ClementineDSPSE

Operations Manual

October, 2006
by
Scott Conklin (Usonian)

TABLE OF CONTENTS

SECTION I	***INTRODUCTION***	
	Background	1-1
	Mission Description	1-1
	Spacecraft Description	1-5
	Orbiter Configuration	1-5
SECTION II	***FLIGHT OPERATIONS***	
	Launch and Orbit Insertion	2-1
	Lunar Transfer and Mapping	2-2
	Geographos Transfer	2-4
SECTION III	***INSTALLATION AND CREDITS***	
	Description	3-1
	Required Programs	3-1
	Recommended Programs	3-1
	Optional Programs	3-2
	Sources	3-2

Introduction
Section 1

BACKGROUND

Although men landed and walked on the moon six times, from 1969 to 1972, no effort was made to systematically map the *entire* lunar surface until project Clementine, launched January 25, 1994.

Formally designated Deep Space Program Science Experiment, the project was a collaboration between the Department of Defense's Ballistic Missile Defense Organization (BMDO, aka "Star Wars") and NASA. The primary mission was to test, over a prolonged period in a harsh space environment, a new generation of lightweight sensors for detecting and tracking ballistic missiles, and to demonstrate new lightweight satellite technologies. The Moon, the spacecraft's own Interstage Adapter, and a near-Earth asteroid were proposed as targets for the primary mission. This suggested the secondary mission of returning valuable data of interest to the scientific community.

Clementine was also the first satellite built under the mantra of Faster, Cheaper, Better. It took only 22 months to bring the spacecraft from initial concept, through design, construction and launch. The entire mission cost, including Titan launch vehicle and mission control, was 75 million dollars. The lunar mapping phase exceeded all expectations, including the first indications of water ice within continuously shaded craters at the lunar poles. However, while in transit to the near-Earth asteroid 1620 Geographos a software problem caused the attitude control system to fire continuously, depleting its fuel supply and effectively ending the mission. Due to the tight time schedule, the satellite was launched with major portions of its software unwritten and untested. Even before the final loss of the spacecraft, mission controllers made extraordinary around-the-clock efforts to correct problems and keep the mission going. Doing things "Faster" forced controllers to make things up on the fly, with the ultimate result of an incomplete mission. On the other hand, doing things faster permitted the same individuals to work on the project from design conception through flight operations. Thus, the emotional commitment was exceptionally high to achieve mission success. Project Clementine was the first attempt at doing deep space exploration in a radically new way, employing many new technologies for the first time. Allowing for the usual difficulties in doing anything new, project Clementine was an astounding success.

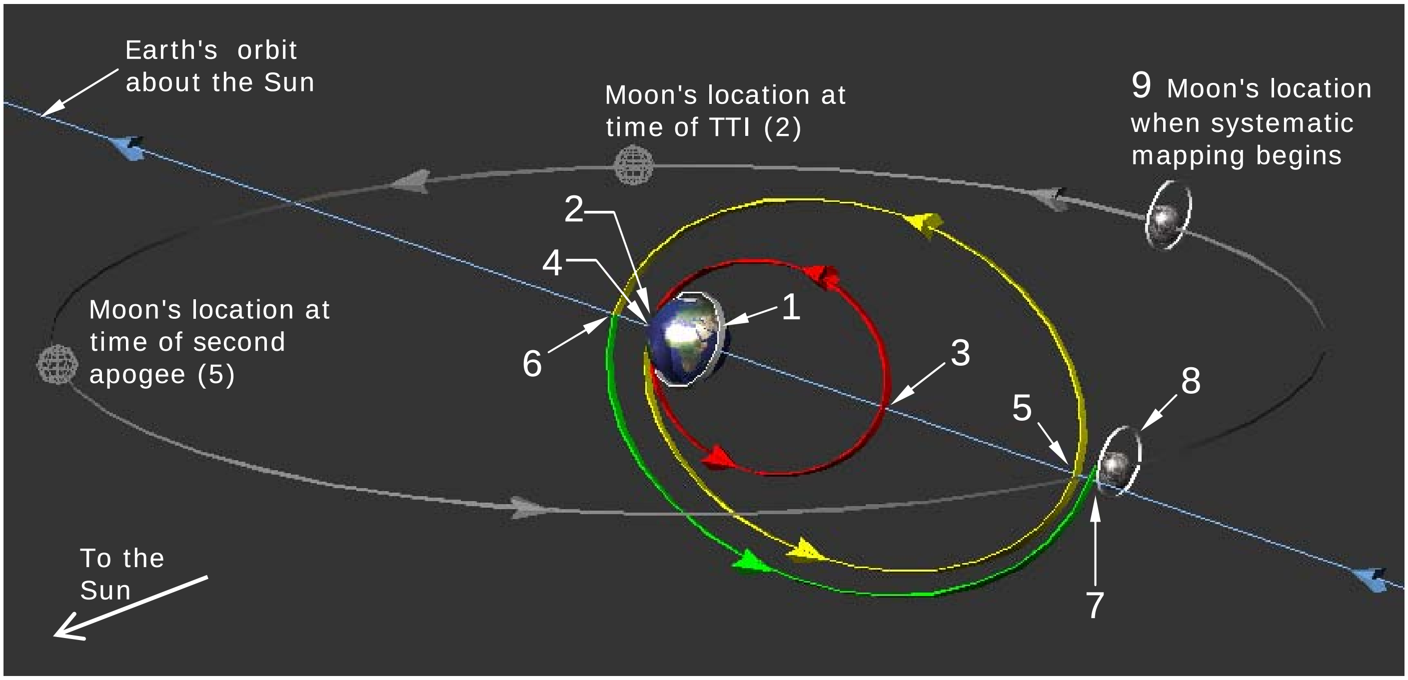
MISSION DESCRIPTION

<u>LAUNCH AND LUNAR TRANSFER</u>

To minimize the volume of onboard fuel, the lunar transfer included 2½ "phasing loops" -- highly elliptical orbits that used reletively small rocket thrusts, plus a slingshot effect from Earth's gravity, to reach the Moon. See Figure 1-1. Clementine was carried into low Earth orbit (LEO) by a Titan IIG missile launched from Space Launch Complex 4 West, Vandenberg Air Force Base. After a week of systems checks in LEO, a solid fuel engine lifted both Clementine and its Interstage Adapter Subsystem (ISAS) into the first phasing loop. The Clementine satellite separated from the ISAS and then used its own liquid fuel engine to boost itself into the second phasing loop. The ISAS remained in the first phasing loop orbit to serve as a target for Clementine's instruments and to collect data with its own instruments as it made repeated passes through the Van Allen belts. Following a second Earth swingby, Clementine entered a polar orbit around the Moon 3½ weeks after launch.

