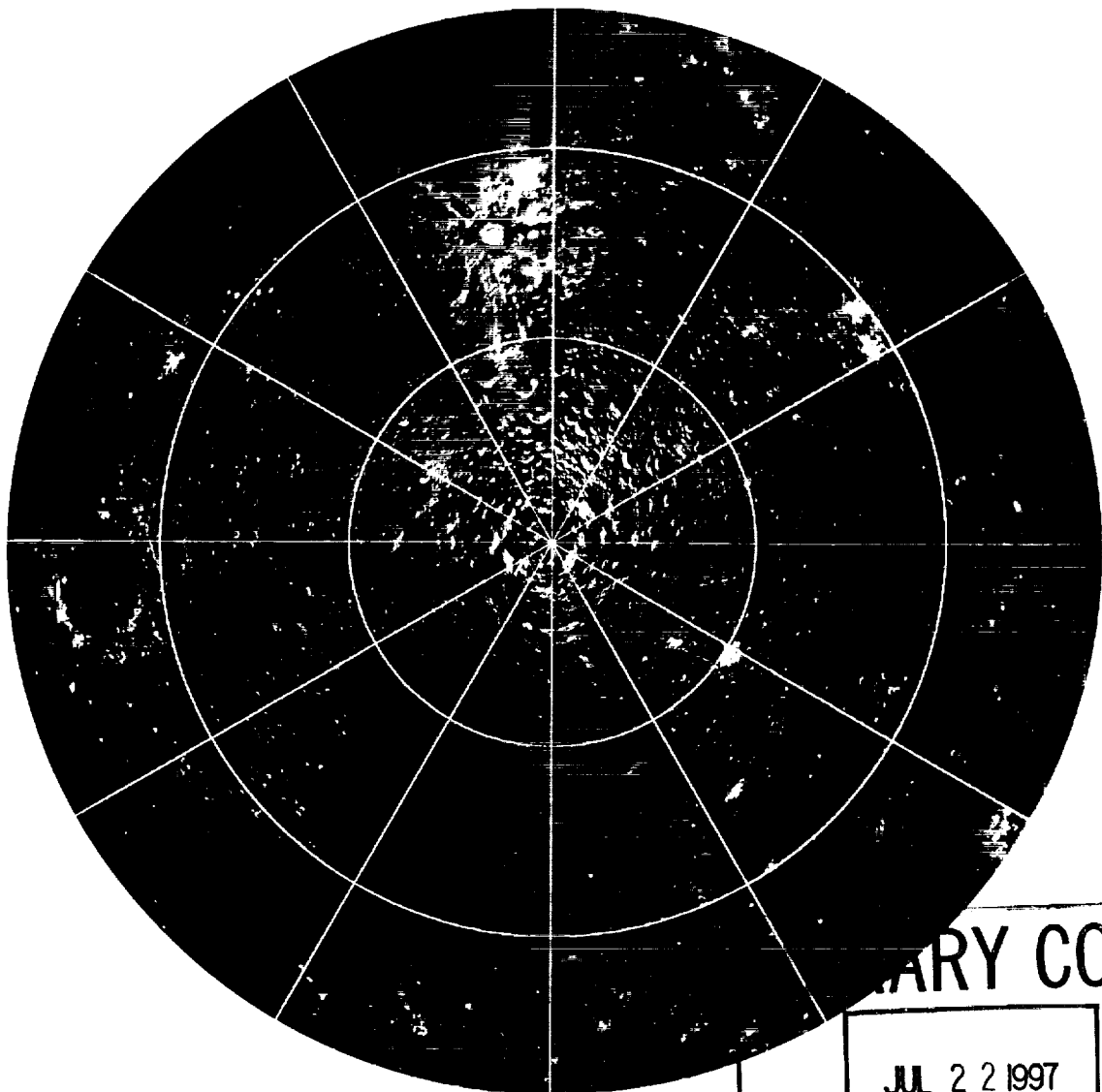


LESSONS LEARNED FROM THE CLEMENTINE MISSION

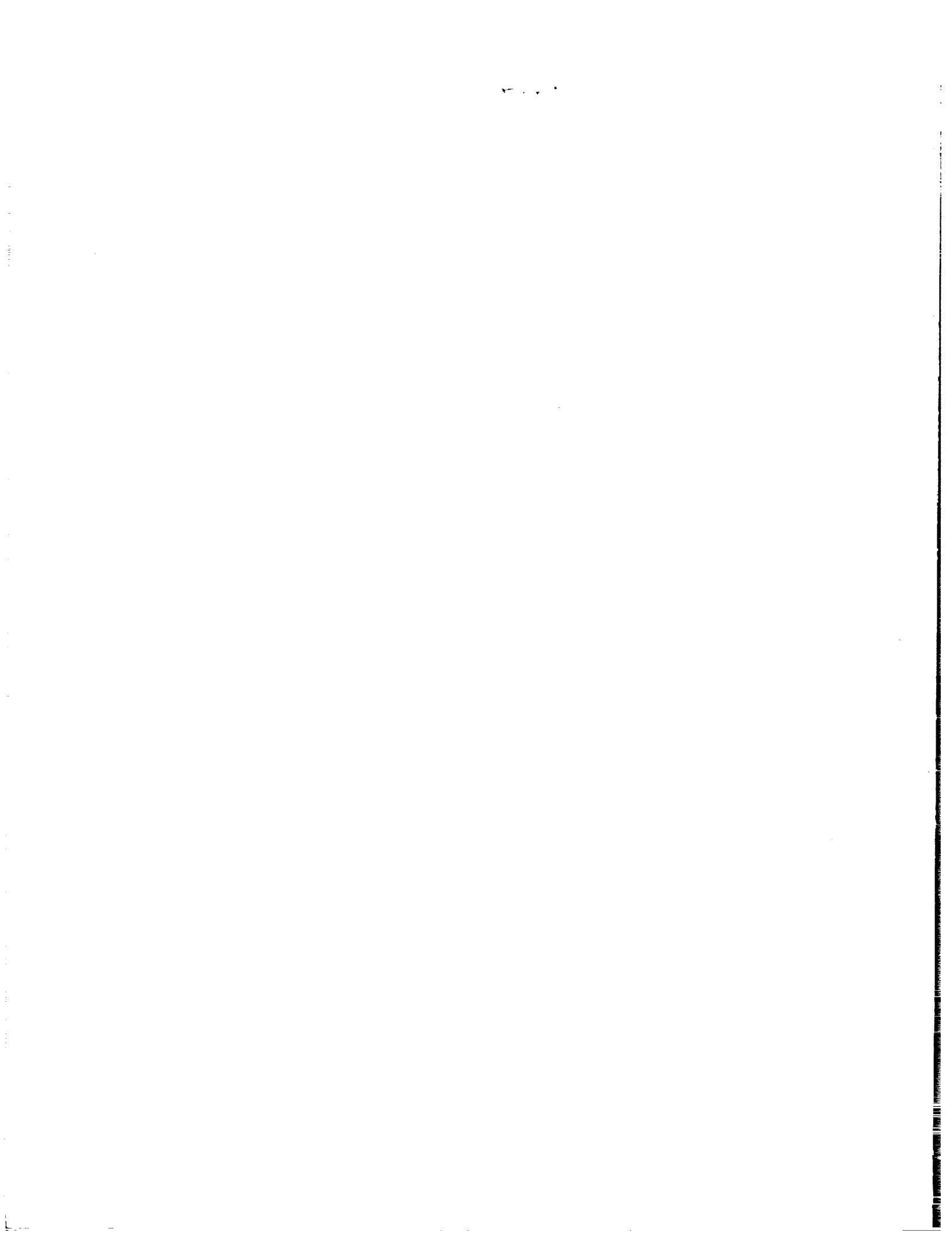


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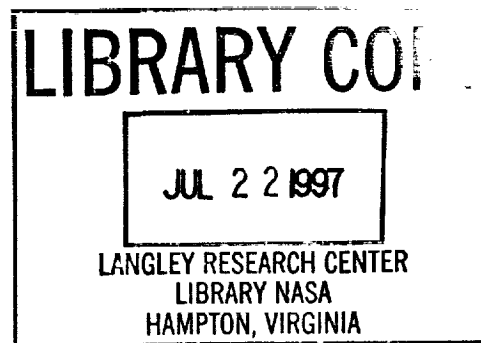
Lessons Learned from the Clementine Mission

