suggesting that the only possible source is Mars. This has since been confirmed by other evidence; but the Apollo samples gave the basic knowledge for settling the problem.

The now-enormous body of knowledge about the Moon has major implications for the evolution of the Earth, in particular for the very obscure primordial stage. Evidence for a high-temperature early stage for the Moon implies a comparable high temperature for the primordial Earth, a complete reversal of the cool accretion theory favoured before Apollo. The evidence of early global differentiation suggests similar differentiation for the Earth, which has led to a radically different but stimulating school of thought on the origin of continents. This concept [13]



Skylab ATM Canister. An engineering drawing illustrating a cutaway view of the experiment canister of the Apollo Telescope Mount of the Skylab space station cluster. Arrows point to various features and equipment of the canister.



Charles Conrad, Jr., Commander of the first manned Skylab mission is shown at the Apollo Telescope Mount (ATM) console. The simulation was conducted in trainers and simulators in the Mission Simulation and Astronaut Training Facility at the NASA Manned Spacecraft Center.

holds the continents to be the greatly altered remnants of a primordial crust analogous to the lunar highlands, rather than amalgamation of younger terranes by plate tectonic processes.

The confirmation of an impact origin for the lunar mare basins, and for most craters, has led to the realisation that the Earth must have undergone similar bombardment. It has been proposed that the first ocean basins were formed this way, leading to mantle upwelling and formation of oceans remotely ancestral to those of the present. The importance of meteoritic or cometary impact in the evolution of life on Earth is now far better appreciated, thanks to the studies of impact cratering that were part of the Apollo Program.

The Apollo lunar missions produced significant new knowledge about the Sun and its history, quite apart from the Apollo-derived Skylab mission to be discussed. The Sun itself was sampled, so to speak, during the Apollo missions in that the astronauts deployed a solar wind composition experiment consisting of aluminium foil. Exposed for duration of the surface stay, this foil was later analysed to determine the composition of the solar wind from implanted gases. Similar techniques were later applied [14] to returned lunar soil samples that had been exposed for several billion years. The results can not be discussed further here, but they have provided new insight to the nature of the Sun both now and as it was several billion years younger.

As explained earlier, the "Apollo Program" included other programmes involving Earth orbital scientific investigations: Gemini, Apollo itself (missions 7 and 9), Skylab and Apollo-Soyuz. These missions produced major scientific results directly, in addition to stimulating second generation innovations to be discussed separately. The orbital science investigations themselves fill many books, and I will cite only a few of the most important results.

Perhaps the most impressive of these results came from Skylab, the first American space station. The Skylab Apollo Telescope Mount (ATM) was the most scientifically productive Skylab experiment, consisting of a solar observatory with six major instruments [16]. With a crew that included a professional solar physicist, Ed Gibson, Skylab demonstrated the value of trained observers to react quickly to unpredicted events such as solar flares. The ATM and other instruments produced 227 days of observations of the Sun and its corona, which Richard Tousey [15] of the Naval Research Laboratory called "extraordinarily valuable , perfect, and complete". For example, the ATM observations revealed coronal transients, clouds of coronal matter larger than the Sun itself, blown sporadically out toward the planets. It may be worth reminding the reader that the Sun is not some remote object of only scientific interest, but the body that totally controls life on Earth. Furthermore, it is still not well-understood; the solar neutrino deficiency, for example, remains unexplained, hinting at a fundamental weakness in theories of the Sun's internal mechanisms.

Skylab produced new knowledge of the Earth, from the wide variety of remote sensing instruments carried - cameras, multispectral scanners, radiometers, and a radar altimeter. The field of remote sensing in general requires a separate later discussion, but the surprising results of the radar altimeter should be briefly mentioned here.

This Skylab instrument, the first Earth-orbiting radar altimeter, produced a topographic map, so to speak, of the mean sea surface that mirrored the ocean floor topography. This feasibility demonstration opened what is now a fruitful and important field [17]. It was followed by a series of radar-carrying satellites intended for geodetic and oceanographic investigations. The novelty of the Skylab discovery is suggested by the fact that the 1973 US Program for the Geodynamics Project [18], an authoritative proposal for global studies of the Earth, had nothing remotely like sea-surface altimetry.

In addition to those mentioned so far, Skylab carried out dozens of investigations in biology, medicine, astrophysics, engineering, remote sensing of the Earth, and materials science. To keep things in perspective, it should be remembered that these investigations were carried out on a single-launch space station, constructed from a Saturn upper stage, and the Apollo infrastructure developed for the Moon programme. Skylab was thus fundamentally a by-product of the Apollo Program, but an enormously productive one.

The last element of the Apollo Program as defined here, the Apollo Soyuz Test Project, also produced impressive scientific results [19]. The Apollo crew carried out 28 separate experiments, five of them jointly with the Soyuz crew. These included zero-g materials processing, life sciences, astronomy and geophysics. The materials processing experiments produced valuable data on the crystallisation of metals and alloys that will be essential in planning later space utilisation programmes. Manganese-bismuth magnetic alloys, for example, grown in the microgravity environment proved to be much stronger than control alloys formed on the ground. Electrophoresis separation of human kidney cells was highly successful. In geophysics, the feasibility of mapping anomalies in the terrestrial gravity field by high-low satellite tracking, between Apollo and the ATS-6 geosynchronous satellite, was demonstrated for the first time. Low-low tracking, between the Apollo CSM and the docking adapter, proved less successful for geophysics, but produced valuable data on the ionosphere. The Apollo-Soyuz Test Project, in summary, was a highly successful scientific and technological mission, though it seemed at the time a programmatic afterthought flown for diplomatic purposes.