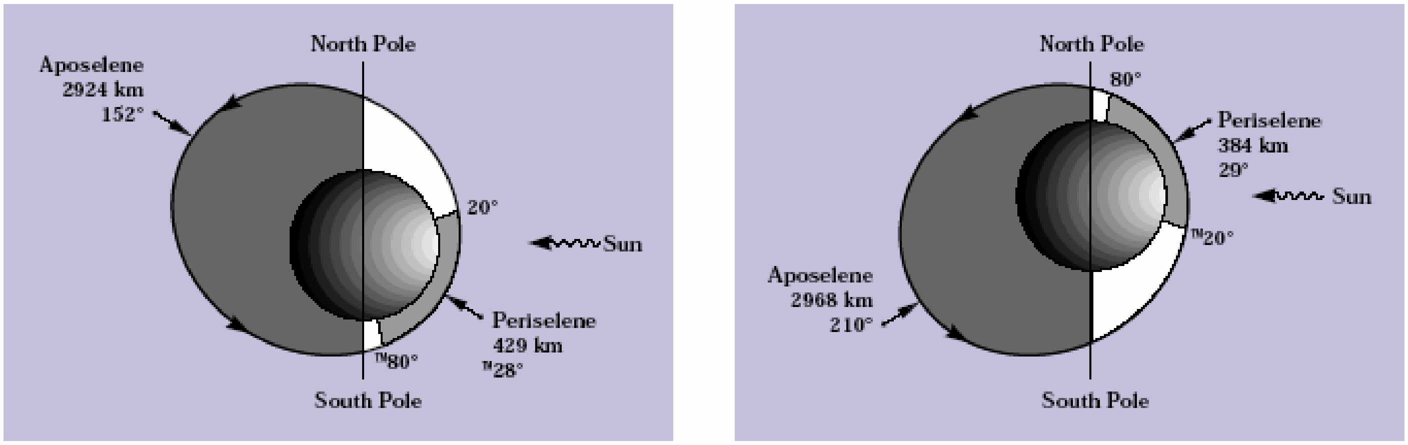
<u>LUNAR MAPPING</u>

The initial elliptical lunar mapping orbit had an inclination of 90° with an argument of periapsis at 28° south latitude. See Figure 1-2. Mapping passes were from south pole to north pole. After one month of mapping, two engine burns rotated the periapsis to 29° north latitude for the second month of mapping. In this way the entire lunar surface was photographed with consistent resolution and lighting conditions. The elliptical orbit provided a prolonged time between mapping passes during which the satellite could aim its high gain antenna at Earth and transmit the recorded data.



Key No.	Event	Date	Periapsis Alt. (km)	Apoapsis Alt. (km)	Comment
1	Launch & LEO	25 Jan 94	260±	260±	Launch from VAFB, 16:34 UT, 67° Inclination
2	TTI	3 Feb	259		Translunar Transfer Injection
3	Apoapsis 1	4 Feb		169,600	
4	Periapsis 1	5 Feb	277		Phasing loop 1 complete (red)
5	Apoapsis 2	10 Feb		385,600	
6	Preiapsis 2	15 Feb	1,141		Phasing loop 2 complete (yellow)
7	LOI 1	19 Feb	401.8	6,000±	Phasing Loop 2.5 complete (green) Lunar Orbit Insertion burn 1 (LOI 1) at 20:25:08 UT Orbit 1 LAN = 103.5° East
8	LOI 2 & LOI 2C	22 Feb	382.5	2,920±	LOI 2 burn on 21 Feb and LOI 2C (correction burn) next day establishes mapping orbit (white)
9	Orbit 32	26 Feb	401.5	2,920±	Systematic mapping begins at 21:08:02 UT LAN = 10.8° East
	Periapsis was rotated to 29° north latitude on March 26, 1994. Systematic mapping ended April 22, 1994.				

Figure 1-1. Lunar Transfer Phasing Loops and Lunar Orbit Insertion



(a) Typical lunar mapping orbit - first month

(a) Typical lunar mapping orbit - second month

Figure 1-2. Typical lunar mapping orbits. Clementine orbited from south to north. Optimal range measurements were obtained from -80° to +80° (light shading) and images from -90° to +90° (white).

TRANSFER TO GEOGRAPHOS

Clementine performed its lunar orbit departure (LOD) burn on May 3, 1994. See Figure 1-3. A large phasing loop around Earth followed by a lunar swingby set the required heliocentric transfer orbit to the near-Earth asteroid 1620 Geographos.

The phasing loop and swingby were unpowered (no Dv added by Clementine's engine) but with the loss of the attitude control system the necessary course corrections for a close encounter with the asteroid could not be made, cameras could not be aimed, and no data was retrieved from Geographos.