Committee on Planetary and Lunar Exploration

Space Studies Board

Commission on Physical Sciences, Mathematics, and Applications

National Research Council



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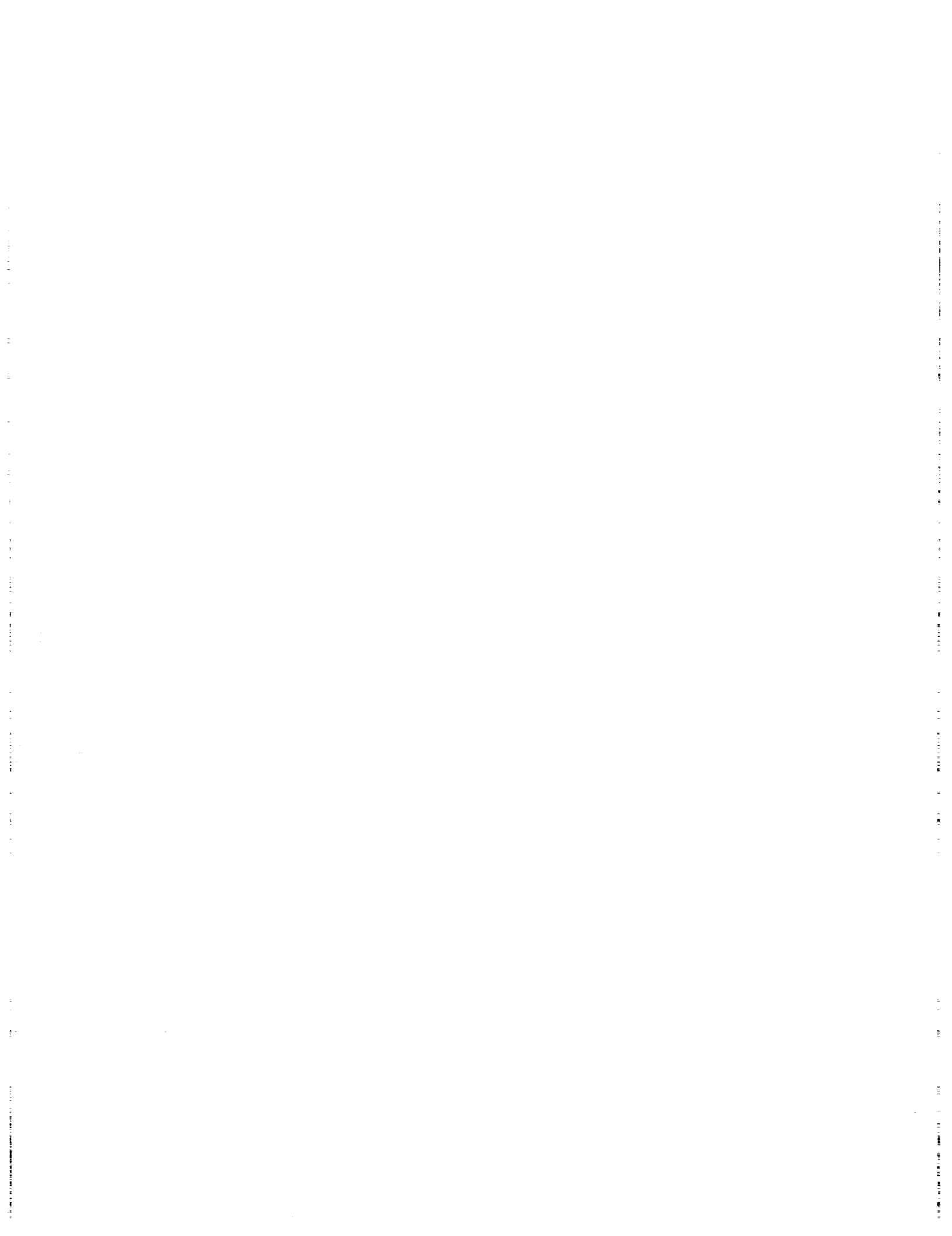
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Foreword

Thirty years after Ranger 7's first close-up photography of the Moon and 25 years after the Apollo 11 astronauts' first steps, the compact Clementine satellite entered lunar orbit. Whereas Apollo remains the most ambitious and expensive U.S. space endeavor, Clementine is an archetype of the "smaller, faster, cheaper" approach dictated by today's fiscal realities.

Clementine was the product of innovative technical and management approaches in the Ballistic Missile Defense Organization of the Department of Defense. Its primary goal was to demonstrate that advanced capabilities could be achieved at relatively low cost; the scientific objectives were secondary.

In this study, the Space Studies Board's Committee on Planetary and Lunar Exploration (COMPLEX) considers some lessons to be learned from Clementine about reaping the most science possible from a technology-focused space mission and about the relevance of this experience to future NASA satellites that leave low Earth orbit. Not surprisingly, many of the findings stated here echo a recent Space Studies Board report assessing changes in the Explorer program of Earth-orbiting satellites.¹ Both studies focus on the need for crisp management structures with adequate authority and responsibility to ensure that projects will be executed quickly—since there are natural limits on how quickly project money can be effectively spent, "faster" is almost synonymous with "cheaper."

This report complements COMPLEX's earlier examination of the role of small missions in solar system research.² Taken together, these studies are cautiously optimistic about the possibility of addressing some high-priority solar system exploration with spacecraft of modest cost. Whatever else it accomplished, Clementine's success in mapping the Moon established an important precedent for the conduct of space research.

Claude R. Canizares, *Chair*
Space Studies Board

¹Space Studies Board, National Research Council, *Assessment of Recent Changes in the Explorer Program*, National Academy Press, Washington, D.C., 1996.

²Space Studies Board, National Research Council, *The Role of Small Missions in Planetary and Lunar Exploration*, National Academy Press, Washington, D.C., 1995.

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Preface

The Committee on Planetary and Lunar Exploration (COMPLEX) advises the Space Studies Board on the entire range of planetary science studies; these include both ground-based activities and space-based efforts. The disciplinary scope of this advice includes the geosciences, atmospheres, exobiology, particles and fields, planetary astronomy, and the search for planets around other stars.

The Ballistic Missile Defense Organization (BMDO)/National Aeronautics and Space Administration (NASA) Clementine mission was designed to space-qualify advanced, lightweight imaging sensors and component technologies and to test autonomous operation for the next generation of Department of Defense spacecraft. A secondary objective was to perform a 2-month global mapping survey of the Moon at several visible/infrared wavelengths and an imaging flyby of the near-Earth asteroid 1620 Geographos. Because of a software error, the asteroid flyby along with its accompanying test of the autonomous acquisition and tracking of a cold body was aborted. Clementine implemented a streamlined management approach that included a rapid design and development program, with an approval-to-launch time line of 22 months and innovative mission operations and data handling setups. The spacecraft was designed, built, tested, launched, and operated for a reported cost of \$80 million.

With a trend toward smaller, focused space science missions (such as those in NASA's Discovery, Mars Surveyor, Earth Probe, Small Explorer, and MidEx programs), the Clementine experience may hold lessons for both the scientific and engineering communities as they enter an era of "smaller, faster, cheaper" missions. As a result, in late summer 1994, the Space Studies Board charged COMPLEX to conduct a study to:

1. Understand the lessons learned from Clementine with regard to its schedule, budget, management approach, technology utilization, mission operations, and data processing procedures;
2. Assess in a preliminary way the scientific return of the Clementine mission in the context of its instrument complement and mission profile; and
3. Make recommendations as to how positive aspects of Clementine can be incorporated into NASA's future small-spacecraft missions.

Although the study formally began at COMPLEX's October 1994 meeting, many of the committee members were already familiar with the outlines of the mission from briefings received from, among others, Eugene

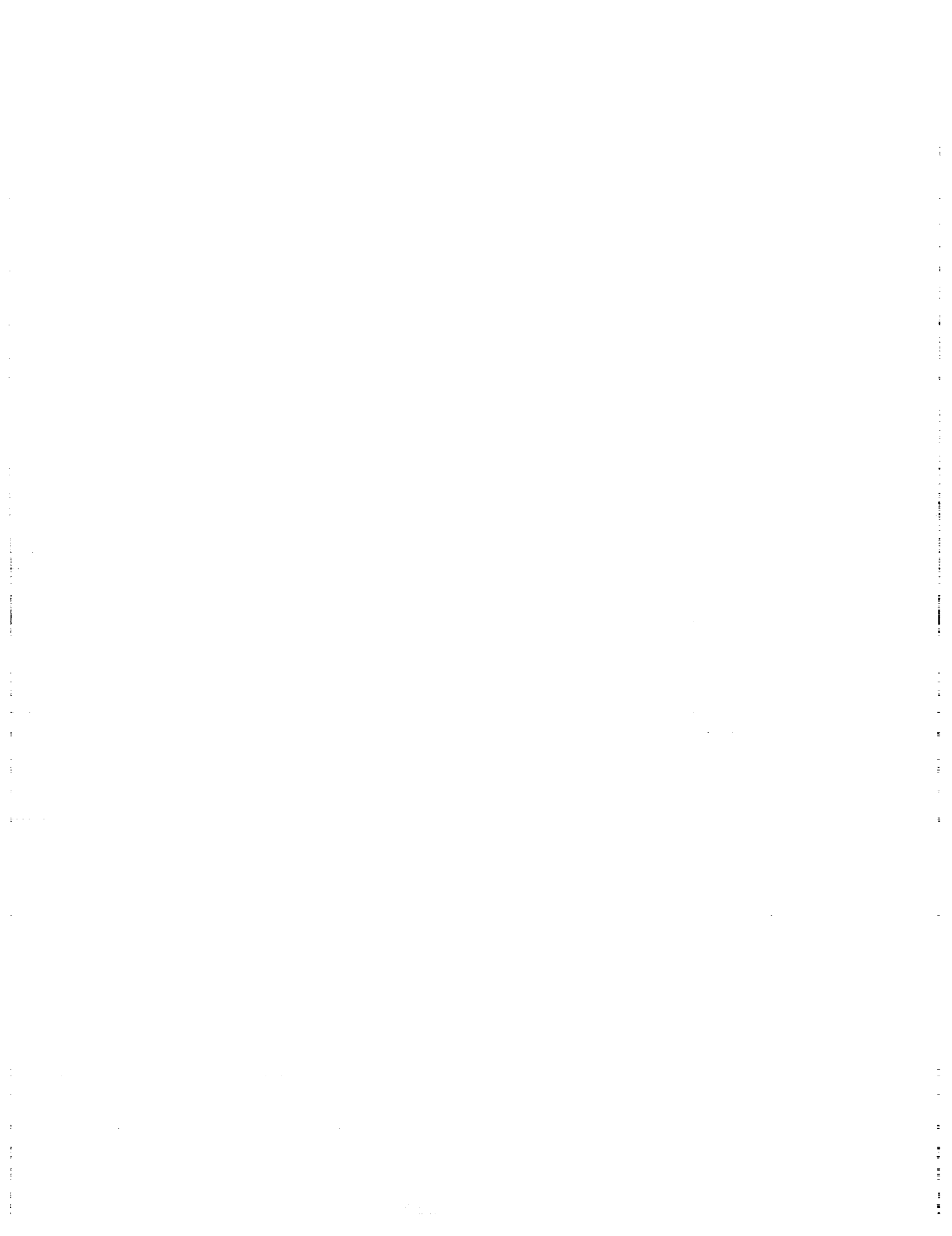
Shoemaker,* leader of the Clementine science team, during the preparation of a short report on Clementine in 1992 ("Scientific Assessment of the Strategic Defense Initiative Organization's Integrated Sensor Experiment (Clementine)," a letter report sent to Simon P. Worden and Wesley T. Huntress, Jr., on August 21, 1992). In addition, COMPLEX was briefed on Clementine by its program manager at BMDO, Col. Pedro Rustan, and also toured the Clementine control center in late 1993 (i.e., prior to launch) during the preparation of its report, *The Role of Small Missions in Planetary and Lunar Exploration* (National Academy Press, Washington, D.C., 1995). Lastly, shortly after the mission ended, Maria Zuber, a member of the committee and a scientist associated with Clementine's Lidar instrument, briefed COMPLEX on the mission's preliminary science findings.