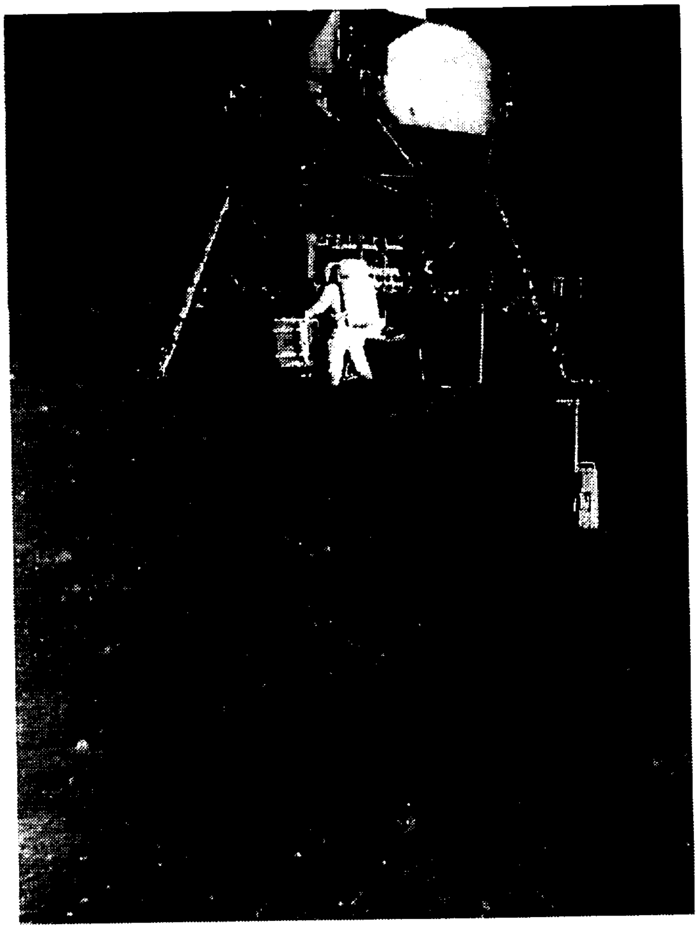
The direct scientific results of the Apollo Program, viewed collectively, can be summarised as fundamental new knowledge of the Moon, the Sun, and the Earth, and of the behaviour of living and inanimate systems in the microgravity environment provided by orbiting spacecraft and space stations.

5. THE MOON: A HABITABLE AND USEFUL WORLD

The Apollo lunar missions showed us that the Moon is, despite its forbidding surface environment, a habitable and useful world. Turning to "habitable" first, we must remember that men have lived on the Moon for as long as three days. They adapted to the low gravity at once, and found it a great aid to mobility and operations in general, without the problems of zero gravity such as motion sickness and misplaced equipment. Videotapes of surface activities show astronauts skipping across the ground, singing and cracking jokes - behaviour unimaginable for a trek across Antarctica. The lunar environment is of course harsh; an unprotected person would be unconscious in about 15 seconds and dead in a few minutes. But a January night in Ontario could kill an "unprotected" person almost as quickly, admittedly not by anoxia.

It will be objected that survival of a few astronauts for three days hardly shows that the Moon is "habitable" in the sense of supporting an autonomous colony. This is true. A colony would have to be protected from long term radiation exposure, practice rigorous recycling of consumables, and for many years receive occasional shipments of material and equipment from Earth. The lack of water appears to be a major problem, although solar hydrogen can be extracted from the lunar soil and the Apollo instruments confirmed gas emissions from areas such as Aristarchus. However, any large city is artificially supported. The problems of a lunar colony are essentially the same ones encountered by Los Angeles, where several million people live in a desert. (Even the supply of breathable air is undependable). How long could the population there survive if cut off, so to speak, from Earth? The point is clear: the Moon would be habitable even with the technology of 1969, and will be far more so with that of the 21st century.

The term "useful" refers to scientific and industrial "uses of the Moon," in Arthur Clarke's term. Since my first article on the



Apollo 11 astronaut Edwin Aldrin leaves a trail of footrpints on the Moon as he moves about setting up scientific equipment.

Apollo Program, in 1975, many intensive studies of possible scientific and industrial activities on the Moon, based on the Apollo experience, have been carried out. Part of this experience has involved the Apollo Lunar Surface Experiment Packages (ALSEPs), nuclear-powered geophysical instruments left behind by the astronauts. These instruments operated successfully for several years, until turned off because of budget cuts. However, they demonstrated that the lunar environment is perfectly survivable by properly-designed instruments. An especially important finding is that the lunar laser retroreflector arrays emplaced by the astronauts continue to reflect laser beams from the Earth normally, even after two decades of exposure on the Moon. This strongly suggests that optical instruments can similarly survive the surface environment.

The best-demonstrated "use of the Moon" will certainly be the emplacement of astronomical instruments and eventually the establishment of an observatory. The Moon provides a stable platform for distributed networks of instruments, continuous exposure times of up to 14 days from any one point, and a solid foundation eliminating the requirement of 3-axis stabilisation needed for orbiting instruments. Its distance from Earth offers a possible escape from problems of light pollution and radio frequency interference, which are increasingly difficult for terrestrial instruments to overcome. A workshop on "Astrophysics from the Moon" [27] held at Annapolis in 1990 produced dozens of papers by astronomers (most of them not NASA employees) advocating a wide variety of astronomical instruments that could benefit from a lunar location. The first lunar telescope was actually emplaced during the Apollo 16 mission, producing striking ultraviolet images of the sky and the Earth. The ALSEPs previously mentioned can be considered small-scale prototypes for remotely-controlled astronomical instruments. Eventually, a large astronomical observatory and exploration base camp could be established, taking advantage of progress in robotics, optical communications, and instrumentation [28].

