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Clementine Engineering Experiments Program

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Spacecraft must survive and operate reliably in the space environments for long periods of time. Radiation, temperature variations, spacecraft charging, surface contamination, micrometeoroids, and space debris all present environmental challenges to spacecraft missions. The environmental issues associated with these effects require in situ space experiments to properly quantify the environment and its effects. To obtain data on specific mirco-electronic and sensor systems in the space environment, several engineering experiments were developed for the Clementine spacecraft and the Clementine lunar transfer booster or Interstage Adapter Satellite. These platforms allowed testing of advanced spacecraft microelectronic and sensor devices in a lunar transfer orbit that intersects Earth's radiation belts and debris environment and in interplanetary space where direct exposure to solar flares, galactic cosmic rays, and micrometeoroids was possible. A suite of experiments was developed by the Naval Research Laboratory, the Jet Propulsion Laboratory, NASA Langley Research Center, the Aerospace Corporation, and NASA Goddard Space Flight Center to investigate in detail specific radiation and environmental reliability issues. This paper presents an introduction to the issues being investigated, the instruments provided for the mission, and the rationale for the engineering program.

I. Introduction

THE advanced lightweight technologies flown on the Clementine spacecraft must operate properly in the space environment. Radiation, temperature variations, spacecraft charging, surface contamination, micrometeoroids, and space debris will all present environmental challenges for long-term operations. Although microelectronic, sensor radiation, and reliability issues related to space operations have been intensely studied in the past, the vulnerabilities of the Clementine components must be resolved with actual in situ space experiments. To obtain data on specific microelectronic and sensor systems in the space environment, several engineering experiments were developed to fly on the Clementine spacecraft and on the Clementine lunar transfer booster (or Interstage Adapter Satellite—the ISAS). These two platforms allowed testing of advanced spacecraft microelectronic and sensor devices in a lunar transfer orbit (LTO) that intersected Earth's radiation belts and debris environment and in the interplanetary space where direct exposure to solar flares, galactic cosmic rays, and micrometeoroids was possible.

The primary engineering objectives of the Clementine program were to

1) Evaluate environmental effects on lightweight space technologies.
2) Demonstrate applicability of Clementine lightweight sensor technologies to NASA missions.
3) Test detection and acquisition capabilities at realistic velocities using celestial bodies as targets.

In meeting these objectives, the Clementine program

1) Tested the following advanced sensor technologies:
a) Ultraviolet–visible camera with wide field of view (FOV).
b) Infrared (ir) cameras (short-wavelength ir, 1–3 μm wide FOV; long-wavelength ir, 7–9 μm, narrow FOV).
c) Lightweight LIDAR for precision ranging and imaging.
d) Wide-FOV star tracker for navigation.
2) Evaluated the performance of advanced, lightweight spacecraft components and systems:
a) Inertial measurement units (IMUs).
b) 2-Gbit solid state data recorder.
c) Data compression chip.
d) Ultrathin gallium-arsenide-on-germanium solar arrays.
e) Lightweight reaction wheels.
f) Nickel–hydrogen (NiH_2) common pressure vessel (CPV) batteries.
g) 32-bit microprocessor.
h) Composite structures and materials.
i) Miniature sterling coolers.

The mission goal of the Clementine Engineering Experiments Program was thus to evaluate the effects of the space environment on the advanced technologies and lightweight spacecraft components being flight-tested on the main Clementine spacecraft and the ISAS. Success for the Engineering Experiments Program was measured in terms of the ability of the instruments to contribute to the flight qualification of these advanced systems in the deep space environment. This required the characterization of the space environment during anomalous operations of the systems on the main vehicle and the evaluation of the effects of the radiation and micrometeoroid–debris environments on the ISAS instruments and their electronic devices under test (DUTs). The instrument configurations were carefully selected to fulfill these goals and to provide adequate redundancy in the case of individual instrument failure. The environmental sensors represented technologies that had been flown and tested on previous missions, thereby allowing intercalibration with earlier results. An integral part of the Clementine Engineering Experiments Program was an ongoing parallel ground test and modeling effort aimed at interpreting the flight results. The Clementine engineering data are being made available to the spacecraft engineering community for the design and testing of similar advanced microelectronic systems.