During the October 1994 meeting COMPLEX received presentations from members of the Clementine science team, including Alfred McEwen, Paul Lucey, and David E. Smith, and from the lunar science community in the person of Roger Phillips (chair of NASA's Lunar Exploration Science Working Group). Details on the operational aspects of Clementine were presented by Paul Regeon (Clementine program manager at the Naval Research Laboratory), Stewart Nozette (BMDO's deputy program manager for Clementine I), Donald Horan (science operations manager), and Trevor Sorensen (lunar mission manager). COMPLEX also received additional input on Clementine's instrumentation, technology, and operations in the form of copies of presentations given at the Clementine Engineering and Technology Workshop (Lake Tahoe, July 18-19, 1994) and follow-up discussions with individual presenters. An initial draft of the report was finalized at COMPLEX's February 1995 meeting and received initial approval by the Space Studies Board in March 1995. The report was updated and extensively revised during the autumn and winter of 1996.

*Although Dr. Shoemaker became a member of COMPLEX in 1995, he played no role in this study.

Contents

EXECUTIVE SUMMARY	1
1 INTRODUCTION	3
The Role of Small Missions, 3	
Different Cultures, 4	
Clementine and Its Goals, 4	
References, 6	
2 CLEMENTINE AND LUNAR SCIENCE	7
Geophysics and Geodesy, 9	
Geology and Surface Physics, 9	
Mineralogy, 10	
Clementine's Contribution to Lunar Science Objectives, 11	
References, 11	
3 MISSION IMPLEMENTATION	12
Schedule, 12	
Budget, 13	
Management Approach, 16	
Technology Utilization, 16	
Mission Operations, 17	
Data Processing, 20	
References, 20	
4 CONCLUSIONS	21
Reference, 22	
GLOSSARY	23



Executive Summary

Clementine was a relatively low-cost, technology-demonstration mission that, as a secondary objective, was designed to survey the Moon and to fly past an asteroid. After a 22-month development phase, the spacecraft was launched in late January 1994. Operated by the Ballistic Missile Defense Organization within the U.S. Department of Defense (DOD), Clementine was the first U.S. space mission to leave Earth's vicinity that was not run by NASA. Because of Clementine's many similarities to NASA's current drive to carry out space missions that are "smaller, cheaper, and faster," this document describes some of the mission's operational features that differ from traditional NASA practice and that might be profitably brought into scientific spaceflights. This report first presents a preliminary assessment of Clementine's scientific return to date. Although much of the data reduction, calibration, and analysis is yet to be completed, Clementine already appears to have returned interesting and valuable scientific results, especially its identification of the lunar topography, which shows much more relief than anticipated. However, the spacecraft's limited instrument complement prevented the mission from accomplishing the highest-priority objective for lunar science, namely determination of the Moon's global geochemistry. This should not be regarded as a failure, because the mission was not motivated by the achievement of any particular scientific objective. Answers to most of the fundamental scientific questions, listed previously by COMPLEX,* will come only after further exploration of the Moon by orbiters and landers.

Clementine carried several new-technology devices and utilized lightweight spacecraft components. These elements are likely to have considerable application aboard small space science missions. Clementine was operated unlike most of the major space science missions of the past two decades: a small, highly dedicated team was given full responsibility for virtually all phases of the mission from design and construction of the spacecraft through to its launch and subsequent operation. The project stayed close within its budget and the spacecraft was delivered on time. Several aspects of Clementine—its cost, its incorporation of new technology, technological cooperation between NASA and DOD, and the scheme for software development—should be studied by groups more appropriately constituted than COMPLEX.

The mission's success rested to a considerable degree on the operational team's substantial freedom to make

*See, for example, Space Studies Board, National Research Council, *An Integrated Strategy for the Planetary Sciences: 1995-2010*, National Academy Press, Washington, D.C., 1994.

decisions and on the easy access to technology already developed. The tight time schedule forced swift decisions and lowered costs, but also took a human toll. The stringent budget and the firm limitations on reserves guaranteed that the mission would be relatively inexpensive, but surely reduced the mission's capability, may have made it less cost-effective, and perhaps ultimately led to the loss of the spacecraft before the completion of the asteroid flyby component of the mission.

For the most part, within its constrained lunar science objectives, Clementine was successful. Because of various factors, Clementine's costs were significantly less than most comparable space science missions might be. Since Clementine was not planned originally as a science mission and did not have science as a primary objective, funds were not allocated for instrument development and scientific calibration, or for data reduction and analysis. Nevertheless, Clementine validated the concept that, with proper operational profiles, small missions (such as those in the Discovery and MidEx programs) are capable of accomplishing significant research in space science.

Clementine also demonstrated the usefulness to space science of missions emphasizing the testing of innovative technologies, fresh management styles, and new approaches to spacecraft operations. Future missions of this type should be initiated provided that they are capable of achieving first-class science and that the scientific community is actively involved in them as early as possible.

The extent to which traditional NASA programs could or should follow this model is unclear at present. What is clear is that Clementine provides an existence proof that a small team of non-NASA researchers can successfully assume the overall responsibility for a deep-space mission.

Introduction

The Clementine mission carried out by the Department of Defense's (DOD's) Ballistic Missile Defense Organization (BMDO) was quite unusual by recent NASA standards: the mission objectives were primarily technological with secondary but significant science goals; the mission's definition and development were completed on a speedy schedule toward a fixed launch date; the project team was small, as was the BMDO program management staff; and fiscal resources were limited, but the team had access to a large pool of newly developed spacecraft technologies and in-place contracts. Clementine occurred during the period when NASA was shifting its program toward "smaller, cheaper, faster" missions, such as those in the Discovery and MidEx programs, that are intended to have many of the characteristics of the BMDO mission. The performance of Clementine is, therefore, directly relevant to the prospects of these new NASA programs.

THE ROLE OF SMALL MISSIONS

Even though NASA has flown "Clementine-style" spacecraft in the past and has periodically made concerted attempts to establish lines of small planetary missions prior to the current Discovery program,¹ the scientific potential of such missions remains a controversial topic. While many claims have been advanced for small missions, it is impossible to ignore the successes of "large" programs such as Viking and Voyager. Moreover, it is difficult, if not impossible, to estimate how many "small" missions would have been required to produce the same yield of scientific results and at what cumulative cost, including the load on the Deep Space Network and other operational expenses. Past COMPLEX reports have some bearing on these issues. The committee's 1994 report, *An Integrated Strategy for the Planetary Sciences: 1995-2010*, explains that a responsive planetary exploration program demands a mix of mission sizes ranging from comprehensive missions with multiple objectives (such as Galileo and Cassini) to small missions with highly constrained scientific objectives.² At the same time *The Role of Small Missions in Planetary and Lunar Exploration* concluded that a series of small missions present "the planetary science community with the opportunity to expand the scope of its activities and to develop the potential and inventiveness of its members in ways not possible within the confines of large, traditional programs."³ Thus, COMPLEX does not believe that there is a simple, all-purpose conclusion to the small-versus-large issue; rather, the potential scientific return per dollar spent is something to be determined in the selection of individual missions and not by an abstract analysis of large versus small.

DIFFERENT CULTURES

No study of the Clementine mission is complete without a note about the quite different “cultures” operating within DOD and NASA. A full analysis of these differences was beyond the scope of this study. Several differences, however, were immediately obvious to COMPLEX. These include:

- The greater resources available overall to DOD versus NASA;
- The underlying sense of urgency surrounding military projects contrasted with the more leisurely pace of civil programs;
- Less involvement by Congress, and reduced micromanagement on the part of DOD leadership in the day-to-day aspects of the program; and
- A narrower, more focused, task-force-like management style that differs greatly from the broad, participatory approach more familiar to members of the scientific community associated with NASA’s missions.

An issue related to the different cultures of DOD and NASA is their potential rivalry. Although the size and scope of DOD’s space activities match or exceed those of NASA’s, there has been little direct competition between the two programs in the past. Recent concerns about the hazards posed by near-Earth objects and the U.S. Air Force’s reported interest in assuming the role of lead agency for planetary defense could exacerbate potential rivalries. With proper management, however, such a rivalry could be constructive.

