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#### LESSONS LEARNED FROM CLEMENTINE ON THE WAY TO PLUTO

J. Carraway, P. Henry, M. Herman, G. Kissel H. Price, R. Staehle, M. Underwood Jet Propulsion Laboratory Pasadena, California

### **Abstract**

Clementine has demonstrated a variety of hardware, system design, and operations innovations. The Pluto design team is currently evaluating the applicability of many Clementine approaches for the Pluto Flyby mission, including:

- A focussed science instrument payload exploiting low mass, low power instruments.
- Using Clementine star cameras.
- A similar flight computer architecture exploiting separate, dedicated spacecraft and instrument computers.
- Using the same high order uplink programming / control language (SCL -"Spacecraft Command Language")
- A similar operations style and organization during cruise.

At the same time, differences in the Pluto mission, lifetime, reliability, trajectory, and data return requirements present the Pluto mission with a set of unique design challenges.

This paper will detail areas of similarities and differences, including:

- mission objectives & programmatics
- mission characteristics
- sensors / science payload
- spacecraft system design
- data, telecom, power, and attitude control subsystem designs
- operations

### I. Mission Objectives & Programatics

Clementine was a joint Ballistic Missile Defense Office (BMDO) / NASA program

approved for funding in early 1992 with the primary objective to demonstrate lightweight component and sensor technology, and a secondary objective to return science data from the moon and an asteroid. Clementine went from conceptual design to launch in 22 months. Technology evaluation and selection was accomplished in the first six weeks. A science team was selected after the instruments were defined. Total costs were only \$80 million conceptual design through from operations. Sponsor funding was immediate and adequate to cover this new, quick reaction way of doing business.

Pluto Flyby's ability to take advantage of Clementine programmatic lessons learned is influenced by sponsor management style, constraints on early-year funding profiles, and a science driven process. Pluto Flyby is a NASA program candidate for a 1996 or 1997 new start approval and a launch in 2001 or 2002. Its primary objective is science return from Pluto and its satellite Charon, and its secondary objective is to demonstrate technology. Science requirements were defined in 1992 by a science Science instruments will be working group. selected via a traditional, competitive NASA Headquarters led Announcement of Opportunity (AO) process. Technology development and evaluation has been going on for the past 2 years, and the Pluto technology design has already been reviewed (and endorsed by) two NASA technology review teams - "challenge teams". Recent design changes have been made to accomodate the possibility of a using a Proton launch vehicle and adding a Russian probe to the science payload. Future design changes may be needed to permit adding a fields and particles instrument and to accomodate the "real" instruments that will be selected by the AO process. Funding in 1993 and 1994 has been at \$7 million per year, enough to support selected instrument, spacecraft, and operations technology development and evaluation, along with design option studies and cost estimation. Total Pluto project costs are estimated to be \$400 to \$600 million including launch vehicles and operations.

Within the above contexts, the Pluto Flyby organization has implemented a variety of management and process innovations successfully demonstrated by Clementine. These include:

- A diversified project team with members from JPL, LeRC, LLNL, DOE, the University of Colorado, the University of Arizona, GSFC, Southwest Research, Washington University, Aerospace Corp, and the USGS.
- Industry skills and technologies via subsystem support contracts.
- A small design team of primary accountables, empowered to make decisions and supported by institutional knowledge and facilities.
- More focussed and effective review and documentation procedures.
- Less emphasis on design studies and analysis, and more on hands on simulation, prototyping, and hardware test bedding.
- Concurrent design of flight system, ground system, and operations.

With the intent of continuing Pluto Flyby process improvements additional management strategies successfully employed by Clementine have been proposed to JPL management and to NASA sponsors. These include:

· Reducing the number of design options

studied and focusing on a single baseline approach.

- Obtaining a more realistic early year funding profile to avoid the driving up of costs due to a trickle-funded, prolonged development cycle.
- Assigning product assurance responsibility to the subsystems.
- Innovative acquisition strategies to allow hardware buys before NASA AO release.