The material resources of the Moon are now, thanks to the Apollo samples, fairly well-known: oxygen, iron, magnesium, aluminium, titanium, silicon and others [29]. An unexpected discovery has been solar wind helium-3 in the lunar soil. Helium 3 may prove extremely valuable if controlled nuclear fusion is achieved because its fusion reactions produce much lower neutron fluxes and hence less radioactivity in the reactor. It may be a profitable material for export to Earth in the next century. However, the big advantage of lunar material resources is the fact that, because of the low escape energy needed to launch from the lunar surface - roughly 1/22 that of the terrestrial energy - metals or other materials could be profitably mined on the Moon for use in near-Earth space, perhaps even in Earth orbit.

Even if the Moon is "habitable", it may be objected, there is still plenty of space on the Earth. The answer to this one is bleak: the Earth itself may not always be habitable. Quite apart from the now-reduced threat of nuclear war, or other man-made disasters, it is becoming clear that the universe is a violent and dangerous place. There is now convincing evidence that many of the great extinctions in the Earth's history, of which the dinosaurs are only one example, were caused by major impacts. The causes of continental glaciation are not well-understood, although the basic mechanism seems to be astronomical. We are presently in an interglacial period, and the glaciers will probably come back. The Earth's magnetic field is known to change polarity frequently, in geologic terms. The field has weakened several percent since Gauss's measurements in 1835, and we may be entering a reversal, which implies that the field strength may first go to zero. Obviously life itself has survived reversals, but the effects of such events on civilisation are totally unpredictable.

Radio astronomers have conducted many searches for extraterrestrial intelligence, obviously with no result. It seems incredible that we are the only intelligent creatures in the galaxy, although it has been so argued. A more likely explanation for the absence to date of intelligent signals is that technologically-capable civilisations become non-communicative, if not extinct, within a few thousand years from external or internal causes. If this is the answer, it emphasises the need for dispersing our species to ensure our long term survival. The Moon represents the most logical starting point for such dispersal. Mars offers a more hospitable colonisation site, and establishment and support of a lunar colony would be invaluable preparation for the eventual settlement of Mars.

6. REMOTE SENSING

This now-familiar term can be loosely defined as the long-range study of an area or object by electromagnetic radiation, usually from aircraft or spacecraft. It is distinguished from study of potential fields (gravity and magnetic),which is generally considered to lie in geophysics.

One of the least-appreciated but most important results of the Apollo Program as defined here has been its enormous stimulus to remote sensing. The twenty year period since Apollo 17 in this case tends to obscure the point, since several generations of remote sensing satellites have been launched since Landsat 1 in 1972. Nevertheless, the connection between Apollo and remote sensing is well-documented, and can be traced back to the Gemini missions starting in 1965 [20].

The Gemini Program was intended primarily to develop techniques and technology for the Apollo lunar missions, but the Gemini astronauts carried out a large number of scientific experiments as well. One of these was the Synoptic Terrain Photography Experiment, in which the astronauts used 70 mm cameras to photograph selected areas of the Earth for geologic, geographic and oceanographic study. They eventually obtained 1100 spectacular colour pictures that established the utility of non-meteorological orbital remote sensing. These pictures generated great scientific and public interest - "exciting glimpses of Earth resources" in the words of a leading remote sensing text [20]. They were immediately used by NASA and the US Geological Survey to justify an electronic Earth resources satellite that eventually became Landsat. The story becomes complicated at this point, for interagency conflicts intervened; a good account of the events up to 1972,when Landsat was launched, has been published by Mack [21]. Meanwhile, the NASA Earth resources programme led by the then-Manned Spacecraft Center forged ahead, using airborne and orbital techniques. A 4-camera multispectral array was flown on the Apollo 9 Earth orbiting missions, returning high quality photographs of the southwest US that, in addition to their own geologic value, served as a feasibility test of orbital multispectral photography. Similar photography, and other remote sensing, was carried out on Skylab, although somewhat eclipsed by Landsat 1, launched in 1972. Hand-held orbital photography was resumed when the Shuttle began flying, producing thousands of photographs that are a useful supplement to Landsat and other electronic satellites.

Landsat 1, its successors, and its later French and Soviet counterparts have become invaluable for monitoring environmental conditions, Earth resources, crops and other features. Destruction of the Amazon rain forest, for example, is now documented by Landsat imagery, which has contributed to awareness in Brazil of the dimensions of the problem. Comparable repetitive monitoring is being accomplished for wetland loss, sand dune migration, Antarctic penguin rookeries, coastline erosion, nitrate availability in deserts, peatlands (major source of atmospheric methane), near-shore water pollution and many other important environmental conditions. S.N. Goward, University of Maryland, described Landsat observations as "one of the greatest scientific accomplishments of the latter twentieth century - a continuous, consistent, quality record of the continental surfaces of the Earth, dating from 1972" [22].

Even the most authoritative space application forecasts as late as 1960 included nothing like Landsat. The point to be made here is that Landsat owes much to Apollo, in that the terrain photography from the Gemini missions contributed directly to its development. Such satellites would probably have been developed eventually anyway, but the rapid rate of global environmental destruction - deforestation, erosion, desertification - shows that we have little time to space. "Eventually" might have been too late.