CLEMENTINE AND ITS GOALS

The Clementine mission’s primary goals were to space-qualify advanced, lightweight imaging and multispectral cameras (as well as component technologies) and to test autonomous operation for the next generation of DOD spacecraft. Shortly after the idea for this mission was conceived, secondary objectives—to perform a 2-month global mapping survey of the Moon and a flyby of the near-Earth asteroid, 1620 Geographos—were added. The specific science goals for Clementine were dictated by the capability of the spacecraft and the availability of instruments that matched this capability, rather than by well-established priorities for lunar science.^{4,5}

To meet BMDO’s goals, Clementine implemented a streamlined management style that included a rapid design and development program, with an approval-to-launch time line of 22 months. Of particular note was an innovative approach to mission operations and data handling, characterized by the intimate involvement of the science team in the day-to-day, indeed hour-to-hour, operation and planning of the science observations. The spacecraft was designed, built, tested, launched, and operated for a reported cost of about \$80 million (\$9 million for spacecraft systems, \$8 million for instruments, \$38 million for spacecraft integration, \$20 million for the launch vehicle, and \$5 million for operations; see Table 1.1).⁶

The spacecraft, whose characteristics are summarized in Box 1.1, was launched on January 25, 1994 (by a refurbished Titan IIG ICBM), and, using a phasing-orbit transfer trajectory, was inserted into a polar orbit about the Moon on February 19, 1994. It orbited the Moon for 71 days, during which it acquired almost 2 million digital images of the Moon at visible and infrared wavelengths, improved the determination of the Moon’s gravitational field, and, through laser ranging, accurately measured the global lunar topography. The asteroid flyby and its accompanying test of autonomous navigation were aborted because, following a software error, the attitude control gas was entirely depleted.

The first half of the remainder of this report provides a preliminary assessment of the science accomplishments of Clementine; this assessment is based on a series of published papers⁷ as well as interviews with team members and other lunar researchers. The report then lists some of the lessons that the space science community might learn from Clementine’s mode of operation, which had more in common with the Discovery and MidEx approach than with traditional NASA missions.

TABLE 1.1 Clementine Budget: Projected and Actual Cost Estimates (in FY 1992 \$) Through May 31, 1994, for Various Aspects of the Clementine Mission

	Projected	Actual
Sensors	\$ 4,800,000	\$ 4,800,000
Attitude control system	2,480,000	1,984,125
Reaction control system	2,360,000	2,359,719
Electrical power subsystem	3,100,000	3,145,796
Sensor processing	2,680,000	2,753,366
Communications system	2,200,000	2,184,918
Payload integration	37,380,000	37,988,944
Total payload cost	\$55,000,000	\$55,216,868
Operations	5,000,000	5,337,292
Launch vehicle	20,000,000	20,000,000
Total mission cost	\$80,000,000	\$80,554,160

NOTE: Although COMPLEX did no detailed analyses to verify any of these figures, none of the data seems unreasonable.

SOURCE: As supplied to COMPLEX by Paul Regeon, Clementine's program manager at the Naval Research Laboratory.

Box 1.1 Characteristics of the Clementine Spacecraft

Mass

- Space vehicle (launch adapter, kick motor, interstage, and spacecraft): 1,691 kg
- Spacecraft (dry weight): 235 kg

Propulsion

- Solid rocket motor for lunar injection
- N₂O₄/MMH* for propulsion
- N₂H₄ for attitude control system

Data Storage

- 2.0-gigabyte DRAM,* solid-state data recorder

Power

- Gimbaled (single-axis) GaAs/Ge* solar array (2.3 m², 460 W at 30 V D.C.)
- 15 amp-hour NiH₂ common pressure vessel battery

Attitude Control

- 3-Axis stabilized via reaction wheels
- ±0.05° Control
- ±0.03° Knowledge
- Ring laser gyro and interferometric fiber-optic gyro inertial measurement units

Processing

- Parallel processor architecture
- Mil-Std-1750A (1.7 MIPS*) for safe mode, attitude control system, and housekeeping
- R3081 (18 MIPS) for image processing, attitude control system, and autonomous processing

Communications

- Deep-space network compatible transponder without encryption
- 128-kilobits per second (kb/s) downlink (max); 1-kb/s uplink

*Abbreviations and acronyms are defined in the glossary.

SOURCE: As reported by Pedro Rustan, Clementine program manager, at the Clementine Engineering and Technology Workshop, July 1994.

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Clementine and Lunar Science

Clementine should be judged by the science community in the context of the rules under which it was planned and conducted. First, it should be recognized that lunar science was a subordinate objective for Clementine, though ultimately an important one. Second, the mission's funding was tightly constrained: not only was the planned cost low, but the reserves were also tightly held. Third, the short schedule (less than 2 years) before launch limited the software development and testing, as well as reduced the prelaunch calibrations of instruments. Fourth, the mission was redirected approximately 12 months before launch from a test of technology, with some scientific participation in the form of an ad hoc science advisory committee, to one that included scientific goals and was open to the full participation of the planetary science community. Taken together, these factors meant that neither the ad hoc science advisory committee nor its successor, NASA's peer-selected science team, could affect the basic nature of the mission or influence the design and selection of Clementine's instruments in any fundamental way. Nevertheless, the mission scientists and BMDO's operational team collaborated very effectively; this cooperation allowed the scientists to make some modifications to the mission design (e.g., rotating the major axis of Clementine's orbit at the midpoint of the mapping mission and using a mix of nadir pointing and oblique coverage at high latitudes) and to participate extensively in prioritizing and planning the data acquisition sequences of the Moon.

The scientific payload on Clementine (see Table 2.1) consisted of four instruments (an ultraviolet-visible camera, a long-wave infrared camera, a combination laser-ranger/high-resolution camera, and a near-infrared camera); in addition, the spacecraft carried two star-trackers, which occasionally were used as wide-field cameras, and an S-band transponder, which provided information on the orbit and thereby allowed the Moon's gravitational field to be inferred. A summary of the instrument payload may be found elsewhere.¹

Before describing the achievements of Clementine, it is valuable to recall COMPLEX's primary objectives for lunar science achievable from orbit:²

1. Global composition and mineralogy;
2. Global topographic and gravitational field mapping;
3. Improved determination of the magnetic field; and
4. High-resolution imaging of selected areas.

Below COMPLEX assesses the extent to which the early analyses of Clementine data³⁻⁷ suggest that these

TABLE 2.1 Characteristics of Clementine's Instruments

	Ultraviolet-Visible Imager	Star Tracker	Near-Infrared Imager	Long-wave Infrared Imager	High-Resolution Imager	Lidar Receiver ^d	Lidar Transmitter ^b
Focal plane array	Thomson CCD ^c	Thomson CCD	Amber InSb ^c	Amber HgCdTe ^c	Intensified CCD	Si APD ^c	
Pixel format	384 × 288	384 × 576	256 × 256	128 × 128	384 × 288	Single cell	
Pixel size (μm)	23 × 23	23 × 23	38 × 38	50 × 50	23 × 23	0.5 mm ²	
Clear aperture (mm)	46	14	29	131	131	Shared with high-resolution imager	38
Focal length (mm)	90	17.5	96	350	350	Shared with high-resolution imager	99
Field of view (degrees)	5.6 × 4.2	28 × 43	5.6 × 5.6	1.0 × 1.0	0.4 × 0.3	0.057	
Resolution per pixel (arc sec)	52.6 × 52.6	262.4 × 268.9	78.8 × 78.8	28.1 × 28.1	3.6 × 3.6	205.2	
Filter bandpass (nm)	415 ± 20 750 ± 5 900 ± 15 950 ± 15 1000 ± 15 400 to 1000	400 to 1100	1102 ± 30 1248 ± 30 1499 ± 30 1996 ± 31 2620 ± 30 2792 ± 146	8.0 to 9.5	415 ± 20 560 ± 5 650 ± 5 750 ± 10 400 to 800 Opaque	0.4 to 1.1	1.064 and 0.532
Integration times (ms)	0.2 to 733	0.2 to 773	11, 33, 57, 95	0.144, 1.15, 2.30, 4.61	0.2 to 773		
Gains	150, 350, and 1000 e/bit ^c	75, 150, and 350 e/bit	0.5 to 36X	0.5 to 36X	150, 350, and 1000 e/bit	100X	
Offsets (bits)	5	5	8	8	5	None	
Power (W)	4.5	4.5	11.0	13.0	9.5	(Housed in high-resolution imager)	6.8 at 1 Hz; 2.6 quiescent
Weight (kg)	0.410	0.290	1.920	2.100	1.120	(Housed in high-resolution imager)	1.250

^aThe A/D resolution of the lidar receiver was 14 bits (40 m per bit), whereas all of the cameras had a resolution of 8 bits.

^bThe laser used for the lidar was an Nd-YAG that produced a pulse of radiation with a duration of <10 ns. At a wavelength of 1.064 μm, the pulse has an energy of 171 mJ and a divergence of <500 μrad. At a wavelength of 0.532 μm, the pulse has an energy of 9 mJ and a divergence of 4 mrad.

^cAbbreviations and acronyms are defined in the glossary.

SOURCE: As reported by the mission and science teams. See S. Nozette et al., "The Clementine Mission to the Moon: Scientific Overview," *Science* 266:1835-1839, 1994; and A.S. McEwen and M.S. Robinson, "Mapping of the Moon by Clementine," *Advances in Space Research*, 1997, in press.

objectives will ultimately be met by further research. In doing so, COMPLEX is cognizant of the fact that Clementine was not designed primarily to address any of the above goals. Thus the fact that it might not have been responsive to some or all of these priorities cannot be interpreted in any way as a failure on its part. COMPLEX notes that Clementine's achievements have been exaggerated in some quarters and denigrated in others. Thus, the spirit of this section is to place Clementine's preliminary scientific results in context and to outline areas where its achievements have motivated additional studies. COMPLEX's assessment covers three areas: geophysics and geodesy, geology and surface physics, and mineralogy.