### II. Comparison of Mission Characteristics

#### Mission Duration

For Pluto Flyby to meet prime mission objectives, it must operate successfully for 10 years, as compared to Clementine's planned mission duration of 8 months. The impact of this long lifetime requirement will be seen in s/c system, hardware, and software reliability design approach differences. It also impacts flight operations, making lifecycle development cost trades more significant, and influencing some different approaches toward flight team staffing and training. Another subtle implication is the pressure to implement more s/c and instrument functionality in software rather than hardware, since software can be changed over the years to accomodate new technology (such as improved data compression algorithms).

#### Solar Distance

The Pluto Flyby spacecraft and instrments must function beyond 30 AU. This impacts power system design, and has led to baselining an RTG (as have typically been used by past outer planet missions). Nuclear sources require complex NEPA compliance reports and a longer, significantly more complicated, more costly launch approval process. Formal environmental studies and design option analysis must be completed before the design can be finalized.

## Communication Range

The communication distance requirements at Pluto result in telecom link capabilities significantly less than Clementine. Maximum Pluto Flyby encounter data return rate using a DSN 34 meter tracking station will be only 80 bps (at 49000 million km) as compared to Clementine's 128 kbps (at 8.5 million km). Plans are to raise this rate up to 425 bps by utilizing the DSN 70 meter net, but this is subject to their availability in the 2010 epoch. Two way light times of up to 8 hours preclude team realtime operations or operations modes and require on-board fault detection and recovery capabilities. These capabilities complicate both flight hw and sw increase the complexity of test requirements.

#### No-Track Periods

Clementine lunar operations were conducted with essentially continuous coverage, 12 hours per day from Pomonkey, and 12 hours per day from the DSN. The desire to hold down Pluto Flyby operational costs, which include tracking station coverage costs, have resulted in a design goal for the Pluto Flyby spacecraft to be able to fly it's nine years of cruise in a highly autonomous mode, with only one 4 hour DSN track per week per spacecraft. This increases unattended operations fault detection and recovery requirements on the Pluto Flyby s/c to 7 days, and implies on-board engineering processing, performance analysis, trend prediction, and adaptive editing.

## Mission Timeline

The Clementine mission required the s/c and operations team to "hit the ground running". They had to launch, stableize the s/c, and execute critical injection maneuvers in the first month of the mission. This was followed immediately by 2 1/2 months of intense lunar mapping operations, requiring continuous around the clock operations to support collection and analysis of spacecraft and sensor technology performance data, the

production of a new orbit script every 5 hours, and the downlinking of thousands of images every orbit. In addition, during its last few days of lunar ops, Clementine demonstrated G&C automation of on-board state vector computation, propagation, and pointing.

After launch and two early trajectory correction maneuvers, the Pluto Flyby mission has 9 years of low activity cruise to prepare for encounter operations. Staffing can be 8 to 5, 5 days per week. Keeping the instruments and spacecraft healthy will be the primary task in cruise with time to test on-board automation. operations technology improvements, and encounter sequence designs. Pluto cruise operations can afford to be fault tolerant and accept reasonable risks, since as long as spacecraft safety can be assured, the penalty for a command error or a software bug that causes entry into a on-board fault algorithm, is only the loss of a routine, low activity cruise sequence.

## III. Science Instruments

First and foremost, the Pluto Flyby mission is a science mission to transform Pluto from an astronomer's planet to a geologists's and atmospheric scientist's planet. The inclusion of advanced technology demonstration is a secondary goal to be pursued where appropriate to meet mass, power, and performance requirements necessary to implement the mission. Clementine was principally a technology demonstration mission with science as a secondary objective.

To accomplish science measurement objectives, instruments must function within the limitations set by physical laws at 30+ AU. Simply stated, it is cold and dark. The instruments are being designed to acquire science quality data under very low illumination conditions from a rapidly moving spacecraft. At the outset of the Pluto mission development, challenging mass and power constraints were set for the science payload: 7 kg total mass and 6 watts total power.

Following is an instrument-by-instrument comparison between the instruments under development for Pluto Flyby and those developed and flown on Clementine.