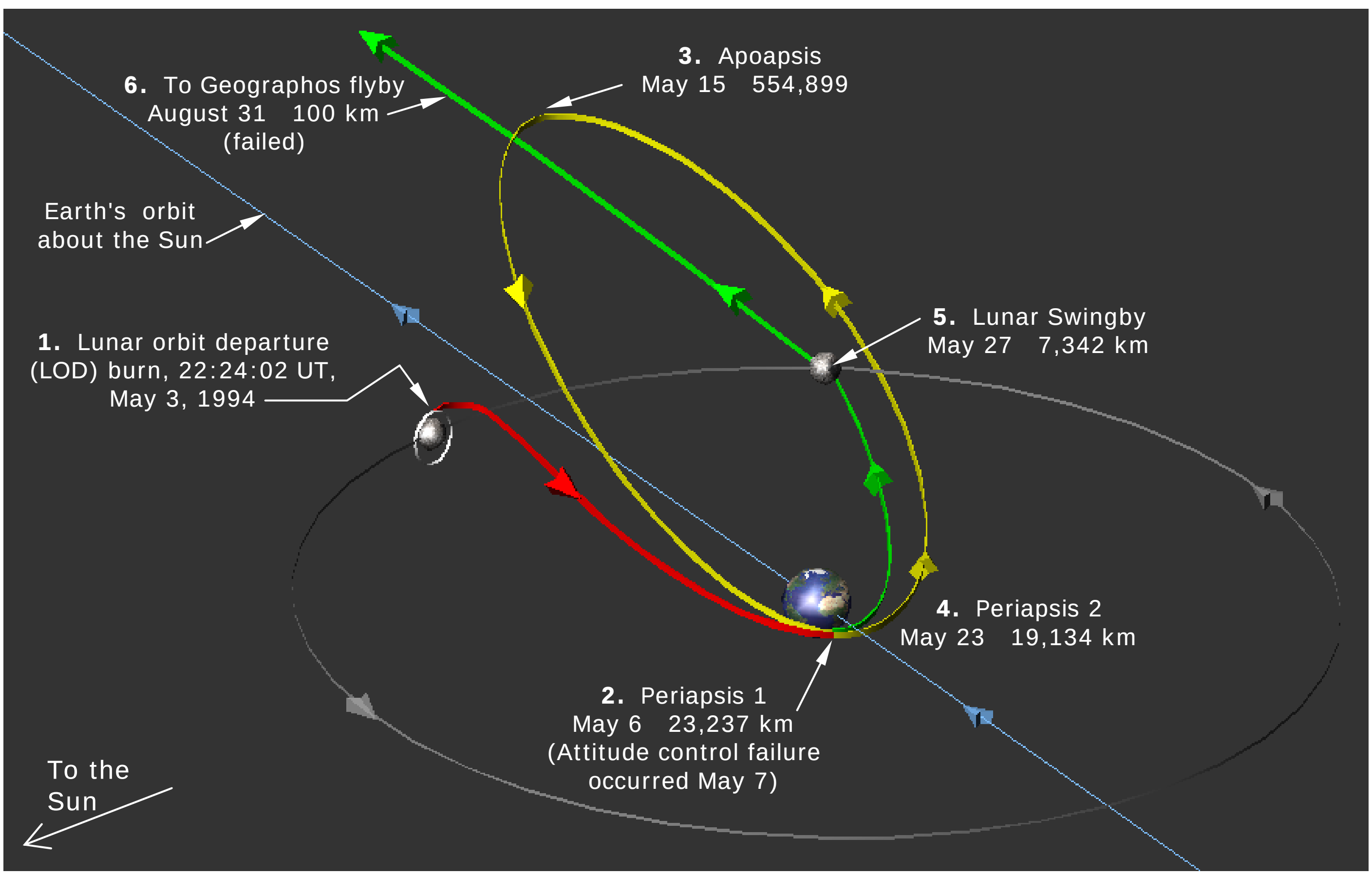


Figure 1-3. Transfer to asteroid 1620 Geographos

CLEMENTINE Delta-V BUDGET

Amount Budgeted for Historical Clementine		Amount Remaining in Orbiter	
Event	Dv (m/sec)	Dv	% Fuel
Launch		2090	100
LEO Trim Burns	8		
LEO Trim Margin	5		
TTI Slip Contingency (1 Day)	10	2060	98
TTI Corrections			
5° TTI misalignment correction			
Delta-V magnitude component	11		
In-Plan error component	72		
TTI magnitude correction	19	1980	93
TTI Make-up Burn	109	1887	87
Phasing Loop Margin	15	1871	86
LOI 1 (80% of total burn)	440	1472	63
LOI 2 (20% of total burn)	110	1358	57
Maintenance DV	9		
Maintenance Dv	9		
Lunar Orbit Trims	20	1320	55
Rotate Perislene to +30° (2 Dv burns)	111 + 114	1097	44
Maintenance DV	6		
Lunar Orbit Trims	20		
Lunar Orbit Trims Dv Margin	15	1012	41
Rotate Perislene to +48° (2 Dv burns)	39 + 39	945	37
Lunar Orbit Departure	540	250	9
Lunar Swingby Phases			
1st Periapsis	8		
1st Apoapsis	6		
2nd Periapsis	9		
Lunar Swingby Trim Burn	20		
Lunar Swignby Trim Margin	30	146	5
Geographos Approach Trims	10		
Geographos Approach Margins	10	94	4
TOTAL Budget	1814 m/sec	1995	
TOTAL Available	1900 m/sec	2090	

This table presents the change in velocity (Delta-V or Dv) provided by Clementine's main engine throughout the mission. This gives a rough estimate of how Clementine is doing on fuel as the mission progresses.

The left side of the table shows the historical Dv budget for each major event. Clementine had a separate fuel system for its attitude control thrusters which were used to aim the spacecraft for the main engine burns, and to provide fine corrections in Dv.

Clementine for Orbiter draws from a single fuel supply for both main engine and thrusters. The right side of the table shows budget figures reflecting 10% addition of total Dv to supply the thrusters.

The % Fuel Remaining can be read from Orbiter's HUD. An estimate of Dv remaining can be read from BurnTimeCalculator MFD. The figures shown represent the amount of Dv and Fuel remaining ***at the conclusion*** of event listed.

Not included in this table is the 3,003 m/sec Dv provided by the STAR 37FM apogee kick motor that is part of the separate ISAS.

Note: See Section III for sources. The historical Dv figures shown here are from December 30, 1992, early in the mission planning process. Final figures probably varied. The addition of 10% total Dv to fuel the RCS thrusters is a guess.

Table 1-1. Clementine Delta-V Budget

SPACECRAFT DESCRIPTION

The Deep Space Program Science Experiment includes two spacecraft, the Clementine satellite and the Interstage Adapter Subsystem (ISAS, also referred to as Interstage Adapter Satellite).

The ISAS is composed of a lightweight graphite-epoxy composite shell permanently joined to a solid fuel STAR 37FM apogee kick motor. The composite shell carries the launch vehicle and kick motor loads to Clementine, and also houses a BMDO radiation experiment, a dosimeter, a micrometeoroid detector, a transmitter, and solar cells. The kick motor performs the TTI burn, after which the Clementine is jettisoned from the ISAS. The ISAS does not have an attitude control system of its own. It remains in the first phasing loop orbit, tumbling freely, making repeated passes through the Van Allen belts, collecting and transmitting data, and serving as a target for the Clementine's acquisition and tracking instruments.