GEOPHYSICS AND GEODESY

To date, the most thoroughly studied measurements from Clementine are those of the laser-ranging (Lidar) and gravitational-field experiments. Although the Lidar instrument was not designed for scientific studies of planetary topography, it provided a near-global topographic data set that is an important advance over our previous knowledge of lunar shape. The single-shot ranging precision of the Lidar was about 40 m and is comparable to the stated accuracy (100 m) of the spacecraft orbit with respect to the lunar center of mass. The high relief observed is unexpected and interesting. The verification of (previously proposed) degraded, ancient impact basins and the uniquely deep floors of Maria Crisium and Humboldtium are other examples of the findings. The fact that the 2° by 2° (60 km by 60 km) grid is complete except at latitudes above 75° makes this set particularly valuable for geophysical studies across regional to global scales. However, because of the data's resolution and the instrument's inability to track over rough terrains (80% of all valid returns were obtained over maria, even though maria cover just 18% of the Moon's surface), the data set is generally not well suited for detailed regional modeling or short-to-medium-scale geophysical characterization of the lunar topography. Improvement in both the horizontal and vertical geodetic control of the Moon is, however, significant. Horizontal control, that is, the accuracy with which we now know the latitude and longitude of features on the Moon, particularly those on the far side, has been improved by about an order of magnitude.⁸ Similarly, improvement in the geodetic control to about 100 to 200 m vertically from the Clementine observations will prove valuable for registration of various data sets. This knowledge will also be useful for targeting future robotic and human exploration missions.

The gravity results also improve our understanding of the Moon, though to a lesser degree. The lunar highlands are found to be nearly isostatically compensated, whereas impact basins display a wide range of compensation states that do not correlate simply with basin size or age. The lunar crust is apparently thinned under all resolvable basins. Thus the Moon's structure and thermal history are more complicated than was previously believed.

The data on the far-side gravity field contain useful new findings but are poorly constrained with respect to the precise magnitudes of the anomalies owing to the usual problems associated with the tracking of an intermittently obscured spacecraft. Accordingly, significant uncertainty remains about the lunar gravity field, especially the far-side values and high-spatial-resolution data; a future mission (including a subsatellite to allow differential tracking) will be required to complete the global gravitational survey of the Moon. In addition, gravitational observations over an approximately 1-year period will be necessary to unambiguously resolve possible tidal signatures that could indicate the presence (or absence) of a molten deep interior.

GEOLOGY AND SURFACE PHYSICS

Clementine yielded global coverage of the surface with digital images of ~100- to 400-m resolution at all latitudes. When fully calibrated and mosaicked, these will form the first global digital image database for the Moon. Such data are appropriate for comparative geological studies of surface morphology, stratigraphy, and structure, although the high Sun-angles of some images severely limit their utility in discriminating the details necessary to allow such studies. This limitation was not due to inadequacies in Clementine's cameras or failures in mission planning but, rather, was a consequence of the advisory committee's decision to concentrate on high-Sun-angle observations necessary for spectrophotometric mapping of the Moon's lithological units rather than low-Sun-angle observations necessary for morphological studies.

An exception to this is the data obtained by Clementine's high-resolution camera. It acquired one-color (750-nm) images in both hemispheres poleward of 50° in the form of narrow strips that overlap at latitudes greater than some 82° to provide continuous coverage of both lunar poles. These images, with naturally low Sun-angles and a spatial resolution of ~20 m, will be valuable for geological analyses of these previously poorly imaged regions. The identification of perennially shadowed areas is a significant finding because these areas are potential depositories of lunar ice.

Processing of the high-resolution data is currently under way, and release of calibrated, monochromatic mosaics of both polar regions is scheduled for late 1997. Calibrated, monochromatic strip mosaics of the data taken between 50° and 82° north and south, four-color strip mosaics of selected areas, and a limited number of four-color maps constructed from pointed observations of areas of special interest are also scheduled for release in late 1997.

Overall, the restricted latitudinal range of the high-resolution, low-Sun-angle imagery and the complete lack of selective very-high-resolution (~1-m) imagery, cited in COMPLEX's previous recommendations,⁹ constrain the usefulness of Clementine's imaging to provide additional information about lunar geological processes and to provide context for interpreting other kinds of data.

The long-wave infrared camera obtained images of ~20% of the Moon at ~100-m resolution. Work on reducing these images is in progress. Algorithms to remove the large number of instrumental artifacts in these images have been developed, and calibration of the images has begun. The complete data set should be available in late 1997. These data may ultimately be valuable for the determination of particle sizes and the evaluation of surface porosity.

Analyses of Clementine star-tracker images of the lunar limb are in a preliminary stage. Nonetheless they have the potential to provide additional constraints on the distribution of any electrostatically levitated lunar dust.

MINERALOGY

The reduction and calibration of the great bulk of the mission data, a vast archive of images in five visible and six near-infrared spectral channels, are currently in progress. A global, one-color (750-nm) mosaic with a resolution of ~150 m is complete and is scheduled for release on compact disks in late 1997. The current rate of calibration and processing efforts suggests that a global data set, in five visible channels and with a resolution of some 150 to 250 m, will be available in early 1998.

The reduction and calibration of the images from Clementine's near-infrared camera have been hindered by instrumental effects such as spatial variations in the detector's dark current. These difficulties now seem to have been constrained, and first-order calibration should be completed by late 1997. Calibration of the entire near-infrared data set should be completed in early 1998. The final product will be a six-channel global mosaic image of the Moon at a resolution of some 200 to 250 m.

Preliminary investigations with a small fraction of the available data indicate that it will be possible to map limited mineralogical information (i.e., major components) for at least near-side areas that can be calibrated through comparison with Apollo and Earth-based data sets.¹⁰ Initial results for the Aristarchus, Copernicus, Tycho, and Giordano Bruno areas show previously unresolved lithologic diversity and indicate that useful comparative results can be obtained, and possibly more. A global map of lunar iron concentration derived after much postprocessing from the multispectral images has yielded useful results supporting evidence from studies of lunar samples for a more mafic lower crust as excavated by impact basins.

The success of ongoing efforts to accurately calibrate Clementine's images will ultimately determine whether or not worthwhile additional mineralogical information can be obtained for regions on the Moon's far side. If current efforts are successful, the analysis of these various data would allow an important first step toward mapping the lithologic diversity of the lunar surface, one of the major objectives of lunar orbital science.

Clementine carried out a simple version of a bistatic-radar experiment in which the spacecraft's radio signals were scattered off the near-polar surface and then these reflected signals were ultimately received by NASA's Deep Space Network. While the observations are consistent with the presence of water ice in the permanently

shadowed region of the Moon's southern polar region,¹¹ such an interpretation requires confirmation with independent data obtained using a less ambiguous approach.

Even if one is optimistic about how much information on lunar composition might be gleaned from Clementine, a systematic global mineralogical and geochemical mapping of the lunar surface will still be necessary. Geochemical mapping is needed to identify concentrations of major elements to the degree that would indicate Mg/Fe ratios and abundances of radioactive elements (U, Th, and K). Another high priority is confirmation of the existence of possible polar ice deposits. Unambiguous mineral identification will require an optimized high-spectral-resolution spectrometer.

CLEMENTINE'S CONTRIBUTION TO LUNAR SCIENCE OBJECTIVES

Clementine measurements made significant contributions to recognized lunar science goals in geophysics and geodesy, demonstrated the potential for limited lithological mapping, and provided a valuable supplement to earlier imaging of the lunar surface. The spacecraft did not furnish information on surface geochemistry, the magnetic field, global heat flow, or deep internal structure.

In summary, most of the work in data reduction and analysis for Clementine is still in progress, but there is reason to hope for a yield of important new understanding of the Moon. If this proves true, this constrained mission will have accomplished significant lunar science. The fact that the majority of the fundamental scientific questions posed by COMPLEX and other groups such as NASA's Lunar Exploration Science Working Group¹² may not be answered with data provided by the Clementine instrument complement is not relevant to an overall assessment of the Clementine mission. It was not designed to achieve these or any other scientific objectives, and so cannot be judged by these standards. To critically assess questions that deal with the origin and evolution of the Moon, further orbiters and landers seem necessary. COMPLEX notes, but does not discuss within the context of this report on Clementine, that NASA has selected Lunar Prospector as the third (but first competitively chosen) Discovery mission.

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Mission Implementation

Clementine operated quite differently from most large space science missions flown during the last two decades, but it is anticipated that many future NASA missions will function along the lines of Clementine. Thus several aspects in the implementation of the Clementine mission are relevant to the lessons that NASA might learn from the successes and failures of this mission. These characteristics are discussed below, and the strengths and weaknesses of the Clementine approach are addressed. Several of the lessons learned from the Clementine mission underscore the recommendations found in COMPLEX's report, *The Role of Small Missions in Planetary and Lunar Exploration*,¹ as well as in previous documents prepared by other committees of the Space Studies Board.²⁻⁴ COMPLEX's prime recommendations in these areas have included the following:

- The budget, schedule, and risk envelope should be defined in advance and adhered to;
- The approach to project management should be streamlined so as to eliminate excessive reviews and oversight; and
- All data and information necessary for their interpretation should be promptly archived in NASA's Planetary Data System.

SCHEDULE

Clementine was launched less than 2 years after it was approved by the Department of Defense. The 22-month (or 28-month, using the criterion assumed in Table 3.1) development schedule imposed on this mission is acknowledged by the project management to have been significantly too ambitious, resulting in inadequate readiness for flight operations. Insufficient time was available to develop and fully test the flight software, to carry out enough end-to-end testing of the spacecraft and telecommunication links, and to recruit and train the full operations team. The deficiency manifested itself in an excessively stressful mission-operations phase that was clearly exhausting to the team and may well have contributed to the ultimate demise of Clementine after the lunar portion of the mission had been completed but before insertion onto the asteroid flyby trajectory.

Although the short schedule caused significant problems, the limited available time brought some benefits. These included a lower total price and accurate cost projections; a focused mission that was able to address problems of current interest with the latest technology; and maintenance of the enthusiasm of the staff, who, for the most part, stayed on for the duration of the mission.

