Space Sci Rev
DOI 10.1007/s11214-007-9273-4

The Mercury Laser Altimeter Instrument for the MESSENGER Mission

John F. Cavanaugh · James C. Smith · Xiaoli Sun · Arlin E. Bartels · Luis Ramos-Izquierdo · Danny J. Krebs · Jan F. McGarry · Raymond Trunzo · Anne Marie Novo-Gradac · Jamie L. Britt · Jerry Karsh · Richard B. Katz · Alan T. Lukemire · Richard Szymkiewicz · Daniel L. Berry · Joseph P. Swinski · Gregory A. Neumann · Maria T. Zuber · David E. Smith

Received: 28 August 2006 / Accepted: 24 August 2007

Abstract The Mercury Laser Altimeter (MLA) is one of the payload science instruments on the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) mission, which launched on August 3, 2004. The altimeter will measure the round-trip time of flight of transmitted laser pulses reflected from the surface of the planet that, in combination with the spacecraft orbit position and pointing data, gives a high-precision measurement of surface topography referenced to Mercury's center of mass. MLA will sample the planet's surface to within a 1-m range error when the line-of-sight range to Mercury is less than 1,200 km under spacecraft nadir pointing or the slant range is less than 800 km. The altimeter measurements will be used to determine the planet's forced physical librations by tracking the motion of large-scale topographic features as a function of time. MLA's laser pulse energy monitor and the echo pulse energy estimate will provide an active measurement of the surface reflectivity at 1,064 nm. This paper describes the instrument design, prelaunch testing, calibration, and results of postlaunch testing.

Keywords Mercury · MESSENGER · Topography · Laser altimeter

J.F. Cavanaugh (✉) · J.C. Smith · X. Sun · A.E. Bartels · L. Ramos-Izquierdo · D.J. Krebs · J. McGarry · A.M. Novo-Gradac · J.L. Britt · J. Karsh · R.B. Katz · D.L. Berry · J.P. Swinski · G.A. Neumann · D.E. Smith
NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA
e-mail: john.f.cavanaugh@nasa.gov

R. Trunzo
Swales Aerospace, Beltsville, MD 20705, USA

R. Szymkiewicz
Orbital Sciences, Greenbelt, MD 20770, USA

A.T. Lukemire
Space Power Electronics, Kathleen, GA 31047, USA

M.T. Zuber
Massachusetts Institute of Technology, Cambridge, MA 02129, USA

1 Introduction

1.1 Mission Overview

The Mercury Laser Altimeter (MLA) is one of seven scientific instruments on the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft. MESSENGER was launched on August 3, 2004, and will enter Mercury orbit in 2011 to perform scientific measurements for a period of one Earth year, equivalent to four Mercury years. MESSENGER will be in a highly elliptical and near-polar orbit around Mercury with a periapsis altitude of 200 to 400 km, an apoapsis altitude of ∼15,000 km, and a period of 12 hours. Figure 1 shows the MESSENGER orbits and MLA measurement geometry. The spacecraft altitude will come within the MLA ranging capability near periapsis for 15 to 45 minutes during each orbit, depending on the time of the year. The periapsis latitude is at 60–70°N to increase the measurement coverage for low-latitude regions. The intense heat from the Sun will require the spacecraft to have its sunshade facing the Sun at all times, which during noon–midnight orbits will confine the payload deck to point within 10° about the normal to Mercury's orbital plane with MLA ranging at a slant angle as high as 50° (Solomon et al. 2001).

1.2 MLA Instrument Overview

MLA is a time-of-flight laser rangefinder that uses direct pulse detection and pulse edge timing to determine range to the surface. Its laser transmitter emits 5-ns pulses at an 8-Hz rate with 20 mJ of energy at a wavelength of 1,064 nm. Return echoes are collected by an