7. TECHNOLOGY TRANSFER AND ECONOMIC GROWTH

It was argued even in the earliest years of the Apollo Program that there would be useful technology developed for it that could be applied to the civilian sector. The term "fallout" was quickly applied and as quickly replaced by "spinoff". Many of the early examples of spinoff were speculative or experimental, and justifiably criticised. But from the vantage point of twenty years later, we can see that the direct or indirect transfer of Apollo Program technology has been of great value. Only a few areas and examples will be cited here.

Probably the most valuable and widespread technological transfer has been the stimulus to the American computer industry. When the Apollo Program was proposed by President Kennedy in 1961, "computer" generally meant a collection of vacuum tubes and other hardware ranging in size from a few file cabinets to an entire room. Three decades later, digital computers have shrunk to the point where several of them ("chips") can be built into an automobile engine to control ignition, fuel mixture and the like. Digital watches - essentially small microprocessors - have become so cheap that they are generally thrown away when the batteries run down or the straps break. This incredible progress owes much to the Apollo Program. The requirements for great computing capability for spacecraft design, launch and guidance, combined with the need for miniaturisation, triggered a great surge of research and development in microelectronics, computer design and software. (The Apollo software has been adapted to a surprising variety of civil uses, such as air traffic control and automated hospital services [23].) The result of this progress was a commanding lead for American industry, whose computer exports increased to $10 billion per year by the mid-1970s. This development typifies the Apollo "spinoff". The major Apollo hardware itself was not widely transferred to the civil sector, there being little use for spaceships anywhere but in space, and there would have been much technological progress even without Apollo. But it has been demonstrated beyond doubt that the requirements of the lunar landing and related programmes accelerated this progress by years, perhaps by decades.

Closely related to computer technology is progress triggered by the Apollo Program in data processing and storage. A specific example of this is the application of digital image processing techniques, originally developed for analysis of Moon photographs, to the enhancement of CATscan and Magnetic Resonance Imaging medical data [24]. Similar applications have been made to cardiac imaging systems, using techniques developed for Landsat. We see here a cascade effect: the Apollo Program, broadly defined, led to Landsat; Landsat in turn led to techniques directly applicable to medical image processing.

The need to monitor astronaut body functions stimulated a surge of progress in medical telemetry, which could take advantage of concurrent progress in microelectronics and miniaturised computers. Thousands of hospitals today use such telemetry and non-invasive instruments that can be traced back to technology first required by the Apollo Program. Cardiac monitoring stations, for example, help nurses in intensive care wards keep track of patients' heart action through NASA-derived biotelemetry devices.

An unusually direct connection to Apollo can be demonstrated in the food industry [25]. The Pillsbury Company, prime contractor for developing in-flight food for the Apollo astronauts, discovered immediately that conventional quality control measures could not insure the absolute purity of the "space food". (Consider the result of food poisoning on astronauts 200,000 miles from Earth!) The company therefore developed a completely new system of continuous quality control, Hazard Analysis and Critical Control Point, that is today applied to all its food products, and is being adapted for use worldwide following its endorsement by the World Health Organisation.

Another example of technology transfer is found in the technique of metallisation of films, fabrics, paper and foam [24]. Metallisation was first developed in the 19th century, and can hardly be credited to the Apollo Program. But there was little demand for metallised products until Apollo, which required large amounts of reflective foil, film and plastic for spacecraft and other space hardware for control of temperature. The gold-coloured film on the Lunar Module seen by millions in the National Air and Space Museum is a typical example. The result of the Apollo requirements was, as for the computer/microelectronics industry, the sudden explosive growth of the market for metallised films. The result is that today metallised films are encountered everywhere: food packages, tents, "space blankets" (used to protect accident victims), flame suits, radar beacons and even guitar covers, not an unimportant item to a professional guitarist.

Early discussions of technological spinoff from the Apollo and related programmes often dismissed it as "trivia", and even as late as 1974 Holman [26] argued that none of the identified NASA-derived inventions could be called "major". The latter view is worth brief discussion. The technological innovations described above in general are not actually "inventions" derived solely from the Apollo Program. They are instead major improvements and wider application of devices or materials already in existence. Digital computers,for example, were fairly common when Apollo began. But the technological spinoff in this area and others can certainly be considered a major advance. The extremely wide variety of such spinoffs suggests that the net result of Apollo was a pervasive surge of the whole technological infrastructure - a rising tide lifting all boats, in the familiar phrase. It seems reasonable to suggest that the Apollo Program pulled us into the 21st century at least 10 years ahead of time.

Little has been said in this section about economic growth. However, it should be obvious that each of the developments cited above has led to the creation of tens of thousands of new jobs, in some cases entire new industries. Locally, the Apollo and related programmes rejuvenated many areas, especially in the deep South, changing towns from low-income backwaters with segregated drinking fountains to modern, thriving cities. The detailed study by Holman [26] demonstrated as long ago as 1974 that, far from being what critic Amitai Etzioni [2] termed "an economic drag", the Apollo Program has been a great and continuing stimulus to the American economy.

The examples given here may seem a roundabout way to achieve the ends described, and it is often asked if we couldn't get the same results simply by spending the money directly on improved technology and new products. The answer is, in brief, that it doesn't work that way. Progress in science and technology is far more haphazard than most people realise, depending heavily on serendipity and cross-fertilisation between widely separate fields. Consider the 1953 discovery of the DNA structure by Watson and Crick. This was one of the greatest scientific achievements in history, revealing the common basis of all life on Earth, from viruses to man. The fundamental problem was to find the specific mechanism of heredity. The answer came, not from continued fruit fly breeding, but from the celebrated model-building by Watson and Crick, based on the X-ray crystallographic studies by Franklin. This discovery was thus achieved by application of a technique from a completely different field, and X-rays themselves had been an accidental discovery by the physicist Roentgen in 1896. Other examples abound. Technology transfer of the sort generated by the Apollo Program is thus actually as efficient, sometimes more so, as the direct approach, because we generally don't know what the direct approach should be.