COMPLEX believes, based on comments from the Clementine operational and management teams, that a 6- to 8-month-longer schedule would have been much more realistic for the mission. Such a development time would inevitably call for a larger budget than that made available to the Clementine team. COMPLEX's discussions with personnel involved with Clementine suggested that this increment would have been a small fraction of the project's total cost.

Future Discovery missions planned by NASA's Office of Space Science assume a nominal 36-month development phase; NASA's other "smaller, faster, cheaper" science programs (e.g., Earth Probes, Earth System Science Pathfinders, Solar-Terrestrial Probes, Small Explorers, and MidEx) also demand short development times. The Clementine experience indicates that such a schedule can be adequate, but only if the Discovery projects enjoy the other advantages of Clementine, such as unchanging objectives, disciplined management, a proven launch vehicle, and resources made available according to the original plan. A 36-month schedule would not be adequate if the scientific instruments required substantial development. No such development was needed for Clementine since BMDO/DOD had earlier made substantial investments to bring the necessary technology to maturity.

BUDGET

The cost of the Clementine mission was, according to the figures supplied to COMPLEX (see Table 1.1), significantly lower (in inflation-adjusted dollars) than that of any previous planetary mission, and less than the projected expenses of three of the four Discovery missions selected to date (Table 3.1). In judging Clementine's price, it must be recognized that the mission had both successes and failures. In the technology arena, Clementine was successful in achieving its goal of space-qualifying sensors and spacecraft subsystems, but the mission failed before autonomous acquisition and tracking of a moving object could be tested. Scientific goals were accomplished at the Moon; however, the asteroid science objectives were not achieved.

Even given the partial failures, the general perception exists that, for planetary missions, Clementine has set a new standard of performance within a constrained budget. This perception needs to be tempered by the fact that there are apples-vs.-oranges reasons that a DOD mission might come out ahead in a cursory comparison with a NASA mission. DOD's inherent advantages included:

- *A corporate culture that was able to dictate a schedule that was too tight.* A more realistic schedule would necessarily add to the cost (as well as perhaps reduce the risk).
- *Previous investments in spacecraft technology by DOD,* which meant that the additional cost for this mission could be relatively modest.
- *A degree of institutional strength in negotiating DOD's many contracts* that has not been achieved by NASA in the past and may not be achievable with the kind of open process traditionally utilized by NASA. For example, government procurement rules prohibit the use of a single vendor, but this restriction compromises a project's ability to quickly develop and purchase specialized technological devices even if it is known that only a few contractors are experienced in a particular line of work.
- *Absence of certain overhead costs that are typically borne by NASA science missions* (specifically, the Clementine project was charged only for its full-time team members and not for part-time support).

On the other hand, a NASA science mission, by its very nature, will incur cost penalties not applicable to DOD missions such as Clementine. These include:

- *The cost of the science team.* NASA established and funded Clementine's science team to validate the data and plan for its archiving.
- *Data analysis expenses.* In contrast to NASA's traditional policy, no data analysis was supported by the mission.
- *The development of an optimized science payload.* Clementine's instruments were not optimized for scientific observations.

TABLE 3.1 Comparison of Small Exploration Missions

	Clementine	NEAR ^a	Mars Pathfinder
Mission type	Orbiter	Rendezvous	Lander
Destination	Moon 1620 Geographos (flyby)	433 Eros 253 Mathilde (flyby)	Mars
Launch date	25 January 1994	11 February 1996	4 December 1996
Arrival time	1 February 1994 (Moon)	June 1997 (Mathilde) January 1999 (Eros)	July 1997
Return date	—	—	—
Lifetime at destination (months)	2	12	1 to 12
Wet mass (kg)	458	805	570
Dry mass (kg)	235	485	325
Dimensions (m)	2.0 × 1.0	1.7 × 1.7	1.5 × 2.65
Payload	Ultraviolet/Visible Imager Near-Infrared Imager Long-wave Infrared Imager High-Resolution Imager/Lidar ^a	Imager Near-Infrared Spectrograph Lidar Magnetometer Gamma-ray Spectrometer	Imaging System α-p-X-ray Spectrometer Meteorology Package
Payload mass (kg)	6.3	55	20 (includes rover)
Cost (FY 1996 \$M) ^b			
Development/Construction	67 (55)	125	199
Operations/Support	6 (5)	48	18
Launch	25 (20)	48	48
Total	98 (80)	221	265
Manufacturer	NRL ^a	APL ^a	JPL ^a
Launch vehicle	Titan IIG	Delta II 7925	Delta II 7925
Development schedule (months) ^c	28	29	39
Primary rationale	Technology	Science	Technology
Management style	"Skunkworks"	Traditional NASA	Traditional NASA
Selection process	Preselected	Preselected	Preselected

NOTE: Clementine and NASA missions such as the first flight in the New Millennium program (Deep Space 1) and the four selected Discovery missions (Near-Earth Asteroid Rendezvous, Mars Pathfinder, Lunar Prospector, and Stardust) display a variety of similarities and differences. However, the only areas where Clementine stands out as an extreme are in terms of its payload (the smallest) and its launch vehicle (a refurbished ICBM).

The process by which Clementine was selected and managed has many elements in common with four of the five NASA missions. Like Mars Pathfinder and NEAR, Clementine was preselected by its sponsoring agency. But Clementine's "skunkworks" management approach (intimate control by a small team with full authority and accountability for every aspect of the mission) has more in common with the principal-investigator mode adopted by the Discovery missions selected through open competition (Lunar Prospector and Stardust) than with the traditional approach adopted by NASA for the preselected Discovery missions. Deep Space 1 stands out as an interesting variant in that it is run as a traditional NASA program but was defined and selected via a hybrid process involving integrated product development teams, that is, groups of experts drawn from industry, academia, and government and charged with the task of identifying and prioritizing technologies likely to increase the capabilities and lower the life-cycle costs of future science missions.

^aAbbreviations and acronyms are defined in the glossary.

Lunar Prospector	Deep Space 1	Stardust
Orbiter	Flyby	Flyby/Sample Return
Moon	3352 McAuliffe, Mars, and Comet P/West- Kohoutek-Ikamura	Comet P/Wild-2
October 1997	July 1998	February 1999
October 1997	February 1999 (McAuliffe) April 2000 (Mars) June 2000 (West-Kohoutek- Ikamura)	January 2004
—	—	January 2006
12 to 24	—	—
233	495	339
126	414	271
1.4 × 1.29 (plus 2.5-m booms)	1.7 × 1.8	1.5 × 2.2
Gamma-ray Spectrometer Neutron Spectrometer α-particle Spectrometer Electron Reflectometer	Integrated Imager and Spectrometer Integrated Plasma Instrument	Imager Aerogel Dust Collectors Aerogel Volatile Collectors Dust-Flux Monitors Mass Spectrometer
55	18	45 (includes return capsule)
30	60	128
26	?	34
5	35	37
61	95 (?)	200
Lockheed Martin	Spectrum Astro	Lockheed Martin
LMLV2 ^a	Delta II 7326	Delta II 7426
25	34	41
Science	Technology	Science
PI ^a	Traditional NASA	PI
Competition	Preselected/IPDT ^a	Competition

^bThe cost figures for Stardust were obtained from its principal investigator. The costs of the remaining NASA missions were taken from the agency's FY 1997 budget. All are shown in FY 1996 dollars. The values for Clementine are estimates of its cost in FY 1996 dollars based on its FY 1992 costs (shown in parentheses) obtained from its program manager. The inflation factor used to make the conversion was that used by NASA in its Announcement of Opportunity for the fifth Discovery mission (NASA, *Discovery Program: Announcement of Opportunity Soliciting Proposals for Basic Research in Space Science*, AO 96-OSS-02, NASA, Washington, D.C., September 20, 1996, page 8). Clementine's operational costs do not include NASA's contributions to science operations. Costs for Mars Pathfinder include the \$25 million for its rover contributed by NASA's former Office of Advanced Concepts and Technology. The figures for total costs include, in some cases, contingency funds.

^cFor consistency, COMPLEX has defined the development schedule of a mission as the interval from October 1 of the fiscal year of its new start through to its month of launch. By this reckoning, Clementine's development schedule was 28 months rather than the usually quoted value of 22 months.

- *The proper calibration of the science payload and the data it returns.* Clementine's data calibration is being paid for by NASA's Office of Space Science.
- *Provisions for making the data available through the Planetary Data System.*

The integrated effect of all these factors on the final budget is difficult to assess without more detailed analysis by those with the appropriate expertise. COMPLEX is confident, however, that even with an adjustment of 50 to 100% (note that in the latter case, the total cost would be only a little more than Discovery's cost cap of \$150 million (FY 1992 dollars), which excludes the cost of the launch vehicle and operations), Clementine still provides a challenging cost standard for space science missions. It appears that this challenge is being addressed by NASA with the Discovery and MidEx missions now under development, as well as by NASA's planned New Millennium missions.

Clementine operated within a rigid cost cap. This was a two-edged sword: the presence of the cost cap was valuable in forcing economies and prompt decisions, but the rigidity of the cap also meant that insufficient funds were available shortly before launch, when monies could have been valuably spent. The obvious (and already well understood) lesson here is that contingency funds, and their proper disbursement, are vital for the effective management of space missions.