### Instrument Comparison

#### Visible Imager:

The Pluto visible imager is designed for low illumination level, long range imaging. It will have a 7-10 cm aperture, F/6.6 optics, a nominal integration time of one second, and a frame rate of one frame every 2 seconds. The field of view is 10 mrad square with a pixel IFOV of 10 micro-radians. Color imaging may be accomplished by either dichroic beam splitters and multiple CCDs, or other filter or interferometric devices.

The Clementine visible imager was designed for illumination near 1 AU, and relatively close targets. It had a 4.6 cm aperture, F/1.96 optics, an integration time range of 0.2-773 msec, and a frame rate of 10 per second. The field of view was 73x98 mrad with pixel IFOV of 255 micro-radians. Color imaging was accomplished by a 6-position filter wheel.

#### Near Infrared Imaging:

The Pluto IR imager will provide contiguous spectral coverage in the 1-2.4 micron range with a spectral resolution of about 300, yielding the complete geochemical spectrum in that band. The field of view is about 14 mrad square with a pixel IFOV of 56 microradians. Primary optics, as well as some electronics, are shared with the visible imager. The focal plane array is passively cooled to about 90 deg K. The full spectral image cube is acquired by scanning the target image across the spectrometer slit or variable interference device. Integration times are 2-5 seconds per spectrum, giving a time to acquire a full image cube of about 8.5-22 minutes for a 256 pixel focal plane array.

The Clementine near-IR instrument

provided images in six spectral bands from 1.1 to 2.7 microns by means of a 6-position filter wheel. The bands were chosen to allow mapping of specific minerals. The longest wavelength bandpass was 60 nm while all others are 30 nm. The instrument had a 2.9 cm aperture, F/3.33 optics, and a 6 mm aperture cold stop. The focal plane array was actively cooled by a Stirling cryocooler. It had a 98 mrad square field of view with a square pixel IFOV of 400 microradians. Integration times ranged from 11-95 ms.

#### Ultraviolet Observations:

The Pluto Flyby ultraviolet instrument is really two instruments, one for observation of absorption spectra in Pluto's atmosphere during occultation of the sun by Pluto, and the other for observing the very faint airglow emissions from Pluto's upper atmosphere. In order to observe certain atomic species, the Pluto instrument must be capable of obtaining high spectral resolution (a few angstroms) spectra in the extreme UV from about 70-150 nm wavelength. In this spectral range, it is necessary to use silicon carbide optics to attain sufficient instrument throughput. A silicon carbide coated grating will be the spectral dispersing element.

The Clementine UV imaging was provided by extending the spectral response of the visible imager into the UV down to 0.3 microns. There was no specific UV bandpass filter wheel and the UV was included in the broadband filter passband.

#### Other Instruments:

The Pluto and Clementine missions each have additional instruments that are specific to each mission and are non-comparable. The Pluto spacecraft will have a radio science subsystem with an ultra-stable oscillator for an uplink radio occultation experiment to profile Pluto's atmosphere down to the surface. There will also be a Russian-supplied atmospheric probe (Zond) and perhaps, a particles and fields instrument.

The Clementine mission carried a laser ranging experiment and a long-wave (thermal) imager in addition to the other instruments.

## Payload Mass and Power Comparison

The Clementine payload was not severely constrained in power and therefore was able to use off-the-shelf components that did, in fact, have a relatively high power consumption. The UV-Visible camera used about 4.6 w plus another 11 w when the filter wheel was stepping. The near-IR camera used 13 w plus another 11 w when its filter was stepping.

The Pluto payload is constrained to a total power allocation of 6 w. Preliminary results from Pluto instrument developers indicate that the total power required to operate the payload is between 4.5 w and 6 wincluding the 1 w radio science subsystem.

The masses of the payloads for the two different missions are more similar with the Clementine UV-visible and near-IR cameras totaling about 2.5 kg while the larger aperture Pluto cameras total about 5-6 kg. It is in the area of low-mass instruments that the Clementine Project led the way in showing existance proof that high quality, very low mass instruments are possible. This has been a major factor stimulating the development of the Pluto payload.