II. Description of Engineering Mission

The Clementine engineering mission actually consisted of two vehicles—the main Clementine spacecraft and an instrumented pallet on the lunar transfer booster. The latter was the result of a series of serendipitous events. Early planning for the Clementine mission indicated the requirement for a lunar transfer booster, for which a Thiokol Star 37FM solid rocket motor (SRM) was selected. The SRM had to be spin-stabilized during the burn requiring stowed solar panels. As the solar arrays provided too little power in the stowed position, it was necessary to wrap additional solar cells around the interstage adapter structure to make up the difference during this time period. The Clementine program team realized that even though this module would be left behind in Earth orbit, it would still be a valuable resource as almost 100 W of power was available. To utilize this capability, the interstage adapter was fitted with a small instrument pallet (total weight ~5 kg) that fitted on the inside adapter wall above the SRM. This led to the creation of the Interstage Adapter Satellite,

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or ISAS, for studying the effects of the Earth's space environment on individual Clementine components.

The two Clementine vehicles created a unique opportunity to simultaneously measure the effects of the space environment on identical or similar electronic systems and components under substantially different conditions. The Clementine ISAS was in a highly eccentric LTO that intersected the Earth's radiation belts (perigee ~300–~700 km; apogee ~127,000 km; inclination ~67 deg). The electronic parts and systems on the ISAS regularly encountered the Earth's Van Allen radiation belts and space debris. While at apogee, the vehicle directly sampled the interplanetary radiation and micrometeoroid environments. The ISAS consisted of the interstage vehicle and its solar arrays, the ISAS experiment package, and a simple communications package. The vehicle had no attitude control or determination and deployed in a random orientation. In contrast, the Clementine spacecraft spent the majority of its time in the interplanetary space environment on orbit around the moon, where it directly observed at least one solar proton event. The vehicle was three-axis stabilized for most of the mission with a pointing accuracy of 0.03 deg. After completion of the lunar mapping mission, a software error during the Earth gravity assist phase of the mission led to a loss of attitude control fuel and spun the spacecraft to 80 revolutions per minute. The spacecraft went dormant soon after but was reacquired in April of 1995, when its solar arrays were again adequately illuminated (aside from the loss of attitude control fuel, the vehicle was in excellent health and the Clementine Engineering Program continued). To take advantage of the dichotomy in environments between the two spacecraft, identical experiments were prepared for both vehicles that allowed simultaneous measurements and tests under widely differing environments. In addition, the ISAS was in an orbit allowing environmental measurements over an altitude range not typically monitored. In turn, the Clementine main spacecraft was one of the few spacecraft to orbit the moon and to pass on into interplanetary space. Both of these vehicles allowed unique studies of the space environment on advanced space systems and components.

In support of the engineering study, three environmental sensors were developed to measure the plasma, total dose, heavy ions, and micrometeoroid–debris environments experienced by the vehicles. For total-dose measurements, NRL provided dosimeters to record the total dose on Clementine and on the ISAS. Aerospace Corporation and NASA Goddard Spaceflight Center provided a charged-particle telescope (CPT) capable of measuring plasma electrons, high-energy electrons, and high-energy protons. This instrument was flown on the main vehicle. NASA Langley Research Center provided the Orbiting Meteoroid and Debris Counter (OMDC) Experiment for the ISAS. JPL produced two identical DUT packages, called the Radiation and Reliability Assurance Experiment (RRELAX). Each contained housekeeping chips to monitor radiation, a digital radiation test chip DUT to test two families of complementary metal–oxide–semiconductor (CMOS) devices, and a linear charged coupled device (LCCD) experiment. This instrument was flown on both the Clementine and ISAS behind minimal shielding (~1 and ~7 mils, respectively). NRL provided a package for the ISAS containing DUTs representative of several advanced microelectronic component designs. In addition, NRL monitored the Clementine solid-state recorder for single event upsets (SEUs).

The Clementine spacecraft design deviated from the normal practice of using military standard components and instead introduced commercial parts, which were not hermetically sealed. Most of the commercial plastic parts were screened to Military Specification 883B and selected to prevent destructive latchup. The spacecraft subsystems were designed to operate in the mission space environment for a full year. A description of the parts incorporated into the lightweight sensor suite and into the major spacecraft subsystems are presented in subsequent papers in this volume. The importance of these components to the engineering program is that they contributed to the requirement that the effects of the space environment on their operation be carefully evaluated before launch. The validation of this process in turn needs to be determined so that future missions will be able to learn from it—a final engineering goal.