MANAGEMENT APPROACH

The management approach adopted by Clementine was, according to many of the presentations given to COMPLEX, typical of that used in DOD space programs since the late 1950s. Early NASA programs adopted a similar style, but many of these practices have been eschewed in recent decades. In essence, a "skunkworks," a small hand-picked team, was given complete responsibility and accountability for the success of the project from design and construction through to launch and operation. BMDO program management served to provide resources according to the agreed schedule and to facilitate procurements and interfaces with other federal agencies; oversight was limited to essential and judicious reviews. In other words, the approach was very similar to that recommended by COMPLEX as the appropriate model for small missions.⁵

Given the obvious high quality of the team and its commitment to success, the Clementine management approach can serve as a model (for NASA and for the other governmental institutions that control the flow of resources) for the management of future low-cost planetary missions.

TECHNOLOGY UTILIZATION

Clementine was a technology-demonstration mission that was partially successful in meeting its primary goals. Its failure to completely meet all of its secondary science goals does not appear to have been due to any deficiency in the advanced technology used. Moreover, the significant deep-space capabilities demonstrated within the payload capacity of a relatively small launch vehicle were, in fact, enabled by the lightweight/high-performance technologies used. So, again, a new standard was established in terms of the speed with which space qualification was achieved for new technology in sensors, electronics, structure, and propulsion. NASA should seek more insight than has been acquired by COMPLEX into the process by which this qualification was achieved so rapidly. Indeed, many of the technological aspects of the Clementine mission, e.g., its use of prescreened, commercially available electronic components rather than special-purpose, radiation-hardened devices, could bear closer examination by groups more appropriately constituted than COMPLEX.

The Clementine technology itself can be of substantial benefit to future missions, both in reducing future costs and in improving science yield. Table 3.2 lists the heritage and possible future applications in the space sciences and elsewhere for some of the advanced technology components that Clementine helped to space-qualify for civilian flight.

A note of caution must be provided to this discussion of Clementine technology. The Clementine mission was carried out in one of the more benign of space environments—lunar orbit, which substantially resembles Earth's orbit. For planetary missions that might transit great distances inward or outward from Earth's orbit, the thermal

environment becomes extreme, solar electrical power generation may be problematic, and communication delays of tens of minutes or hours create the need for substantial autonomy. Clementine's transit time to the Moon was short and the mission lifetime was abbreviated. By contrast, a more typical planetary mission may take years simply to reach its target, and an Earth-orbiting observatory might have an operational lifetime of a decade or more. Hence, some question must remain as to whether the new technology employed by Clementine would survive an extended flight in a more hostile environment, either much closer to or farther from the Sun than Earth.

Managers' conservatism with respect to the use of new technology in deep-space missions derives legitimately from the extremely challenging environment faced by their spacecraft as well as from the traditional reluctance of NASA to take risks. Such conservatism may be costing NASA's space exploration program a substantial price because the newest technologies can greatly enhance performance at the same time that cost and mass are reduced. Reductions in mass can translate into major savings in launch costs. Since COMPLEX does not claim expertise in spacecraft design and operation, it cannot attempt to resolve the issues associated with new technology and risk. Nevertheless, COMPLEX is encouraged by the general success of Clementine and, accordingly, anticipates that the balance will turn toward the use of the latest technologies with their many potential benefits.

In COMPLEX's view, the Clementine mission, though technological in nature, has been useful for space science. Programs like it, which emphasize technology, should be initiated. The testing of new technologies, fresh management approaches, and innovative spacecraft-operation schemes as the primary objectives in a low-cost, short-duration program is an important component of a healthy space program. Two essential features of such missions must be that they do first-class science and that the scientific community become involved in them as early as possible.

NASA's New Millennium program could, potentially, continue the role of technological innovation begun by Clementine. To do so, however, the organization of New Millennium will have to differ considerably from various past NASA programs that were organized with the intended goal of developing valuable space technologies; occasional external oversight of such a program might be useful.

A broader issue raised by the Clementine mission concerns the degree to which DOD's space-technology activities, such as Clementine and its possible successors, should be coordinated with similar NASA technology endeavors such as New Millennium. NASA's technology programs have been roundly criticized for many years.⁶ Competition from other organizations—whether governmental laboratories (e.g., the Naval Research Laboratory or Phillips Laboratory), quasigovernmental facilities (e.g., the Applied Physics Laboratory), or commercial ventures—could be constructive, if properly managed. A full assessment of the potentially important benefits to space science that could be achieved by a technological alliance between NASA and DOD deserves attention at the highest levels in both organizations and close scrutiny by a group more appropriately constituted than COMPLEX.

MISSION OPERATIONS

The mission operations phase of the Clementine project appears to have been as much a triumph of human dedication and motivation as of deliberate organization. The inadequate schedule, referred to above, ensured that the spacecraft was launched without all the software having been written and tested. The inflexible budget imposed on the project also meant that the complete operations team was not recruited and trained in time to be ready for launch. Thus the team was under enormous pressure from the outset. This pressure was heightened by the operation team's self-imposed determination to completely achieve the science goals related to mapping the entire lunar surface (which required, for example, some ingenuity to fill inevitable gaps in coverage by reprogramming the observation sequences). Clementine's operations team was able to accommodate orbit-by-orbit variations in the configuration or operational mode of instruments based on the science team's examination of data already in hand. The team also agreed to conduct last-minute additions to the scientific program, such as the bistatic radar experiment, and was remarkably responsive to the additional requests of the science team. Further, the spacecraft performance was marred by numerous computer crashes. It is no surprise that the team was exhausted by the end of the lunar mapping phase.

The extraordinarily large volume and completeness of the lunar data set acquired in the face of the problems

TABLE 3.2 Clementine's Advanced Technology Components, Their Heritage, and Examples of Future Applications

Item	Heritage	Flown Before?	Examples of Subsequent Uses	Examples of Future Uses
Lightweight reaction wheel	LOSAT-X ^a (with different configuration)	Yes (no information)	—	GFO
R-3000, 32-bit RISC Computer	Brilliant Eyes and Brilliant Pebbles flight test programs	No	MSTI-3	Lewis, Clark
1750A Computer	USAF spacecraft	Yes: TAOS	Milstar, NEAR, MGS	IUS, MISR
GaAs/Ge Solar Arrays	DOD applications MSTI-1	Yes: classified program	Mars Pathfinder, Sojourner, TRACE, STRV-1B	Iridium, TRMM, GFO
Solid State Data Recorder	Classified applications	Yes (no information)	NEAR, MGS	Cassini, Lewis, Clark, ACE, SBIR
Frangibolt Release Mechanism	NRL (general applications)	No	TOMS, Mars Pathfinder	STRV-2, SAPPHIRE, Lewis, Clark
Single Pressure Vessel Battery	Communications satellite industry	No	MGS	Iridium, Lewis, Clark

Inertial Measurement Unit	THAAD, LEAP	No	Derivative of instrument on missiles flight test program	Deep Space 1, LMLV, DOD applications including Apache helicopter
Data-compression Chips ^d	CNES program	—	—	Cassini
Star Tracker	Brilliant Pebbles flight test program	Yes: early version on BMDO suborbital flights	—	Bitsy, Mars Surveyor 1998 Orbiter and Lander
Ultraviolet/Visible Imager	Brilliant Pebbles flight test program	Yes: early version on BMDO suborbital flights	—	—
High-Resolution Imager/Lidar Receiver	Brilliant Pebbles flight test program	Yes: early version on BMDO suborbital flights	—	—
Laser Transmitter	Brilliant Pebbles flight test program	No	—	—
Near-Infrared Imager	Space surveillance applications	No	—	—
Long-wave Infrared Imager	No	No	—	—

NOTE: Abbreviations and acronyms are defined in the glossary.

^dInformation on the data-compression chips could not be confirmed, but the entries are consistent with information presented by Jacques Blamont (Centre National d'Etudes Spatiales) at the July 1994 Clementine Engineering and Technology Workshop.

SOURCE: Information and choice of entries based on material initially supplied by Paul Regeon, Clementine program manager at the Naval Research Laboratory, and later updated with additional material supplied by Stewart Nozette and David Barnhart of the Clementine II team at the U.S. Air Force's Phillips Laboratory. Individual entries were confirmed and updated, whenever possible, by members of the relevant mission teams or the manufacturer of individual components.

cited above indicate that the Clementine project's approach to organizing and staffing the operations phase of the mission enjoyed many essential strengths. The organization of the operations team was carefully designed by the project management to provide minimal sufficiency and, within the severe limits of schedule and budget, intense training and rehearsal. It would be very useful for some group, more appropriately constituted than COMPLEX, to undertake a study into the process by which the mission operations software was developed. Given Clementine's small budget, it seems likely that relatively little software was custom-designed; there are likely to be valuable lessons to be learned by Discovery program participants here.

To observers of recent space science programs, a curious aspect of Clementine's failure to achieve one of its primary objectives (namely, autonomous tracking of a cold target) was that BMDO suffered little public embarrassment over this loss. This was in sharp contrast to NASA's disgrace when Mars Observer was lost just 6 months prior to Clementine. The message may be that technology-demonstration missions are expected to be difficult undertakings, whereas even challenging space science missions, such as Galileo, are assumed by the public to be fail-safe because of their high cost.

DATA PROCESSING

The volume of data returned by Clementine was very large, about 10% of the amount returned by the Magellan mission from Venus. Thus the task of data management was a daunting one, given the limited budget available to the project. The project evidently succeeded in collecting the data, storing them in an orderly way, and making them available to the science team during real-time operations. Thus, to first order, the Clementine project has demonstrated that, despite tight budget constraints, large volumes of data can be managed. Full reduction and organization of the data set for inclusion in NASA's Planetary Data System were not planned for, nor budgeted for, by the Clementine project. This responsibility devolved upon the scientists and was stated in NASA's Announcement of Opportunity⁷ to be the primary role for members of the science team. Nonetheless, funds to allow calibration of the returned data were not provided and are now coming from other sources in NASA's Office of Space Science.

An important concern about the ultimate value of the Clementine measurements remains the degree to which the data can be calibrated for quantitative analysis. This concern arises more from the way in which the sensors were selected and developed for flight than from inherent limitations in the Clementine data management process.