### IV. Spacecraft Design

## Spacecraft System Design

Clementine flew a mission using a single spacecraft that had only limited redundancy (redundant telecom transponders were flown). A clever flight computer redundancy scheme was implemented that would have allowed the non-redundant housekeeping computer and the sensor computer to provide limited functional back-up for one another.

To meet reliability requirements to complete its 10 year mission, Pluto Flyby

requires a two spacecraft mission and block redundancy for most spacecraft subsystems.

Block redundancy implies more complex flight sw, fault algorithms, built in test, and resource management. A second driver for a Pluto Flyby two spacecraft mission is the science requirement to perform full surface imaging of Pluto, and this requirement can only be met with two spacecraft, given the flyby velocity and Pluto's 6 day rotational period.

In spite of the mass penalties of block redundancy, the Pluto Flyby spacecraft design dry mass is 140 kg (compared to Clementine's 230 kg). This includes the science payload and a possible 15 kg Russian Drop Zond probe. Pluto Flyby power capability is 78 watts (compared to Clementine's 360 watts). These severe mass and power spacecraft design constraints require creative subsystem technology development and aggresive use of advanced, low mass, low power technology. All of this in a cost constrained programmatic environment.

A list of low mass technologies being developed by Pluto Flyby includes:

- a micro-packaged x-band digital receiver (MMIC, MCM)
- · a composite structure high gain antenna
- a high efficiency x-band & ka-band SSPA (MMIC)
- high efficiency power converters
- advanced, high density flight computer (ASIC, MCM)
- · ring laser gyros
- high density data storage (ASIC, MCM)
- composite structure with thermal zoning bus
- micro-low leakage cold-gas thrusters
- miniaturized pressure regulator and latch valves
- · light weight louvers
- piezoelectric "inchworm" actuators

Even with the significantly different objectives, programatics, and mission characteristics outlined above, there still are Clementine spacecraft design and technology features applicable to Pluto Flyby. These next

few sections describe the applicable features for selected subsystems.

### Spacecraft Data Subsystem

Clementine successfully flew a 2 Gbit Solid State Data Recorder (SSDR). Pluto Flyby also plans to fly a solid state recorder, probably of about the same capacity. This recorder will be utilized during cruise to store engineering data during the long no-track periods, but it's primary function will be to store the 1 Gbit of catagory 1A science data captured during flyby. It will take about 6 weeks to downlink this data after encounter and the reliability and flexibility of this recorder is critical. Several of the memory management schemes used by Clementine are being considered including SSDR scrub-refresh logic, error reporting, and segment/slice management.

Clementine flew 3 computers, a Sensor Image Processor (SIP), a Data Handling Unit (DHU), and a Housekeeping Processor (HKP). The SIP performed star camera image and on-board navigation processing. The DHU provided interface, formatting, and on-the-fly compression for Clementine's six optical sensors. The HKP controlled telemetry, hosted the spacecraft command language (SCL), and executed the SCL rules and scripts uplinked by operations.

Pluto Flyby has baselined a somewhat similar data system architecture, with two separate computers, one for spacecraft command & data handling and a second for instrument interface, science data processing, and science data formatting. Clementine's innovative use of RAM, PROM, and EEPROM memories seem applicable to the Pluto Flyby design.

At the same time, the Pluto Flyby data system design will do several things different from Clementine, based on Clementine lessons learned. These differences include:

· The two computers will be of the same

type and will have similar operating systems and development environments. Clementine software development and test seemed unnecessarily complicated because a 1750A 16 bit processor running ADA and C was used for the HKP computer and an R-3000 32 bit processor running C was used for the SIP. For Pluto Flyby, identical processors will significantly simplify the ability to migrate functions between the s/c and payload computer as well as functionally back-up capabilities.