8. SUMMARY

Looking back with the perspective of 20 years, we now see clearly that the Apollo Program eventually did meet the highest expectations of those who proposed it. The world of 1961 was dangerously unstable, far more so than the present generation can realise. Apollo helped maintain at least a thin link of cooperation between the two major nuclear powers, and a wide net of cooperation among dozens of countries. By demonstrating the superiority of democracy in areas more fundamental than colour television and automobile tail fins, it contributed to the eventual end of the cold war - a war unique in that both sides won. Scientifically, Apollo expanded our understanding not just of the Moon but of the Earth, the Sun and the entire Solar System. It laid the foundation for the utilisation and perhaps the colonisation of a new planet just three days' travel away. It stimulated explosive growth of remote sensing and led to observation satellites that have become invaluable tools for monitoring and protecting the Earth's soil, water, forest cover, and other resources. The surge of technological progress Apollo initiated has now cascaded through a second and third generation, bringing the 21st century in years ahead of its time.

These collective results cost the United States, over 14 years, roughly half as much as the appropriation for the Department of Health, Education and Welfare in 1975 alone. The defence rests.

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CANDIDATE SITE FOR A ROBOTIC LUNAR OBSERVATORY: THE CENTRAL PEAK OF RICCIOLI CRATER

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This paper proposes the central peak of Riccioli crater as the most promising site for an initial lunar observatory. If only one site can be chosen, it should be on the near side, close to the limb, in continual line of sight from the Earth and on or close to the equator. The terrain should be suitable for landings, surface traverses and instrument emplacement. Anticipating an eventual manned observatory and surface exploration base, the site should be geologically diverse and have usable material resources. The central peak of Riccioli, 2.5 deg S and 83 deg W, and adjacent areas, meet these requirements and are recommended for initial telerobotic exploration and instrument emplacement. The floor of Grimaldi is suggested for a sub-site or an alternate site.

1. INTRODUCTION

One of the most important "uses of the Moon", in Arthur Clarke's phrase, will undoubtedly be astronomy from the lunar surface. The justification for astronomy from the Moon, as distinguished from space in general, is summarised in Table 1. Specific instruments that could benefit from the lunar environment have been proposed by many authors [1,2] and a composite list is presented in Table 2. It is clear that thinking about Moon-based astronomy has advanced since the Apollo missions, on one of which the first telescope was actually operated on the surface. However,there has been relatively little discussion in the open literature of where a lunar observatory could best be

TABLE 1: *Advantages of astronomy from the Moon.*

1. No atmosphere; all radiation (EM and particulate) reaches the lunar surface directly; no background radiation from atmosphere; no radiation belts; unlimited spectral window; no weather.
2. Ground emplacement; distributed instrument network and wide separation essentially eliminate experiment integration problems; simple telescope drives possible (vs. orbital instruments); high reliability from independent instruments; single point failure reduced. Large interferometer arrays practical.
3. No orbital debris problem; micrometeorite flux similar to earth orbital; no glow effects from collisions with residual atmosphere (vs LEO)
4. Slow rotation time permits up to 14 days continuous exposure (vs. LEO, frequent eclipse by Earth) from low latitudes sites; polar sites permit exposures of indefinite length for corresponding hemisphere
5. Distance from Earth greatly reduces terrestrial source interference (RFI, gamma ray, radar) by inverse square of distance
6. Far side offers complete radio silence at all frequencies (assuming regulation of radio use); ideal site for SETI, VLF investigations
7. Near side observatory permits use of Earth as calibration/comparison target for reflectance spectroscopy and other observations
8. Astronomical study of Earth possible; almost entire hemisphere visible at once including one pole, possibly two
9. Ultra-long baseline Moon-Earth interferometry possible; extremely high resolution and sensitivity

TABLE 2: *Potential instruments for lunar-based astronomy.*

Instrument	Rationale for Lunar Location
Optical interferometers	Ground emplacement possible Large arrays, long baselines possible Low seismicity (vs Earth)
Millimetre-wave interferometers, single telescopes	Large arrays, long baselines for mm wave interferometers
Thermal IR instruments	Thermal environment and ground emplacement permit easy thermal control, esp. polar sites
Large aperture optical telescopes	Ground emplacement possible Low but useful gravity field
2 meter class optical telescopes	Ground emplacement possible Long exposure times High observing efficiency (>50%)
Fixed transit telescope	Ground emplacement and motion of Moon replace telescope drive
Large aperture radio telescope	Craters permit Arecibo-type facility Low RFI, even on near side
Centimetre-wave radio telescopes	Low RFI, even on near side Large arrays, long baselines for interferometer arrays Earth-Moon distance permits ultra long baseline interferometry
Far-side VLF array	Shielded from terrestrial auroral radiation interference
Far-side centimetre-wave radio telescopes	High sensitivity ETI search possible with complete freedom from RFI
Gamma ray, X-ray detectors	No terrestrial or LEO interference Ground emplacement Large arrays possible Raw materials locally available
Gravity wave antennas	Low seismic noise Earth-Moon ULBI