III. Clementine Engineering Instruments

Since the Clementine advanced technologies and lightweight sensor systems are described elsewhere, only the principal engineering instruments and their objectives will be briefly defined here. Table 1 lists the instruments and DUTs flown as part of the Clementine Engineering Experiments Program. The majority of the radiation instruments are physically grouped in terms of two major packages—the JPL RRELAX on the Clementine spacecraft and the ISAS and the NRL Data Acquisition System (DAS) on the ISAS. In addition to these packages and the other instruments in the table, data from the Clementine optical instruments, its computer systems, IMUs, and housekeeping functions are available for specific studies. A final section will discuss the use of the environmental sensors, DUTs, and other Clementine systems in carrying out specific engineering experiments.

RADMON (RRELAX)

An ultracompact Radiation Monitor (RADMON), part of the JPL RRELAX instrument package, was developed to record the total dose and SEU environments. The objectives of this experiment were to provide dose and temperature (required to calibrate the dose data) measurements, profile the Earth's trapped-proton environment, and characterize the solar-flare proton and cosmic-ray fluxes for the Clementine and ISAS. The success of these measurements has established static random access memories (SRAMs) as inexpensive, low-power SEU monitors and the *p*-channel field-effect transistor (*p*FET) dosimeter as low-cost, low-power total-dose detectors. Comparing the Clementine results with other spacecraft and ground-based measurements enhances our understanding of the effects of radiation on electronic components, aids in the design of robust, radiation-tolerant systems, and helps to update models of the radiation environment.

LCCD (RRELAX)

The objective of the RRELAX LCCD instrument was to improve the capability to predict space radiation effects on CCDs like those being flown on the main Clementine spacecraft. Specifically, repeated measurements of the charge transfer efficiency (CTE), dark current (I_{dark}), and flat-band voltage shift (V_{fb}) of a LCCD were made as the LCCD and associated buried-channel metal–oxide–semiconductor field-effect transistor (MOSFET) test structures accumulated radiation damage in the Earth and space environments. The observed degradation is being compared at JPL with prelaunch predictions derived from laboratory measurements and theoretical predictions. This comparison will allow the evaluation of techniques for extrapolating laboratory data to the space environment and accurately predicting in-flight degradation. The instrument will also verify CCD ground-test methodology and quantify radiation degradation for buried-channel test MOSFETs. Ultimately the information will contribute to more robust CCD sensor designs.

CMOS and Inverter DUTs (RRELAX)

This instrument determined the damage coefficients in situ for Honeywell RICMOS-III (radiation-hard) and MOSIS (radiation-

Table 1 Clementine engineering instruments

Name	Location	Institution
RRELAX:		
RADMON	Clementine, ISAS	JPL
LCCD	ISAS	JPL
CMOS, inverters	Clementine, ISAS	JPL
DAS:		
EEPROM	ISAS	NRL
FPGA	ISAS	NRL
SRAM	ISAS	NRL
Dosimeters	Clementine, ISAS	NRL
CPT	Clementine	Aerospace, GSFC, NRL
OMDC	ISAS	LaRC
Solid-state data recorder (SEU rate)	Clementine	NRL

soft) CMOS test structures and measured the effects of feature size on total dose. Radiation effects on these test structures are being used to establish the limits for using radiation-soft quick-fab CMOS for digital logic in spacecraft and to establish inverter parameter spreads by measuring a statistically significant number of inverters (four sets of 64). The data will aid system designers in designing optimized fault-tolerant systems. The instrument is allowing the characterization of FET and inverter array threshold-voltage shifts in space that will be compared with ground-based QML flight qualification tests. The threshold voltage of the radiation-soft FET test structures is expected to change with the spacecraft dose level but the radiation-hard FETs and the shielded inverter arrays should not experience a radiation-induced change in their threshold voltages. This will permit the effects of the radiation and reliability variables to be separated and, at the same time, validate the use of radiation and reliability QML test structures in predicting the performance of integrated circuits in space. The use of wire resistor test structures for on-chip temperature measurement is also being demonstrated.