- Pluto Flyby flight computers will be high performance with adequate processing margins. Specified capabilities are 32 bit, 4 MIP, 4 Mbytes SRAM, 256K PROM, and a 1 Mbyte Flight sw boot PROM. The R3000, RAD 6000, and a NASA advanced microprocessor are all candidates. Limitations in the 1750A constrained the Clementine mission to fly the ADA version of SCL (rather than the more capable C version) and limited capabilities for self test.
- Pluto Flyby computers will be designed with built-in-test and watchdog timers to prevent prolonged operation in a failure mode, such as what happened when the Clementine thrusters were left open. The use of the block redundant, back-up computers is a possibility for an extra level of fault protection during critical events.
- Pluto Flyby computers will capture and record fault data for eventual recovery and analysis by ground operations. Such data should help troubleshoot anomalies like the unexplained HKP computer resets that occurred during the Clementine mission.

## Telecommunication Subsystem

Higher science data return rates translate directly into mission cost savings for Pluto Flyby. For this reason, an X-Band (8.4 Ghz) downlink has been baselined, rather than S-Band (2 Ghz). Even higher data return rates would be possible by using Ka-Band, and the costs of adding a Ka-Band downlink is being

evaluated. Part of Pluto Flyby subsystem design methodology is to estimate life cycle costs in order to determine transmitter power, antenna size, and mass. Based on this end-to-end perspective, a 5 watt, X-Band transmitter and a 2 meter high gain antenna have been selected. This may be compared with Clementine's 8 watt, S-Band, 1 meter high gain antenna. As indicated in the section on communication range, the Pluto Flyby range is 576 times greater than Clementine's.

Compared to Clementine, the Pluto Flyby transmitter power is slightly lower and the antenna is larger. Telecom prime power with everything on is similar (approximately 30 watts) and masses are comparable (18 kg including emergency low gain antenna and redundant RFS controllers vs. 13.6 kg for Clementine). Since Pluto Flyby is launching in the 2001 time frame, X-band uplink was chosen rather than Ka-Band since the ground system infrastructure around the world already exists to support X-Band and because spacecraft receiver hardware is cheaper. A further consideration is that in the future, not all 34 meter antennas will support Ka-Band.

The Pluto Flyby telecom subsystem team may have the opportunity to work on a possible Clementine follow-on for a lunar lander experiment. This would afford a strong future mechanism to share lessons learned between Clementine and Pluto teams.

#### Power Subsystem

Any power subsystem implementation is driven by the load requirements and the availability of a power source. Because of the different mission trajectories and lifetimes, Clementine and Pluto Flyby use different power sources, but many similarities are found in the power electronics designs.

Because of Clementine's solar range (1 to 1.1 AU), solar energy and photovoltaics were the clear choice for a power source. Eclipses required the addition of a battery. Clementine used an advanced technology Nickel-Hydrogen

Common Pressure Vessel (CPV) battery. The Clementine solar array supplied the 360 W<sub>e</sub> demand with significant power margin during all mission phases. The array produced ~480 W<sub>e</sub> at 1 AU in March 1994 (Short, 1994) for a 33% power margin. As Clementine receded to 1.1 AU the margin reduced to a still adequate 8%. The project controlled power demand growth and maintained power margin through the development cycle and into flight. The flight power margin allowed greater flexibility in operations of the spacecraft.

Pluto Flyby will encounter the planet near 30 AU after a long cruise. The solar range and cruise has led Pluto Flyby to baseline a radioisotope thermoelectric generator (RTG) as the prime power source. The final decision on the power source can not be made until after studies of environmental considerations and alternative design trades have been completed and formally reviewed. As currently designed (Schock, et. al., 1994), the RTG will produce 78 We nine years after launch. This will meet the current best estimate power demand of 67.8 We with a 15 % margin. However, at the current stage of development, the project must control the growth in power demand to assure that an adequate flight power margin is maintained, since Pluto Flyby will have significantly lower power margins than Clementine.