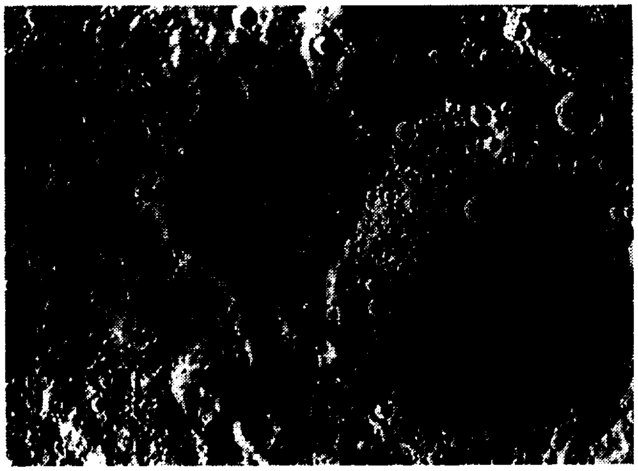

Fig. 2 *(above)* Riccioli crater (top Centre) and Grimaldi (lower right), as photographed by Lunar Orbiter IV. Composite of Lunar Orbiter images IV-173H3 and IV-168H3.

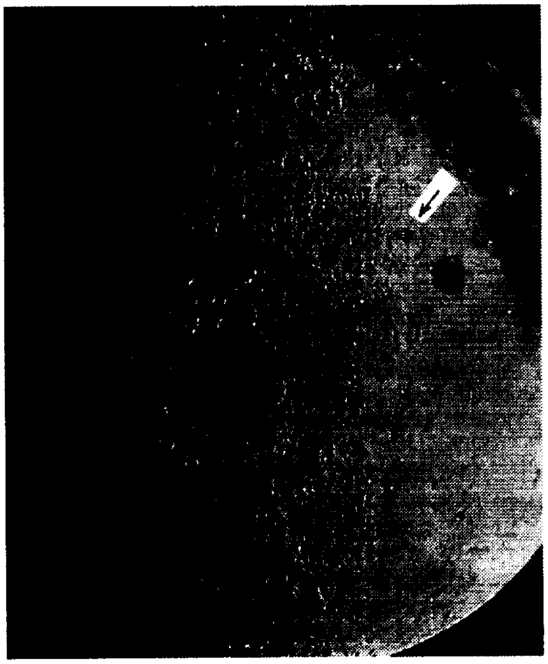

Fig. 1 *(left)* The Orientale Basin, as photographed by Lunar Orbiter IV, North at top. Riccioli marked with arrow. Lunar Orbiter image IV-181M.

located. Ideally a minimum of 5 sites would be occupied for visibility of any object in the sky at any time, viz: 3 on the lunar equator, roughly 120 deg apart, and one at each pole. For the purposes of discussion, it will be assumed that only one site can be occupied, at least initially. A specific site, the central peak of Riccioli crater (fig. 1, 2) and adjacent areas on the crater floor is proposed first for small robotic telescopes and eventually for a manned observatory and exploration base. An alternate or sub-site for specific purposes is the floor of the crater Grimaldi. The reasoning for this was presented at a workshop on site selection strategy for a lunar outpost sponsored by Johnson Space Center in August 1990 [3] and at a conference on "Low-Cost Lunar Access" in May 1993 [4]. Neither of these publications is easily available and new developments in telerobotics and lunar exploration since indicate a revised presentation.

2. NATURE OF AN OPTIMUM SITE

The site should be on the Earthward or near-side, outside the longitudinal libration limits. A near-side site in continual view of the Earth would be able to transmit the presumed large volumes of data directly and continuously, without the need for lunar communications relays on the ground or in space. In addition, if the Apollo mission mode is used for renewed lunar missions, a near-side site would permit tracking and communications during the landing phase. A far side site is desirable, however, for low frequency and SETI radio astronomy, so as a compromise a near side site should be located as close to the far side, i.e. to the limb, as possible. An equatorial or near-equatorial site is desirable for at least two reasons.

(1) For return to Earth, if lunar orbital rendezvous is used, equatorial sites have a launch window essentially open all the time for launch to lunar orbital rendezvous.

(2) More important for astronomical purposes, each degree of latitude away from the equator costs roughly that much visibility of the northern or southern celestial sphere. A site on or near the lunar equator provides access to the entire celestial sphere or close to it.

A site with trafficable and workable terrain is desirable, both for initial telerobotic operations and for eventual human occupation. To serve as an exploration site, the observatory should be close to geologically interesting features and material resources such as high-Ti basalts or water-bearing rocks (if any). In summary, a single optimum lunar observatory would best be at an equatorial near side site close to the limb, and in a geologically diverse area.

Two general areas which fit this description, as brought out at the 1990 site selection meeting, are Mare Smythii and the crater Riccioli. The arguments for M. Smythii have been presented by Spudis and Hood [5] and for the NE Orientale Basin by Lowman [6].

3. ASTRONOMICAL CHARACTERISTICS

Riccioli is on the near side of the Moon and, at 83 deg ", is outside the optical libration in longitude of 7.7 deg. It is within continuous line of sight visibility of Earth, thus avoiding the extra expense of surface or orbiting communication relays. Furthermore, it is far enough from the limb to permit precursor astronomical and radar study from the Earth, without the extreme foreshortening of the M.Smythii site. If an Apollo-like landing mode is used, this longitude would permit tracking and communication during the descent phase of missions. Finally, continual line of sight visibility would greatly aid initial telerobotic missions for instrument emplacement and exploration. Although the use of libration point relays could, in principle, permit telerobotic operations almost anywhere on the Moon, direct realtime communication links are obviously preferable.