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Conclusions

According to BMDO, the Clementine mission achieved many of its technology objectives during its flight to the Moon in early 1994 but, because of a software error, was unable to test the autonomous tracking of a cold target. The preliminary analyses of the returned lunar data suggest that valuable scientific measurements were made on several important topics but that COMPLEX's highest-priority objectives for lunar science were not achieved. This is not surprising given that the rationale for Clementine was technological rather than scientific. COMPLEX lists below a few of the lessons that may be learned from Clementine.

Although the Clementine mission was not conceived as a NASA science mission exactly like those planned for the Discovery program, many operational aspects of the two are similar. It is therefore worthwhile to understand the strengths and faults of the Clementine approach. Some elements of the Clementine operation that led to the mission's success include the following:

1. The mission's achievements were the responsibility of a single organization and its manager, which made that organization and that individual accountable for the final outcome.
2. The sponsor adopted a hands-off approach and set a minimum number of reviews (three).
3. The sponsor accepted a reasonable amount of risk and allowed the project team to make the trade-offs necessary to minimize the mission's risks while still accomplishing all its primary objectives.
4. The development schedule was brief and the agreed-on funding (and funding profile) was adhered to.

COMPLEX recommends that these attributes should be incorporated into future small-scale NASA missions such as those in Discovery (similar recommendations were made in a recent COMPLEX report¹) and MidEx.

Among the operational shortcomings of Clementine were the following:

1. An overly ambitious schedule and a slightly lean budget (meaning insufficient time for software development and testing, and leading ultimately to human exhaustion); and
2. No support for data calibration, reduction, and analysis.

The principal lesson to be learned in this category is that any benefits from the constructive application of higher risk for lower cost and faster schedule will be lost if the schedule does not allow adequate time for the development of all essential systems or makes no allowance for human frailties.

Another lesson to be drawn is that despite its limitations, if judged strictly as a science mission, Clementine attested that significant scientific information can be gathered during a technology-demonstration mission. In the current era of limited funds, when science missions will be infrequent, the opportunity to fly scientific instruments aboard missions whose objectives might be other than science must be seized and, indeed, encouraged. During such opportunities it would be inexcusable to do second-class science. Thus the scientific community must be actively involved in such projects from their initiation.

In terms of budget and schedule, Clementine was undertaken in an even more challenging environment than might be expected for most programs within the Discovery and MidEx designations, according to current guidelines for these programs. Thus, the substantial accomplishment of Clementine provides a measure of confidence that NASA's Discovery program can be successful provided that the same degrees of team independence and risk acceptance are granted. Clementine's performance allows clear identification of many of the essential ingredients for success in carrying out low-cost, deep-space missions. Therefore, COMPLEX is encouraged to believe that the Discovery program has a significant opportunity to underpin NASA's program of solar system exploration in the years ahead. It is also likely that "smaller, faster, cheaper" programs—if properly designed and operated—can accomplish much in other areas of space research such as astronomy/astrophysics and space physics.

Many of the apparent innovations of Clementine, compared to practices on recent scientific missions, lay in areas where COMPLEX had some experience but not full expertise. Areas where more appropriately constituted groups may be able to draw additional lessons from the Clementine mission include the following:

- An accurate comparison of the cost of Clementine compared to that of a typical science mission;
- The use of new technology on Clementine;
- The pros and cons of a technological alliance between military and civilian space organizations; and
- Clementine's software development practices.

In conclusion, perhaps the most basic lesson from the Clementine mission is that the ability to carry out end-to-end planning and implementation of a (U.S.) planetary mission has evolved beyond NASA's domain. Thus an underlying assumption of the Discovery program—that a non-NASA principal investigator can be successful when assuming overall responsibility for a deep-space mission—has, in effect, been validated.

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1. Space Studies Board, National Research Council, *The Role of Small Missions in Planetary and Lunar Exploration*, National Academy Press, Washington, D.C., 1995.

Glossary

ACE—Advanced Composition Explorer.

ACS—Attitude control system.

A/D—Analog to digital.

APD—Avalanche photodiode detector.

APL—Applied Physics Laboratory at Johns Hopkins University.

Bitsy—Microsatellite developed by Aero Astro Corporation for the U.S. Air Force's Phillips Laboratory.

BMDO—Ballistic Missile Defense Organization: The arm of the U.S. Department of Defense charged with developing missile-defense systems. BMDO was formerly known as SDIO.

Brilliant Eyes—A generic name for a family of small, space-based missile early-warning satellites.

Brilliant Pebbles—A generic name for a small, space-based ICBM interceptor with a nonexplosive warhead.

Cassini—A very large Saturn orbiter scheduled for launch by NASA in October 1997.

CCD—Charge-coupled device: An electronic detector used for low-light-level imaging and astronomical observations. CCDs have now replaced photographic emulsions for sensing visible light in most space science applications.

CNES—Centre National d'Etudes Spatiales: The French National Space Agency.

Discovery—A continuing line in NASA's budget dedicated to small planetary missions characterized by a 3-year development schedule and a budget cap of \$150 million (FY 1992). Mars Pathfinder and Near-Earth Asteroid Rendezvous (NEAR), the first two Discovery missions, were granted new starts in NASA's FY 1994 budget. Two additional missions, Lunar Prospector and Stardust, were competitively selected for new starts in NASA's FY 1995 and 1996 budgets, respectively.

DOD—Department of Defense.

DRAM—Dynamic random access memory.

Earth Probes—A series of small Earth observation satellites including TOMS and TRMM.

Earth System Science Pathfinder—A line of small Earth observation satellites characterized by a 36-month

development schedule and capped life-cycle costs. The first two such missions, the Vegetation Canopy Lidar and the Gravity Recovery and Climate Explorer, are scheduled for launch in 2000 and 2001, respectively.

e/bit—electrons per bit.

GaAs/Ge—Gallium arsenide/germanium: Semiconductors used in the construction of solar arrays.

GFO—Geosat Follow-On mission.

HgCdTe—A type of infrared array detector composed of an alloy of mercury (Hg), cadmium (Cd), and tellurium (Te).

ICBM—Intercontinental ballistic missile.

InSb—A type of focal-plane array used for sensing near-infrared radiation composed of indium (In) and antimony (Sb).

IPDT—Integrated product development team.

IUS—Inertial Upper Stage.

JPL—Jet Propulsion Laboratory.

LEAP—Lightweight Exo-Atmospheric Projectile.

Lidar—Light identification, detection, and ranging.

LMLV—Lockheed Martin Launch Vehicle.

LMLV2—Second-generation Lockheed Martin Launch Vehicle.

LOSAT-X—SDIO experimental satellite.

Lunar Prospector—NASA's third Discovery mission, a small lunar orbiter scheduled for launch in October 1997 (see Table 3.1).

Magellan—The first Shuttle-launched interplanetary spacecraft. Following its launch from Atlantis in 1989, Magellan mapped almost all of Venus's surface using synthetic aperture radar and conducted measurements of the planet's gravitational field.

Mars Observer—The first and last of NASA's Planetary Observer series. It was launched in 1992 and was lost shortly before entering orbit around Mars in 1993.

Mars Pathfinder—Formerly known as the Mars Environmental Survey (MESUR) Pathfinder, this spacecraft is one of the first two Discovery missions and was launched in December 1996. The mission consists of a lander and a surface rover, "Sojourner" (see Table 3.1).

Mars Surveyor—A continuing line in NASA's budget dedicated to the launch of two small- to intermediate-sized Mars missions at every launch opportunity (every 26 months) between 1996 and 2005. The first Surveyor mission, Mars Global Surveyor, was launched in November 1996 and is expected to arrive at Mars in September 1997.

MGS—Mars Global Surveyor: The first of NASA's Mars Surveyor missions.

MidEx—Mid-sized Explorer: A continuing line in NASA's budget dedicated to low-cost (<\$70 million) missions in space physics and astrophysics.

Milstar—Military Star: A series of large military communications satellites.

MIPS—Million instructions per second.

MISR—Multi-Angle Imagery Spectral Radiometer.

MMH—Monomethyl hydrazine.

MSTI—Miniature Seeker Technology Integration.

NEAR—Near-Earth Asteroid Rendezvous: One of NASA's first two Discovery missions, it was launched in February 1996 and will rendezvous with 433 Eros in January 1999 (see Table 3.1).

NRL—Naval Research Laboratory.

OSS—NASA's Office of Space Science.

PI—Principal investigator.

RISC—Reduced instruction set computer.

SAPPHIRE—Stanford Audio-Phonic Photographic Infrared Experiment. A graduate-student project at Stanford University designed to space-qualify a micromachined infrared sensor developed at JPL.

SBIR—Space-based Infrared: A series of small satellites designed to provide early warning of the launch of tactical and intercontinental ballistic missiles.

SDIO—Strategic Defense Initiative Organization: The predecessor of BMDO.

STRV—Space Test Research Vehicle: A series of microsatellites sponsored by the U.K.'s Defence Research Agency to investigate the effects of the space environment on spacecraft electronics.

TAOS—Technology Autonomous Operational Satellite.

THAAD—Theater High-Altitude Area Defense: A long-range, ground-to-air missile system.

TOMS—Total Ozone Mapping Spectrometer: A small NASA spacecraft launched in 1996 and designed to make global measurements of atmospheric ozone.

TRACE—Transition Region and Coronal Explorer: A mission in NASA's series of Small Explorers designed to study the Sun's photosphere and corona. Launch is scheduled for September 1997.

TRMM—Tropical Rainfall Mapping Mission: A joint NASA-Japanese mission designed to measure global tropical rainfall, scheduled for launch in the fall of 1997.

USAF—United States Air Force.



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