The power electronics serve the role of controlling the power from the power source distributing power the to Information about the Clementine power electronics was drawn from Short (1994). both Clementine and Pluto Flyby, the power bus is loosely regulated and power is distributed to the users through dedicated or semi-dedicated At least for Pluto Flyby, power converters. loose bus regulation allows more flexibility and less expensive development of the power The details of the power control circuitry. control circuits are largely driven by the power Clementine incorporated a solar array and battery controller while Pluto Flyby uses a single, internally redundant shunt regulator and a discharge controller for peak transients.

distribution Power involves many functions in addition to switching power to the users. Table 1 summarizes these functions for both Clementine and Pluto Flyby. between the two implementations include the control of the power converters by the power subsystem instead of by the users even though the requirements on the converters (voltage, regulation, load level) are determined by the Another similarity is the ability to sense the current to each individual load. This allows greater insight by the spacecraft controllers into the operation of each load so that a load failure might be predicted. In this case the load can be turned off predictably, before it fails.

Significant differences between the power electronics of Clementine and Pluto Flyby are in the use of new technology. While no new power electronics technologies were incorporated into Clementine, Pluto Flyby has baselined four new technologies in this area. The first is a solid state power distribution switch (PDS) now under development. The PDS will incorporate switching, a re-settable circuit breaker, and telemetry in a single, hybridized electronic package. The PDS will reduce the PPS mass and volume while adding reliability and functionality. The tight power budget will be loosened by the use of a second new technology: a high efficiency power converter based on the synchronous rectifier (Krauthamer, et. al., 1993). This converter will be able to convert from bus voltage to 5 V or lower with up to 90% efficiency. Another new technology is the ultra capacitor (Banes, 1994) which is baselined to reduce the mass and volume of the capacitors required in the discharge controller. Finally, the Pluto Flyby Power and Pyrotechnic Subsystem (PPS) also includes a small pyrotechnic switching assembly. Pluto Flyby has baselined laser initiation for this assembly as the fourth new technology. Laser pyros (Brown, 1994) will improve the safety of the pyrotechnic assembly, slightly reduce the mass and energy required, and permit a simple end-to-end test of the assembled pyrotechnic system during launch operations. In these areas Pluto Flyby is taking advantage of the longer development time to incorporate advanced technology.

**Table 1**: Implementation Comparison Between Pluto Flyby & Clementine Power Subsystems

Function	Clementine	Pluto Flyby
Power Switching	Magnetic latching relays on s/c loads No switching on essential loads FET loads switch with TO-5 relay control on most sensors	All loads switched with solid state power distribution switch
Power Conversion	Some users get converted voltage, some get bus voltage. Individual converters used for most power supplies.	All subsystems supplied convereted power through semi- dedicated converters.
Current Sensing	On all loads	On all loads
Voltage Monitoring	On all converter outputs	On all converter outputs
Overload Protection	Non-essential loads fused	Circuit breaker function in switch
Telemetry	Analog	Digital
Commands	Puise	Digital
Undervoltage Protection	Analog with non- essential load shed & interrupt to s/c controller	2 stage. Stage 1 is an interrupt to SDS for evaluation and individual load shed. Stage 2 is analog with non-essential load shed and interrupt to SDS

#### Attitude Control Subsystem

(to be supplied)

## V. Operations

Clementine demonstrated innovative, low cost operations concepts in many areas including:

- ground data system development methodology
- · staffing strategy and training
- use of high order / high capability command language
- · compatible flight and ground data-bases.
- validation of command scripts using a low cost operational test bed.
- · on-board automation

Pluto Flyby intends to use an operations approach similar to Clementine in every one of these areas, modified where necessary to meet different mission requirements, and extended where technology advances and a long duration mission make ops automation technologies particularly cost effective.

### Ground Data System Development Methodology

Early in the development phase, the Clementine ops manager identified 8 console positions and defined the responsibilities and duties for each. He then named 8 console cognizant engineers (Cog Es) to fill these positions plus a ground data system hardware czar and a ground system software czar. Each console cog E developed the requirements for his console and delivered these requirements to the czars who coordinated and negotiated them, and who then were responsible for delivering the coordinated agreed-to console capabilities. The Pluto Flyby GDS is being developed using a similar approach. The only real difference is that work station / consoles will be provided for spacecraft subsystem cog E's, (Clementine's spacecraft console was at the system level), with each cog E defining the data access, processing, display, and analysis tools that they require to perform calibration, health monitoring, performance analysis, and trend prediction for their particular subsystem. As a technology extension, each Pluto flyby cog E will "own" on-board flight software and will be allowed to migrate these traditional ground

functions to be automated on-board the two Pluto Flyby spacecraft. The development of this on-board automation will occur not just during the pre-launch development phase, but during the nine years of cruise operations as well. The goal is to transfer to the spacecraft, a major portion of the processing and analysis functions that currently go on in ground consoles.