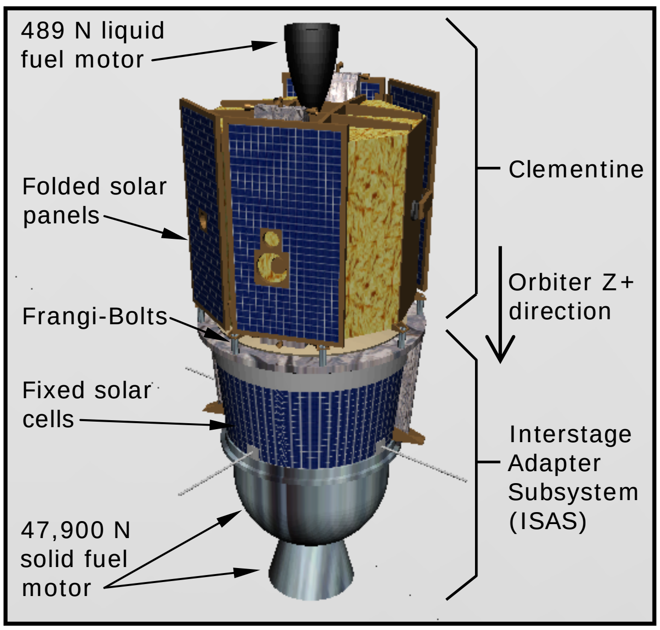


Figure 1-4. Orbiter screen shot of the Clementine and ISAS as they appear prior to the TTI burn

The Clementine satellite is an eight-sided prism of conventional aluminum frame construction with a liquid fuel Dv motor and 12 attitude control thrusters. Reaction wheels provided fine pointing and additional attitude control, reducing the volume of attitude control fuel needed. There are no Z-axis thrusters. Separation from the ISAS is achieved by

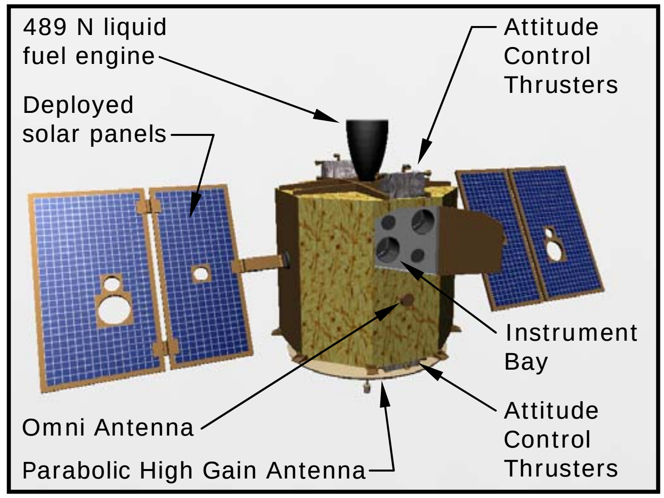


Figure 1-5. Orbiter screen shot of Clementine

the eight spring-loaded "Frangi-Bolts" that join the two spacecraft. These are a lightweight alternative to the traditional explosive bolts and are used for the first time on Clementine. Clementine's imaging sensors include an Ultraviolet/Visible Camera, a Long Wave Infrared Camera, a Laser Imaging Detection and Ranging System/High-Resolution Camera, and two Star Tracker Cameras. Additional instrumentation includes four dosimeters, a Radiation and Reliability Experiment and a Charged Particle Telescope. The sensors are housed in an equipment bay shielded from exhaust gasses during thruster maneuvers by a hinged cover panel. Clementine's solar arrays remain folded during LEO and TTI, providing 160 to 268 watts of power depending on their orientation to the Sun. When deployed, after separation from the ISAS, the gimbaled solar array can track the Sun autonomously, generating 360 watts. Power is stored in a lightweight NiH2 Common Pressure Vessel (CPV) battery used for the first time in space flight on Clementine.

ORBITER CONFIGURATION

ClementineDSPSE for Orbiter is configured with Spacecraft3.dll and launched by a CVEL Titan II. In LEO the historical Clementine provided attitude control and the ISAS solid fuel motor provided Dv for the TTI burn. This suggests that Clementine and ISAS for Orbiter would best be configured as separate, docked spacecraft, each with its own fuel supply. But, neither CVEL nor Spacecraft3 can "spawn" a payload in the form of two separate, docked ships. When jettisoned from the Titan booster, the ISAS is spawned with Clementine as its payload. Focus shifts automatically to the ISAS. Pressing the [J] key again jettisons the Clementine payload and shifts focus to Clementine. The Clementine payload is configured with zero separation velocity, and the two ships have docking ports located at their connecting point. Therefore, when the Clementine is "spawned" as a separate ship it immediately docks with the ISAS. There is no change in appearance of the joined ships, just a shift in focus from ISAS to Clementine. Pressing the F3 key will now list both the Clementine and the ISAS as separate ships. The ISAS is docked onto the "Z+" end of the Clementine (like an Agena docked on the nose of a Gemini capsule) so the Clementine/ISAS stack must be turned in a retrograde direction to make the prograde TTI burn.

The historical Clementine's main engine could produce a maximum Dv of 1,900 meters/second (a total burn time of 1,287 seconds at full throttle). The main engine and reaction control thrusters had separate fuel supplies. Spacecraft3 supports only one fuel supply, so the Clementine for Orbiter is configured (rather arbitrarily) with an ISP providing 10% addition burn time to offset the drain from the RCS thrusters.

In addition to the Clementine satellite and the ISAS, the add-on includes a satellite mounting adapter for the Titan II. This gives the ISAS/ Clementine satellite stack a realistic appearance while it is still attached to the launch vehicle, after the fairings are jettisoned. The satellite mount is configured as a second payload of the Titan II, but it remains attached to the spent booster.

CLEMENTINE CUSTOM KEY COMMANDS

[J] means press the "J" key. [CTRL] + [/]numpad means press and hold the control key, then press the slash key on the number pad.

[J] Jettison ISAS/Clementine from Titan
Jettison Clementine from the ISAS

[LShift] + [1]numpad
Extend the High Gain Antenna Boom

[LShift] + [2]numpad
Deploy the Solar Aarray

[LShift] + [3]numpad
Open/Close the Instrument Bay Door

LIMITATIONS

Achieving a polar lunar orbit, not to mention the transfer orbit to Geographos, requires some familiarity with Interplanetary MFD and/or TransX. Detailed instructions on using these MFDs is beyond the scope of this manual and (truth be told) beyond the abilities of this author. My proficiency with these MFDs is limited, as will be obvious when I explain my method for getting to the Moon. I have yet to achieve a satisfactory transfer to Geographos, but I do not care to delay the release of this add-on while I learn every aspect of how to fly it. I will be pleased to hear from any user who can offer detailed descriptions of alternative Lunar and Geographos transfer methods.