SRAM (DAS)

SRAMs provide a very simple, fairly low-cost source of on-board memory in space systems. These devices require no peripherals to operate and are representative of present advanced technology processes. Characterization of single-event effects (SEE) performance in the space environment will provide significant data for SEU predictions and may indicate that these parts are acceptable for many future applications. If so, then a source of off-the-shelf products will be available for future space systems. In addition, the SEE and total ionizing dose (TID) data will provide a valuable database for confirmation of ground-based test results.

EEPROM (DAS)

Electrically erasable programmable read-only memories (EEPROMs) provide the capability to change mission parameters or even functions while still in space and to nonvolatilely store program data during a mission. Although these are desirable technical features, the electrically erasability and programmability of EEPROMs make them suspect in an SEE environment. The EEPROMs on the ISAS were intended to provide valuable information regarding the part's susceptibility to upset and the extent of program degradation with each upset. The objectives of this test were to qualify these devices for long-term space use; characterize single- and multiple-bit cell upsets; determine degradation of SEU performance with total dose; characterize the upset rates in read-only modes vs read/write operation; correlate space test results with ground testing; and determine whether the error correction methods proposed for these devices were necessary and, if so, the degree of fault tolerance provided.

FPGA (DAS)

The field-programmable gate array (FPGA) flown underwent ground-based radiation testing with mixed results. TID hardness was observed up to 300 Gy. It demonstrated immunity to proton-induced single-event latchups and upsets with a threshold LET of 15 MeV/(mg/cm^2) and a cross section of 2×10^{-3} cm^2/device. Latchups, when they occurred, were current-limited to 800 mA maximum and not destructive at this level. The instrument was intended to provide a valuable database for correlation with ground-based test results. Exposure to the low-dose-rate TID accumulation seen in orbit should determine whether the part may be used in Earth orbit radiation environments with predictable performance. Qualification of this high-density FPGA would prove to be a valuable asset for low-weight, low-volume space applications because of the larger internal gate count.

PMOS Dosimeters

P-channel metal–oxide–semiconductor (PMOS) transistors are susceptible to radiation as their threshold voltages shift with total ionizing dose. Dosimeters based on this technology were flown on the CRRES spacecraft to monitor total dose during the mission. These PMOS dosimeters, with minor modification, were flown on Clementine and the ISAS. As they need to be sampled only once per orbit, their data and power requirements were very minimal. These factors made them ideal lightweight, low-power sensors for measuring the total ionizing dose. For Clementine, varying thickness of shielding was used to obtain radiation dose–depth curves at selected locations on the spacecraft and the interstage, allowing real-time mapping of the radiation dose on these vehicles.

CPT

The CPT measured the fluxes and spectra of energetic electrons and protons encountered by the Clementine spacecraft. The primary objective was to measure energetic protons (and electrons at 0.3–1.0 MeV) emitted by solar flares during the mission. The lower-energy electron channels provided data on spacecraft charging and on interactions between the moon and the Earth's geomagnetic tail plasma. The CPT sensor consists of a single 3000-μm silicon detector collimated to a 30-deg FOV. Outside of the FOV, the shielding is equivalent to at least 2 mm of copper. The detector has channels set at 30, 48, 90, 115, 220, 500 keV, and 1, 3, and 10 MeV. The first channel is an integral channel and the rest are differential. The upper two channels are sensitive only to protons and heavier ions; the 1-MeV channel has a low sensitivity to electrons. The other channels are sensitive to both electrons and ions.

OMDC

The OMDC provided data on the near-Earth natural meteoroid and man-made debris environments. In the long term, these observations will contribute to both the NASA and the military space environments and effects programs by providing data that are critically needed to plan and design future spacecraft. The experiment also demonstrated the performance of an ultralightweight particle impact detector that can be used on spacecraft in the future to continue the monitoring of the man-made debris environments in space. The specific objectives of the OMDC were as follows:

1) Establish altitude variations in the population of small-mass manmade debris.

2) Establish the population of small-mass meteoroids near the Earth.

3) Determine the meteoroid and debris hazards to spacecraft employing an Earth gravity assist for deep space travel.

4) Demonstrate performance of an ultralightweight particle impact detector that can be used in the future to continue the monitoring of man-made debris and/or to monitor the health of the spacecraft.