As brought out by Douglas and Smith [7], the only observations for which the expense of a far side site is justified are low frequency and SETI radio astronomy, to avoid interference from auroral radiation and terrestrial microwave communications. Because there is some RF diffraction around the limb as frequencies as high as 259.7 MHz [8], an ideal far side radio observatory should be located tens or hundreds of kilometres beyond the mean optical limb. The longitude of Riccioli is not at the optical limb but this will add only moderately to travel requirements to a far side radio observatory site.

The latitude of Riccioli, 2.5 deg S, would provide access, essentially, to the entire sky over the lunar month. Because the southern celestial sphere is relatively less known, and contains features such as the galactic centre, astronomers would probably agree that a slight southern offset is acceptable. Polar locations have their own advantages, such as low temperatures and continual visibility os much of the corresponding celestial hemisphere, so polar sites should be occupied eventually [9].

Although not all instruments would be located on the central peak, this would offer maximum sky visibility and freedom from terrain obstacles, especially in view of the Moon's radius of curvature. Conversely, instruments nearby on the floor of Riccioli east or west of the central peak could use it as an occulting edge for celestial sources.

4. TERRAIN CHARACTERISTICS

Pending detailed study of the Clementine imagery and reanalysis of Lunar Orbiter photographs of the Riccioli area, discussion of the operational aspects of the local terrain must rely largely on analogy with better known areas of the Moon. A large (160 km diameter) pre-Orientale crater, Riccioli has a correspondingly large variety of terrain types.

In the NE quarter, the floor of Riccioli is occupied by mare fill, presumably basalt flows like all mare sites previously investigated. If similar to other maria, this terrain would provide extensive level areas well-suited to landing and surface travel. It would also be ideal for large optical interferometer arrays and other instruments but the possible conflict between landing operations and such instruments would require careful planning. An alternate site for installations requiring large level ground areas would be the floor of Grimaldi (fig. 2).

Much of the floor of Riccioli is the ridged, relatively high-albedo terrain mapped by McCauley [10] as the Hevelius Formation, interpreted as impact ejecta from the Orientale Basin. The closest analogy to this terrain is the Apollo 14 landing site on the Fra Mauro Formation, which is ejecta from the Imbrium Basin. As shown in fig. 3, the Apollo 14 landing site proved essentially similar to other sites in physical characteristics and presented no particular difficulties in landing or surface operations. Since the Orientale Basin is younger than the Imbrium Basin, the regolith may not be as mature as that at the Fra Mauro site. However, even the more rugged Descartes site visited by Apollo 16 proved trafficable. On balance it seems safe to say that, on a whole, the terrain of Riccioli crater should present no major obstacles of landing, instrument emplacement or surface exploration.

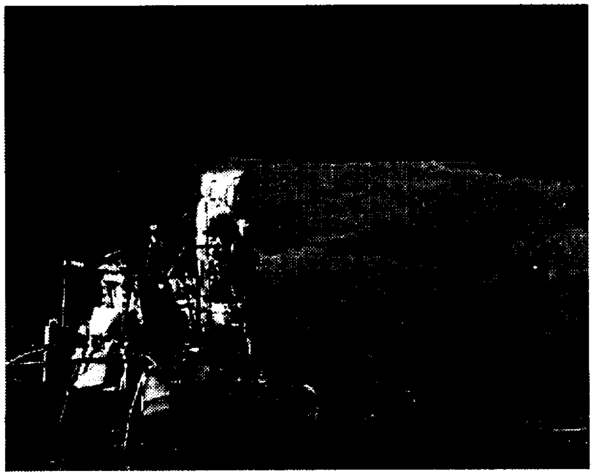

Fig. 3 Apollo 14 surface view showing terrain at Fra Mauro landing site.

The central peak itself is actually a subdued ridge not more than a kilometre or so higher than the surrounding terrain. Although high-resolution imagery should be studied, even the Lunar Orbiter pictures indicate that the peak should be accessible by surface vehicles, the north flank having slopes not over about 30 degrees. The physical properties of the ground are not predictable but the geomorphic age and blanket of orientale ejecta imply a mature and relatively deep regolith, suitable for instrument emplacement and eventually excavation to depths of tens of metres for manned shelters. At this point, it may be said that, unlike the peaks of younger craters such as Tycho and Copernicus, the peak of Riccioli should be reasonably trafficable for telerobotic vehicles that could verify its suitability for more extensive operations.

5. REGIONAL GEOLOGY

An observatory site should serve as the starting point for initial surface exploration by telerobotic vehicles, if only as a byproduct of instrument emplacement traverses. An eventual manned base will certainly carry out extensive surface traverses, both for scientific investigations and resource assessment. Accordingly, it is necessary to consider the regional geology, reasoning again largely by analogy with better-known areas.

The Riccioli area, in general, is one of great geologic interest if for no other reason than its location on the NE flank of the youngest large multi-ring basin on the Moon. As brought out by Spudis [11], multi-ring basins are extraordinarily important for understanding the crustal evolution not only of the Moon but of all solid planets and satellites. The orientale Basin should provide clearer evidence for its formative processes than older basins, and surface traverses to the southwest from Riccioli would reveal a cross section of the Basin and its ejecta blanket. The ejecta itself covers much of the floor of Riccioli.

The crater Grimaldi is a 440 km multi-ring mascon basin [11], so even short-range traverses from Riccioli could reach it. The floor of Grimaldi, an extensive mare plain, would be excellent as a landing site or for location of large interferometer arrays, should other considerations argue against the Riccioli mare area for these purposes.