The information available on-line regarding the Clementine is very patchy. A U.S. Geological Survey web site provides links to an interactive Lunar Atlas, and an Excel file with an orbit-by-orbit summary during the lunar orbit phase of the mission. Information is harder to come by for events outside the lunar orbit phase. The dates of the major lunar transfer events (apoapsis and periapsis) were found in one technical paper, precise distances for those events were found in another paper. A third technical paper provided dates and distances for the transfer to Geographos. No paper included precise times for any of these events. The launch time is known only to the nearest minute. There are contradictions between papers (and even some contradictions *within* a single paper). And yet, they call this rocket science...

All of the technical papers attempt to illustrate the phasing loops as if they occurred in the same plane as the Moon's orbit, similar to the manner in which Apollo flights are (accurately) illustrated. It is difficult to convey the three-dimensional character of Clementine's flight path with a two-dimensional illustration. In this one regard, I think I have outdone the professionals.

Sources can be found in Section III of this manual.

Flight Operations

Section II

LAUNCH AND ORBIT INSERTION

The CVEL autopilot will not achieve the desired orbit at 260 km altitude with zero eccentricity. The launch must be flown manually. The Titan boosters do not have attitude control thrusters, steering is done by main engine thrust vectoring. Therefore, the "kill rotation" key [5] numpad does not function. Rotational "damping" is provided, which nulls the rates somewhat, but some counter-thrust must be applied to end pitch, yaw and roll maneuvers. To make fine adjustments, use 10% attitude "thrust" by holding down [CTRL] key while pressing numpad keys. As in all flight, small corrections are best -- in most cases, a few taps of a key works better than holding it down.

LAUNCH

Launch time is 16:34 UT. A launch azimuth of 155° will achieve the required orbital inclination of 67°. During the launch you will roll and yaw to the correct azimuth, and pitch "backwards" toward an inverted orientation.

TITAN II LAUNCH PROFILE for CLEMENTINE

260 km Orbit ***CVEL Titan II v1.3***	
MET +0	Launch
MET +30	Pitch to 80°
MET +60	Pitch to 70°
MET +90	Pitch to 60°
MET +120	Pitch to 50°
MET +141	Fairing Jettison (occurs automatically)
MET +150	Pitch to 30°
MET +158	Stage 1 Jettison (occurs automatically)
MET +160	Pitch to -10°
Reduce thrust to 30% [CTRL]+[-]numpad	
Continue on table at right	

Maintain -10° pitch. The Orbit MFD will indicate Apoapsis Altitude (ApA) of 300+ km and it will be decreasing. Altitude will be increasing. Maintain 155° heading and check progress toward 67° target Inclination (Inc).
Watch the Surface MFD. When the red Apoapsis marker appears in the altimeter reduce thrust to 10%. When altitude reaches apoapsis Vertical Speed (VS) will be zero. Pitch up as needed to maintain zero Vertical Acceleration (VACC).   Periapsis will still be well below the Earth's surface, but rising. Adjust thrust as desired to increase or decrease the rate at which the periapsis rises.
Continue adjusting pitch down to maintain zero VS and zero VACC as velocity increases and periapsis rises. Watch the Orbit MFD. When Ecc reaches zero shut down the booster [*]numpad   A final orbit of 260 km and zero eccentricity is ideal. An orbit of 250km x 300 km is acceptable.

Note: Flight pitches "back" to an inverted orientation during launch. Indications of pitch "up" and "down" in this table are relative to the horizon.

Table 2-1. Titan II Launch Profile

Pre-flight

- Prior to starting Orbiter, open the Orbiter Sound Configuration program (SoundConfig.exe) and check the box for the T+ 300 second counter in the "More options" section on lower right area of the screen.
- Start Orbiter and open an appropriate launch scenario. The scenario begins a few minutes before launch time.
- Jump to Titan IIG, cockpit view.
- Verify the instrument settings:
  - Surface MFD on left side
  - Orbit MFD on right side:
    Projection = Ship
    Distance Display = Altitude
    Frame = Equator
  - HUD set to ORBIT mode.

Launch

- At 16:34:00 UT ignite the Titan IIG and lock it on [+]numpad + [CTRL]
- Between MET +10 to +30 roll right about 23° [6]numpad

NOTE

The Surface HUD and Surface MFD will not return reliable heading information at 90° pitch. The Orbit HUD display helps estimate the roll angle. AttitudeMFD can also be used.

- Following the initial roll maneuver, set the HUD to Surface mode [H]
- At MET +30 pitch back to 80° [2]numpad, then…
- Correct heading to 155° using 10% yaw thrust [CTRL]+[1]numpad or [CTRL]+[3]numpad, then...
- Roll as need to bring the Surface HUD pitch ladder vertical [CTRL]+[4]numpad or [CTRL]+[6] numpad
- At MET +40 pitch back to 70° and repeat the yaw and roll maneuvers as needed to establish 155° heading and vertical pitch ladder.
- Maintain the 155° heading and continue making pitch adjustments as shown in the launch profile on Table 2-1.

LOW EARTH ORBIT

The target orbit of 260 km and zero eccentricity is ideal, but the LEO can be as eccentric as 250 km x 300 km without appreciably effecting the mission. ***However, the 67° inclination is critical.*** Clementine has a very little fuel budgeted for trimming LEO. Proper orbit must be achieved by the Titan booster alone.

- At completion of the launch, jettison the ISAS/ Clementine from the Titan [J]
- Jettison the Clementine from the ISAS [J]
  There will be no change in appearance of the ISAS/Clementine stack, but there will now be two separate and docked spacecraft. Focus will shift automatically to Clementine.

WARNING

Do not attempt to exit and save the scenario until after the TTI burn is complete. When a Spacecraft3 ship is configured with a payload the mass of the payload will be deducted from the "parent" when the payload is jettisoned, as it should be. But if the scenario is saved and then reloaded, Spacecraft3 reads the CURRENT_PAYLOAD line from the scenario file, renders the parent ship mesh correctly, showing no payload, but continues to load in the payload mass listed in the "parent" ship's configuration file. This "phantom" payload mass, added to the mass of the Clementine docked to the ISAS, will retard the performance of the apogee kick motor. This appears to be a minor bug in Spacecraft3.

Clementine's solar array remains stowed throughout low Earth orbit.