## -Operations Staffing Strategy and Training

The core of Clementine operations was staffed with development engineers, who were responsible for operating the systems that they developed. This was true for both the flight and ground systems. An alternate approach is where a development organization "delivers to ops" and another, different group of ops specialists fly the mission. Pluto Flyby intends to staff ops in a way similar to Clementine, with spacecraft GDS development engineers doing operations. A benefit of this approach is that it full these engineers life-cycle gives responsibility and motivates them to think seriously about the operational characteristics of the systems and subsystems that they are developing.

Another benefit of using the development team to staff ops is that training time and costs are reduced, since these people already know their systems. A lesson learned by Clementine was that operators hired just before launch to supplement the core staff, could have used more training.

This approach worked well for the Clementine four month mission and will work for Pluto Flyby for the first year or two, but clearly, the development engineers are not likely to work full time on Pluto operations for 10 years. One approach is to exploit the low cruise activity level and the on-board automation mentioned in the previous section to allow ops positions to be staffed part time. A second approach adopted by Pluto Flyby ops is to partner with a university to provide operational support using students and university professionals. JPL cog E's will mentor students and delegate ops tasks to

them. The university will develop training tools and capabilities to teach new students coming on the project as well as new JPL engineers who will be replacing the original operations people over time. Using a university to achieve low cost, long duration ops was successfully demonstrated on the Solar Mesospheric Experiment (SME) project, where JPL partnered with the University of Colorado to perform mission ops.

Several additional benefits are afforded by a university partnership for Pluto ops. Costs are held down. Having two ops centers and teams available to fly the two Pluto spacecraft, provides a margin of ground system redundancy that will be useful during mission critical phases. NASA headquarters educational outreach goals are addressed - what better way to get students interested in science, engineering, and the space program.

# Use of High Order / High Capability Command Language

Clementine successfully demonstrated the first space flight use of Spacecraft Command Language (SCL), a high level, object oriented language developed for spacecraft control. It provides a wealth of capabilities including hyper scripting, a rule based inference engine, multi-tasking, and autonomous scheduling. Clementine found that SCL allowed automation of many tasks traditionally performed by ground operators.

Pluto Flyby is planning to use SCL and is currently testing its capabilities. Where Clementine was constrained to use an ADA version of SCL because of 1750A limitations, Pluto will be able to use the more capable C version. Pluto is evaluating extensions of SCL capabilities beyond those demonstrated by Clementine, including concurrent as well as nested (hyper) scripts, rule based fault protection algorithms, adaptive downlinking, and auto-scheduling of the pluto / charon fly-by sequence based on late on-board optical nav solutions.

#### Compatible Flight and Ground Data Bases

This feature provided by SCL was mentioned as being useful by Clementine as part of their ground software lessons learned briefing at the Tahoe conference. A particularly powerful attribute of SCL that Pluto Flyby intends to make use of is that the same data base and process control software architecture—that is running on the spacecraft, can be run on the ground as well and can be used to automate ground processes such as data handling, display, alarm monitoring, etc. Pluto plans to extend the use of SCL to automate ground process control.

The ultimate power of using the same command language and software architecture on both the spacecraft and ground data system is that it simplifies the migration of functions from flight to ground. A Pluto ops goal during cruise is a continuous ops cost reduction / efficiency enhancement program that exploits ops automation demonstrated first off-line on the ground, next in-line on the ground, and finally in-line on-board the spacecraft.

# Operational Test-Bed / Uplink Sequence Validation Tool

The Clementine Operational Test Bed (OTB) consisted of a brassboard of the flight computer that interfaced with table-driven software sim models of subsystems & instruments. This OTB was used to validate every command load. A new command load was uplinked every 5 hours during lunar ops.