The OMDC measured the near-Earth natural meteoroid environment at high altitudes where man-made debris (hopefully) does not yet exist in significant amounts, thus allowing the contribution of the meteoroid impacts to be separated from measurements of the combined meteoroid and debris impacts. The experiment also made measurements of the smaller debris populations over a much greater altitude range than previously attempted. By doing so, it will provide the first data on the man-made debris population at altitudes up to and including synchronous orbits. The OMDC experiment utilized an improved version of a flight-proven technique to measure the impact frequencies of submicrometer meteoroid and man-made debris particles as a function of time and spatial position. The ultrasensitive particle detectors are thin MOS (metal–oxide–silicon) capacitors that are partially discharged when impacted by hypervelocity particles. The OMDC instrument consisted of ~1400 cm^2 of these MOS capacitor impact detectors. The detectors were mounted around the periphery of the ISAS. Approximately 80 impacts were detected over the life of the ISAS.

Solid-State Data Recorder

The Clementine solid-state data recorder (SSDR) had in excess of 2 Gbits of storage capacity, which is more than 4 times the capacity of any previous flight-qualified SSDR. The recorder used commercially available 4-Mbit $\times$ 1 Hitachi dynamic random-access memories (DRAMs) and had a data throughput greater than 20 Mbit/s with a bit error rate of less than 1 part in 10^{10}. The design incorporated redundant error detection and correction (EDAC)

Table 2 Clementine engineering experiments

Radiation effects
Total-ionizing-dose effects on advanced microelectronic devices
Single-event effects on advanced microelectronic devices
Evaluation of lightweight CCD sensor radiation hardness
Radiation effects on ultracompact IMUs
Solar proton event effects
Evaluation of error detection and correction algorithms
Radiation effects on advanced solar arrays
Radiation effects on the R3000 microprocessor
Micrometeoroid–debris effects
Performance of an ultralightweight micrometeoroid detector
Interplanetary micrometeoroid environment at 1 AU
Space debris environment as a function of altitude (500–125,000 km)
General environmental effects
Plasma interactions with advanced space sensors
Space environment effects at solar minimum
Lunar occultation effects on space systems (light, solar wind, energetic particles)
In situ performance of advanced spacecraft systems
NiH_2 CPV batteries
Gallium-arsenide-on-germanium solar arrays
Lightweight reaction wheels
Composite structures and materials
Sterling coolers
IMUs
In situ performance of advanced sensor systems
Ultraviolet–visible wide-FOV camera
Short-wavelength ir 1–3-μm wide-FOV camera
Long-wavelength ir 7–9-μm narrow-FOV camera
Lightweight LIDAR
Wide-FOV star tracker

with active fault management and built-in test capability. As part of the normal housekeeping functions on the Clementine spacecraft, the SSDR was continuously monitored for SEUs during the mission. These data were correlated with the radiation environment and operations to evaluate the performance of the SSDR and its error detection/correction capabilities and to serve as a secondary monitor of SEU rates.

IV. Clementine Engineering Experiments

The purpose of this section is to review the experiments needed to meet the Clementine engineering goal, namely the evaluation of the effects of the space environment on the advanced technologies and lightweight components being flight-tested on the Clementine and the ISAS. In addition to the evaluation of the day-to-day performance of the specific technologies and sensors, this goal divides the Clementine and ISAS experiment plan into three general areas of interest—radiation effects (primarily total dose and SEE), micrometeoroid–debris effects, and general environmental interactions. Although periods of anomalous operations are clearly of primary importance, long-term effects of the environment and basic environmental characterization during nominal operations are also of great value in establishing an understanding of the behavior of the systems in the space environment. Finally, the environmental data collected by both the Clementine and ISAS sensors, particularly for solar events and micrometeoroid–debris impacts, are of general interest and value to both the scientific and engineering communities. Table 2 summarizes the range of experiments selected by the Clementine Engineering Team for study. Many of the papers presented in this collection address these specific experiments.

V. Conclusion

This paper has summarized the key aspects of the Clementine Engineering Program—the issues being investigated, the instruments provided for the mission, and the rationale for the engineering program. At the outset of the Clementine program, the desire to evaluate advanced technologies and sensor systems in the stressing space environment was established as an overriding goal. We believe, based on the many papers presented in this issue, that Clementine has been successful in meeting this goal. We hope that Clementine will continue both as a mission and as a concept for evaluating future technologies and systems.

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