LUNAR TRASFER & MAPPING

Figure 1-1 illustrates the Translunar Transfer Injection (TTI) burn, and the 2½ phasing loop orbits that transfer Clementine from orbiting the Earth to orbiting the Moon. The object is to push Clementine's periapsis out to that point along the Moon's orbit where the Moon will be 16 days after the TTI burn. A simple way to accomplish this is to make the TTI burn on the historically correct date, at a time when the Clementine is crossing the plane of the Moon's orbit. During the phasing loops, follow the orbital parameters shown in Figure 1-1, and the Dv budget numbers in Table 1-1. During the last leg of the trip use InterpanetaryMFD's Planet Approach program to make course corrections to a lunar orbit with 90 inclination. Those users who are skillful with IMFD or TransX may be able to set up a slingshot plan from Apogee 2, make earlier, smaller course corrections, and consume less fuel.

TRANSLUNAR TRANSFER INJECTION

After achieving LEO and separating from the Titan booster, fast forward nine days to February 2, 1994, 23:55 UT. (Or simply use the TTI scenario included with the add-on.) TTI burn will take place at the earliest opportunity on February 3, 1994. As shown Figure 1-1, the TTI burn will occur as Clementine is moving from north to south.

- Set the HUD to ORBIT mode [H]
- Open the Map MFD and set the Moon as the target. Figure 2-1 shows the Clementine moving south, approaching the Moon's orbital track..

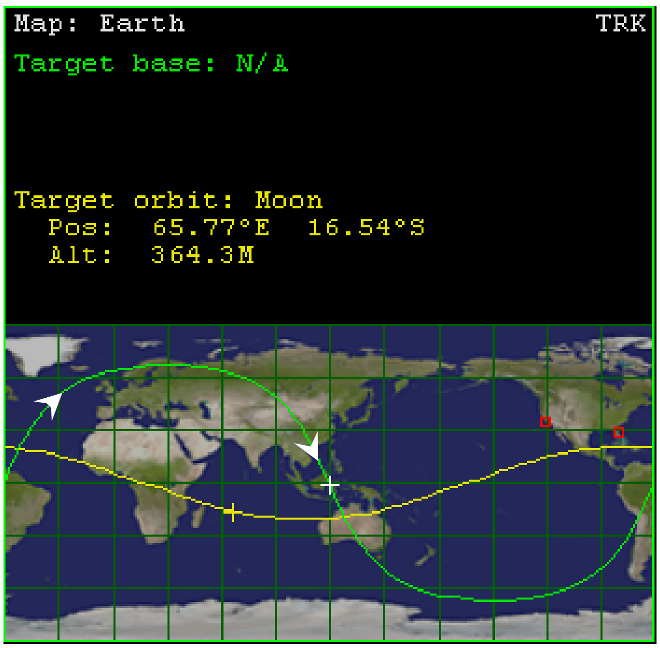


Figure 2-1. Map MFD shows Clementine moving south on its orbital track, approaching the Moon's Orbital track.

- Turn Clementine retrograde and lock in the retrograde orientation with the on-screen button.

CAUTION

Clementine's attitude control is sluggish with the ISAS still attached. Do not us the on-screen retrograde button or key command **]** to turn the spacecraft as this will waste fuel. Turn to retrograde orientation manually, using short burst of pitch, yaw and roll thrusters. Once the Orbit HUD direction indicator is close to the retrograde marker use the on-screen retrograde button to complete the maneuver and lock in the retrograde attitude.

- Jump to the ISAS [F3]
- Click the ZM button on the Map MFD to get a close-up view. When the crosshair first touches the Moon's Orbital track (Figure 2-2) ignite the ISAS motor and lock it on [**-**]numpad+[CTRL] This is a *retrograde* motor. Press the ***minus*** key.

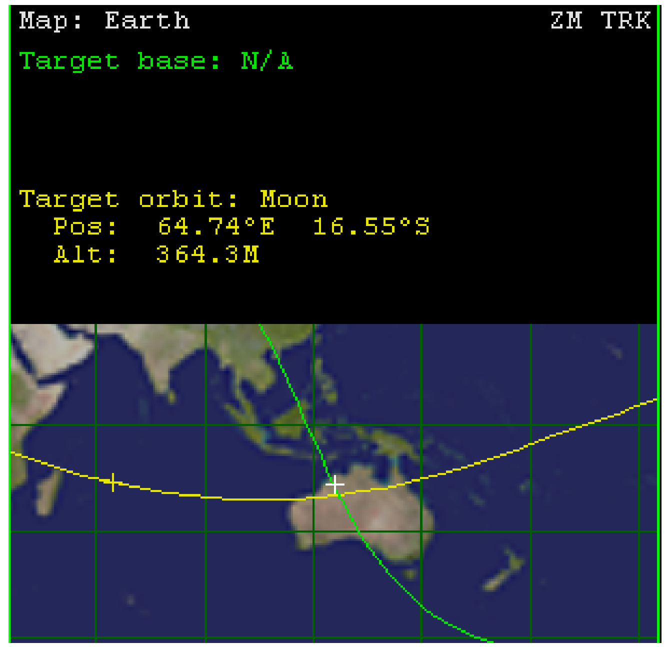


Figure 2-2. Map MFD shows Clementine's position at the beginning of the TTI burn

The ISAS motor will run for 64 seconds to burnout. Clementine will maintain the retrograde attitude. After the ISAS motor burns out:

- Jump back to Clementine [F3]
- Separate the Clementine from the ISAS by undocking [CTRL]+[D]
- Open the Orbit MFD and use the Clementine's RCS thrusters to trim apoapsis altitude (Apa) to 169,600 km (169.6 M)
- Extend the boom on Clementine's High Gain Antenna [LShift]+[1]numpad
- Deploy the solar array [LShift]+[2]numpad

PHASING LOOPS

At Apoapsis 1 use the IMFD Planet Approach Program and Autoburn to make course correction burn establishing the correct altitude for Periapsis, (277 km). Make additional course corrections as need.

NOTE

As the Phasing Loops continue the orbital inclination will decrease somewhat from the original 67°. Perhaps the historical Clementine mission planners anticipated this when establishing the initial inclination. No doubt there is a correct inclination, especially following Periapsis 2, but that detailed information can not be found on-line. Maintaining a 67° orbital inclination throughout the flight does not produce a favorable result, just let the inclination drift.

Approaching Periapsis 1, turn and lock the Clementine prograde. Open the BurnTimeClacMFD. Set the Dv to 109 m/sec as for the TTI Make-up Burn, see the Delta-V Budget, Table 1-1. Arm the BurnTimeClacMFD to make an automatic burn at periapsis. After the make-up burn is complete, use the Clementine's RCS and OrbitMFD to correct the altitude of Apoapsis 2 (385,600 km).