Clementine operations concluded that this OTB had about the right fidelity and functional capabilities for this purpose. It could not run faster than real time, but it could skip ahead, so for instance they could skip through the 2 hours of earth-pointed downlinking in every sequence, and run a 5 hour sequence in 3 hours or less.

Clementine experience was that the OTB was severely oversubsribed during lunar ops. It was basically used up supporting the sequence development & validation process and was not

adequately available to support software development and test, its own repair and maintainance, operatons training, or s/c fault characterization and analysis.

Pluto flyby intends to develop a similar test bed capability and use it operationally to validate command loads. Clementine, used their OTB during development to develop, debug, and test flight software. Pluto plans to do this as well and extend its use to test and evaluation of spacecraft breadboard and brassboard hardware.

The OTB overload experienced by Clementine should be less of a problem for Pluto ops, since during cruise the routine ops activity level is significantly lower. However, requirements for post-launch continued automation technology development and test, and for continued new operator training will increase requirements for OTB use. Emergency scenarios where one Pluto spacecraft is in a critical state, and the second spacecraft demands OTB support has led Pluto Flyby ops to plan to implement 2 identical OTBs, one at JPL and one at the university ops site. It is expected that these will provide adequate resources to operate two spacecraft, support continued sw development, support anomaly reconstruction & analysis, support training, and provide time for maintainance & upgrade.

#### On-Board Automation

Clementine successfully demonstrated the use of on-board automation to reduce ops costs and to improve mission performance. Clementine used SCL rule-based commands to allow spacecraft event-driven scheduling rather than requiring ground ops to model, predict, and schedule spacecraft commands at specified times. A simple example was that commands to be executed after the sensor cover opened would execute when the spacecraft sensors on board indicated the cover was open, rather than the ground personnel having to calibrate and model cover opening times and then allow some margin before scheduling sensor commands to

start a fixed time later.

Clementine also successfully demonstrated on-board guidance and control. Routinely, spacecraft state vectors were loaded from the ground and propagated by the spacecraft. Toward the end of the lunar mapping phase, Clementine used on-board limb-tracking software to update the state vector and to autonomously adjust the spacecraft scheduling and pointing.

Pluto Flyby ops intends to exploit SCL rule-based commands to reduce ops costs during cruise. The r.sk and benefits of using rule-based, event driven commands to improve the efficiency of the flyby sequence is being investigated. On-board, adaptive optical navigation is already an operations requirement to allow the encounter sequence start time to be adjusted autonomously by the spacecraft based on near encounter on-board optical navigation computations.

Clementine received engineering data in realtime, essentially 24 hours per day during lunar operations. During cruise, the Pluto Flyby spacecraft will continuously capture and process engineering data on-board, but data routinely downlinked and seen by ground operations will be limited to a total of 4 hours per week at 80 bits per second. Engineering data downlinked during the 6 week postencounter playback, will be severely limited in order to get the encounter science data back as fast as possible. Pluto mission requirements downlinking extremely efficient engineering data imply on-board automation to perform health monitoring, failure recovery, performance analysis, and trend prediction that is traditionally performed on the ground. promising approach to this automation task being evaluated is the application of an automated monitoring tool called SELMON (Selective Monitoring System). This tool was developed at JPL and is currently in operational use as part of the JSC shuttle ops ground data system.

An additional Clementine lesson learned in ops automation that Pluto intends to take

advantage of is to automate the interface between schedulers & planners and the sequence implementers. A current JPL advanced uplink process tool called SUPAR (Seamless Uplink Architecture and Representation) is attempting to provide an integrated process flow between opportunity analysis, scheduling, command generation, and constraint checking tools.

## VI. Summary

Clementine demonstrated many design and management innovations that are applicable to the Pluto Flyby mission. Differences in programmatics, project objectives, and mission characteristics require modifications extensions to some of the Clementine approaches. The Pluto Flyby spacecraft and benefitted operations designs have significantly from Clementine's lessons learned.

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