Even without leaving the Riccioli crater, surface expeditions would encounter a large variety of geologic features and potential resource sites. Dark halo craters (fig. 2) are generally considered volcanic and may have material from the deep interior. If water-bearing rock is to be found anywhere on the Moon, such craters are promising sites. The central peak would merit intensive investigation for the understanding of cratering mechanics, as it is conceivable that post-impact volcanism may have occurred there. Several large rilles are accessible within Riccioli. The hevelius Formation should provide a broad sample of the western highland crust, excavated by the Orientale impact. The ridges inside the NE rim of Riccioli may be deceleration dunes [10] deposited by a base surge from the impact and would be of particular interest as an excellent if well-scrambled collection of highland crust rock.

The material resources of the Riccioli area should be as useful, *a priori*, as those of any comparably varied area on the Moon. The mature regolith should be easily excavated for bulk shielding material and for extraction of elements such as helium-3, oxygen, aluminium and iron. The mare regolith, especially if rich in ilmenite, would be of interest for oxygen extraction. The use of lunar resources may be closer than commonly realised, since telerobotic techniques [12] could begin such use long before manned landings are resumed.

The continual line of sight visibility of Riccioli from Earth would meet the first requirement for a lunar solar power system as described by Criswell [13], although such a system is far in the future at this point.

5. ESTABLISHMENT OF A LUNAR OBSERVATORY

The term "lunar observatory" has traditionally invoked visions of a manned base with an astronomical staff. However, recent progress in microelectronics, computers and lightweight materials makes it possible to outline an extremely capable observatory complex that could be established and operated before manned missions to the Moon resume. Robotic (or telerobotic, i.e. remotely-controlled) telescopes have come to increasing use [14] for remote locations on Earth. Telescopes in Earth orbit have demonstrated the feasibility of the technique for more than two decades. The geosynchronous International Ultraviolet Explorer, in particular, shows what can be done with small instruments in locations permitting long uninterrupted viewing.

The value of telerobotic vehicles in lunar exploration was demonstrated by two Soviet Lunokhods in the 1970s; modern versions of such vehicles as outlined by Spudis and Taylor [15] and Burgess [16] would be far more capable. More to the point astronomical instruments could be emplaced telerobotically and operated from Earth [17,18]. Several scenarios for an initial unmanned lunar observatory have been proposed [19]. A detailed one by Sykes et al [20] would involve a series of Dedicated Astronomical Research Telescopes (DARTs) of one-metre class. An initial DART might be the simplest of all, a fixed transit telescope that would be continuously swept across the sky by the Moon's motion [21]. Later DARTs could include a wide range of instruments similar to those outlined in Table 2. Such instruments could be surprisingly light. Chen *et al* [22] have developed a prototype 42 cm reflector using replica mirrors and a graphite epoxy frame that, with auxiliary instrumentation, could weigh less than 25 kg. Payloads of this mass could be sent to the Moon with relatively small launch vehicles, Delta or smaller.

An initial robotic lunar observatory complex would resemble a scaled-up analogue of the Apollo geophysical instruments. The central peak of Riccioli would be occupied by small telescopes of the sort described. In addition, the height of the peak would make it ideal for location of a central station that could receive telemetered data, from instruments deployed on the crater floor, for transmission to Earth.

6. SUMMARY AND CONCLUSIONS

Establishment of a lunar observatory at Riccioli, or elsewhere on the Moon, could begin well before the end of the century. Cost estimates are beyond the scope of this paper but the use of telerobotic techniques could begin the programme with short range traverses around Riccioli and emplacement of the firs simple telescopes. The low cost and absence of risk to life of such missions imply that an extensive (and expensive) series of precursor reconnaissance missions such as those done before Apollo is not needed. The terrain around Riccioli appears fundamentally similar to that at several other sites at which successful manned and unmanned landings were made. The astronomical advantages of the Riccioli site are already known. It is therefore suggested that the long-advocated return to the Moon begin with the landing of telescope-carrying telerobotic vehicles near the central peak of Riccioli.

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13. ABSTRACT *(Maximum 200 words)*

This paper proposes a comprehensive incremental program, Lunar Limb Observatory (LLO), for a return to the Moon, beginning with robotic missions and ending with a permanent lunar settlement. Several recent technological developments make such a program both affordable and scientifically valuable: robotic telescopes, the Internet, light-weight telescopes, shared-autonomy/predictive graphics telerobotic devices, and optical interferometry systems. Reasons for focussing new NASA programs on the Moon include public interest, Moon-based astronomy, renewed lunar exploration, lunar resources (especially helium-3), technological stimulus, accessibility of the Moon (compared to any planet), and dispersal of the human species to counter predictable natural catastrophes, asteroidal or cometary impacts in particular. The proposed Lunar Limb Observatory would be located in the crater Riccioli, with auxiliary robotic telescopes in M. Smythii and at the North and South Poles. The first phase of the program, after site certification, would be a series of 5 Delta-launched telerobotic missions to Riccioli (or Grimaldi if Riccioli proves unsuitable), emplacing robotic telescopes and carrying out surface exploration. The next phase would be 7 Delta-launched telerobotic missions to M. Smythii (2 missions), the South Pole (3 missions), and the North Pole (2 missions), emplacing robotic telescopes to provide continuous all-sky coverage. Lunar base establishment would begin with two unmanned Shuttle/Titan-Centaur missions to Riccioli, for shelter emplacement, followed by the first manned return, also using the Shuttle/Titan-Centaur mode. The main LLO at Riccioli would then be permanently or periodically inhabited, for surface exploration, telerobotic rover and telescope operation and maintenance, and support of Earth-based student projects. The LLO would evolve into a permanent human settlement, serving, among other functions, as a test area and staging base for the exploration, settlement, and terraforming of Mars.

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