At Apoapsis 2 use the IMFD Planet Approach Program and Autoburn to make course correction burn establishing the correct altitude for Periapsis 2 (1,141km).

Soon after Periapsis 2, use the IMFD Planet Approach Program to set up Lunar Orbit Insertion (LOI). Set the reference to Moon and target to Equator. Set periapsis at 400 km. Set the inclination to ***minus*** 90° (- 90°). The IMFD will give a reading of the Dv required to make the manuever. As time passes this figure should decrease. The rate of decrease will slow, stop, and then begin to slowly increase. Clementine is now at the point where this manuever will be most fuel efficient. Perform an Autoburn.

LUNAR ORBIT INSERTION

As Clementine approaches the Moon set up the BurnTimeClacMFD to make the LOI 1 burn. Set Dv to 440 m/sec (from Table 1-1) and Arm the MFD to make an automatic burn at periapsis.

Clementine should approach peripasis on the sunlit side of the Moon, moving from south to north. Argument of Periapsis should be located close to 30° south latitude and 103° west longitude. The Orbit MFD may give strange readings for AgP, but the Map MFD will give an accurate visual representation of Clementine's orbit, and Surface MFD will give accurate readings of the spacecraft's longitude and latitude as it passes periapsis.

After LOI 1 burn, apoapsis will be around 6,000 km. Perform the LOI 2 burn to lower Apoapsis to 2,920 km and to make necessary corrections to AgP. The historical Clementine needed an LOI 2C (correction) burn to establish the desired mapping orbit.

Open the sensor bay door [LShift] + [3]numpad

Mission controllers performed engineering tests, instrument tests and sensor calibrations for five days following LOI. Systematic mapping began February 26, 1994.

On March 26, 1994, after one month of mapping, the periapsis was rotated to 29° north latitude by means of two engine burns. Details of these burns can not be found from on-line sources. They probably involved a prograde burn at the mid-point between periapsis and apoapsis, then a retrograde burn at the mid-point between apoapsis and periapsis. See Figure 2-3

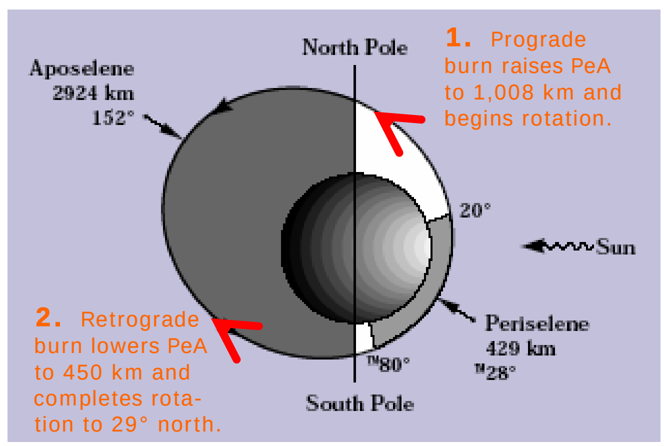


Figure 2-3. Two Dv burns rotate periapsis from 28° south to 29° north.

GEOGRAPHOS TRANSFER

Figure 1-2 contains just about all of the on-line information available regarding the transfer to asteroid 1620 Geographos. The Lunar Orbit Departure (LOD) burn takes place as the spacecraft approaches the Moon's north pole, with the Earth about 90° outside of Clementine's orbital plane.

This may "feel" counter-intuitive, with the LOD burn pushing Clementine's apoapsis away from the Moon in a direction nowhere near the Earth. Think in terms of orbiting the Earth, rather than orbiting the Moon. The LOD burn is retrograde with respect to Clementine's orbit about the Earth, lowering the periapsis of Clementine's geocentric orbit.

LUNAR ORBIT DEPARTURE

The Delta-V Budget (Table 1-1) is derived from a 1993 technical paper that indicates two burns rotating periapsis 18° (further north, I am guessing, to 47° north latitude). These burns were planned to occur five days before LOD. Presumably, the early planning had the LOD burn taking place at this more northerly periapsis location.

The Lunar Orbit Summary (from the USGS web site) shows no indication of the periapsis rotation burns taking place. According to the summary, the final orbit crossed the south pole at 21:19:48 UT. The LOD burn took place 1 hour five minutes later, at 22:24:02 UT. This appears to place the *beginning* of LOD burn very near 29° north latitude, which is the unaltered mapping orbit periapsis. But the location of the mid-way point of the LOD burn is further north, perhaps near 47° latitude.

To further the confusion, the technical paper for the Delta-V Budget shows 540 m/sec for the LOD burn. That same paper also has an illustration of the Geographos transfer with the LOD labeled as 570 m/sec.

ClementineDSPSE includes two scenarios for LOD, one with periapsis at 30° north, the other at 48° north. The 30° north scenario is probably correct, although the LOD burn may begin at periapsis, rather than centering on it. The correct magnitude of the burn is anyone's guess. By trial and error, find a burn duration that results in an Earth orbit with a periapsis of 24,200 km. The first Earth swingby is supposed to be un-powered (no Dv added) and result in an apoapsis altitude of 554,900 km. Good luck with that.

The Moon's orbit is inclined 5° from the ecliptic plane (the plane of Earth's orbit about the Sun). Geographos is inclined 13° from the ecliptic, although the asteroid is supposed be close to the ecliptic plane by the time that Clementine makes its 100 km flyby. See Figure 2-4. Presumably, the LOD burn should produce a phasing loop orbit having an inclination close to zero with respect to the ecliptic plane.

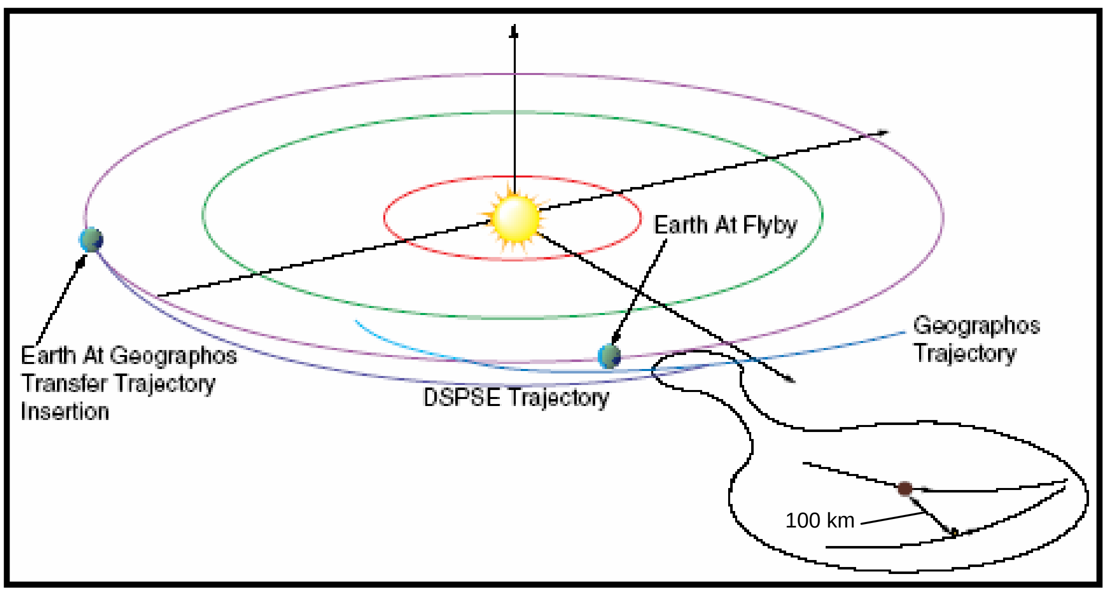


Figure 2-4. Geographos transfer and flyby.

Installation and Credits

Section III

DESCRIPTION

ClementineDSPSE is a stand-alone add-on for Orbiter Space Flight Simulator and Spacecraft3. Several scenarios can be flown without additional add-ons. The Launch scenarios require installation of CVEL Titans 1.3 A flyby of Geographos requires installation of the AsteroidPack 1.00

ClementineDSPSE has been tested only on "clean" installations of Orbiter with only the required, recommended and optional add-ons listed here. *ClementineDSPSE* installs configuration, mesh and texture files to their own custom folders, so conflicts with other add-ons should not occur. As with any Orbiter add-on, there is no guarantee.

REQUIRED PROGRAMS

The following programs are needed to operate all of the included scenarios. Unless noted otherwise, all programs can be found at Orbithanger.com In these instructions FOLDER names are shown in all upper case, File names appear in upper and lower case. Install the programs in the order shown.

Orbiter Space Flight Simulator 2006-P1 (Base) (available at: www.orbitersim.com) (Orbiter060929) by Martin Schweiger.

Spacecraft3 by Vinka (available at: http://users.swing.be/vinka/)
The required files are included with the installation of *ClementineDSPSE*

CONFIG\SPACECRAFT\Spacecraft3.cfg
MODULES\Spacecraft3.dll

Downloading the entire Spacecraft3 program is recommended for the documentation and test scenarios.

CVEL Titans v1.3 by Erik Anderson (Sputnik). Copy the contents of the .zip file to your Orbiter / *ClementineDSPSE* folder, preserving the directory structure. Note that the Titan II Launch Profile, Table 2-1, applies only to version 1.3 Titan II performance is corrected for greater realism in v 1.3

Asteroid Pack 1.00 (AsteriodPack_v1.00.zip) by NightHawke. Copy the contents of the .zip file to your Orbiter / *ClementineDSPSE* folder, preserving the directory structure. Follow installation instructions for editing Sol.cfg file to add the asteroid to the "planets" list. Installing only files for asteroid 1620 Geographos is recommended. Asteroids have odd orbits and installing all of them may create confusion when using the IMFD Map program. This is an older add-on, but it works when installed according to the instructions that come with it.

ClementineDSPSE by Scott Conklin (Usonian). Copy the contents of the .zip file to your Orbiter *ClementineDSPSE* directory, preserving the directory structure.

RECOMMENDED PROGRAMS

OrbiterSound 3.0 by Daniel Polli (DanSteph) (available at: www.orbiter.dansteph.com)
the T+300 second timer is vital for manual control during Titan launches. Installation is easy from a self-extracting file.

BurnTimeCalcMFD (BTC) 1.3 (BTC13.zip) by Kawn3217 Practically indispensable tool. Copy the contents of the .zip file to your Orbiter *ClementineDSPSE* directory, preserving the directory structure.

InterplanetaryMFD (IMFD) v. 4.6 by Jarmo Nikkanen (jarmonik) available at http://koti.mbnet.fi/jarmonik/Orbiter.html The "easier to use" orbital mechanics navigation MFD. It has its limitations, but it is beautiful.

OPTIONAL PROGRAMS

VandenbergAFB SLC-4 West (VandenbergAFB_SLC4W.zip) by Scott Conklin (Usonian) Realistic structures for Titan II launches from Vandenberg. Can be used with or without the VandenbergAFB add-on. Copy the contents of the release .zip files into your Orbiter/*ClementineDSPSE* folder. Preserve the directory structure.

VandenbergAFB (VandenbergAFB-2006.zip) by Scott Conklin (Usonian) Provides surface tiles for VandenbergAFB and surroundings. Copy the contents of the release .zip files into your Orbiter/*ClementineDSPSE* folder. Preserve the directory structure. Remember to edit the base.cfg file as described in the installation instructions.

SOURCES

1. www.pxi.com/clementine Clementine web site for Praxis, Inc. Praxis is an engineering and management services company and one of the major sub-contractors for the DSPSE mission. The most complete one-stop web site with links to most other worthwhile sites and to technical papers.

2. http://astrogeology.usgs.gov/Projects/Clementine/nasaclem/timeline/mission_timeline.html The Lunar Orbit Summary Excel file can be downloaded from here. Gives precise times and orbital parameters for LOI, periapsis rotation and LOD.

3. *Clementine "The Deep Space Project Science Experiment*" April 14-15, 1994 at the Low-Cost Planetary Missions Conference, Laurel, MD by: P.A. Regeon, R.J. Chapman, R. Baugh. Source of mission event altitudes and Figure 2-4 of the Geographos transfer and flyby. Good description of the spacecraft and subsystems.

4. The Clementine Satellite, Energy & Technology Review, Lawrence Livermore National Laboratories, June 1994 by Michael J. Shannon. Source of mission event dates and Figure 1-2 of the typical lunar mapping orbits. Good description of sensors designed by Lawrence Livermore National Laboratories.

5. Mission Characterization of the Clementine/DSPSE Spacecraft, University of Texas at Austin, February 17, 1993 by Mark T. Soyka. Source for the historical information shown in Delta-V Budget, Table 1-1.

The artist who created the painting appearing on the title page is unknown. This painting appears on many web pages and articles but no credits are given. I assume it was commissioned by NASA or DoD.