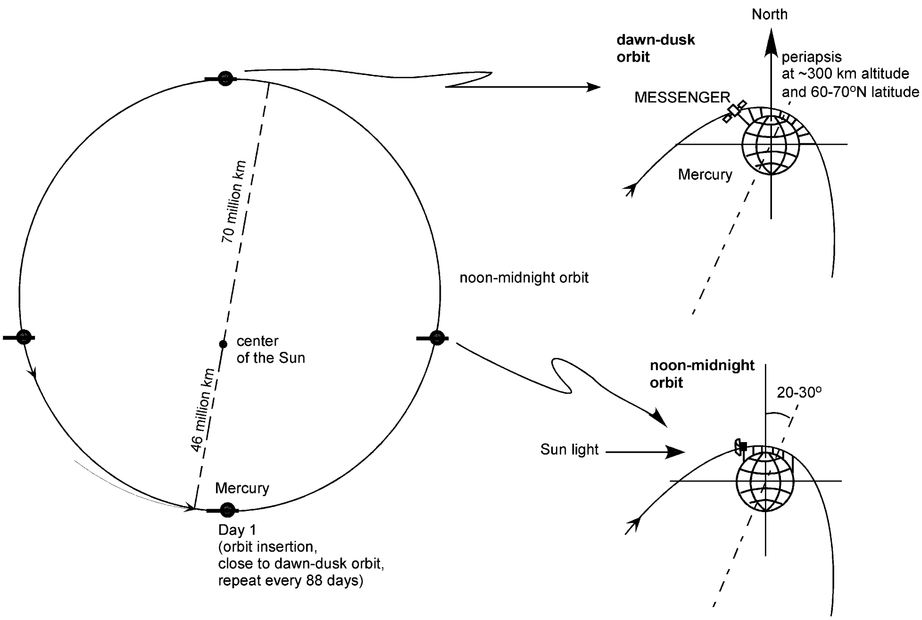

Fig. 1 MESSENGER spacecraft orbit around Mercury. MLA will measure range to the surface when the spacecraft is less than 800 km from the surface and the instrument's optical axis is within 50° of nadir. For optical axis angles approaching 0° (nadir pointing) MLA can range to the surface from 1,200 km

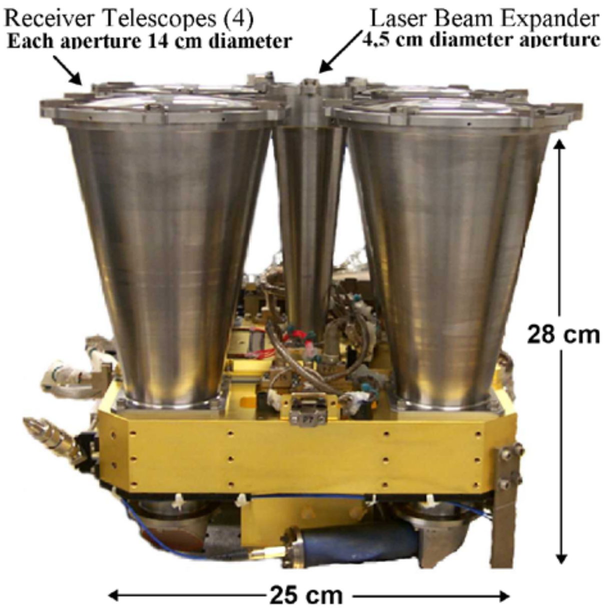

Fig. 2 MLA instrument shown without thermal protection blankets

array of four refractive telescopes and detected using a single silicon avalanche photodiode and three matched low-pass electronic filters. Pulse timing is measured using a combination of crystal-oscillator-based counters and high-resolution time-of-flight application-specific integrated circuits (ASICs). The MLA instrument is shown in Fig. 2.

2 Science and Measurement Objectives

2.1 MLA Science Objectives

The primary science measurement objectives for MLA are to provide a high-precision topographic map of the high northern latitude regions; to measure the long-wavelength topographic features at mid-to-low northern latitudes; to determine topographic profiles across major geologic features in the northern hemisphere; and to detect and quantify the planet's forced physical librations by tracking the motion of large-scale topographic features as a function of time. An additional goal of the MLA instrument is to measure the surface reflectivity of Mercury at the MLA operating wavelength of 1,064 nm (Sun et al. 2004).

2.2 MLA Instrument Objectives

MLA will measure the topography of the Mercury northern hemisphere via laser pulse time-of-flight data and spacecraft orbit position data in an approach similar to the Mars Orbiter Laser Altimeter (MOLA) (Abshire et al. 2000). MLA is designed to perform range timing measurements up to 1,800 km from the planet's surface. Since the single-pulse signal link margin is close to 0 dB for altitudes above 800 km, the MLA data acquisition scheme allows collection and downlink of up to 15 returns per shot in order to allow the use of correlation techniques to process the range signals on the ground. Measurement of both the outgoing pulse energy and received pulse shape enable the surface reflectivity measurement. The MLA functional requirements are enumerated in Table 1; allocations and constraints are listed in Table 2.

Table 1 Summary of MLA functional requirements

Time-stamp laser pulses to better than ±1 ms with respect to the ephemeris
Support determination of pointing stability to ±50 µrad peak-to-peak
Measure laser pulse time of flight from 1 to 8 ms with return pulse widths from 6 to 1,000 ns
Total ranging error <1 m with probability of detection $P_d > 95\%$ at 200 km altitude nadir pointing
Laser pulse repetition rate of 8 Hz
Produce laser footprint ≤16 m diameter at 200 km altitude, nadir pointing
$P_d > 10\%$ at 800 km slant range and 50° angle
Maintain long-term ranging bias error to ≤0.50 m over the mission lifetime
Measure the reflectivity of the ranging targets

Table 2 MLA design allocations and constraints

Parameter	Requirement
Instrument design life	6.6-year cruise with power off, followed by 1 year of operation
Orbit definition	Periapsis altitude = 200 km, apoapsis altitude = 15,193 km, inclination = 80°, latitude of periapsis ≤60°, period = 12 hours
Flight environment	Infrared irradiance from Mercury not to exceed 1 W/cm^2 onto the instrument for a 60 minute pass centered about periapsis; cold space viewing for the remaining 11 hours of the orbit
Testing environment	Protoflight verification program per MESSENGER Component Environmental Specification, drawing #7384-9101
Mass	7.4 kg
Power	<25 W for 60 minutes centered on periapsis and <16 W for the remaining 11 hours of the orbit. <17 W orbit average
Telemetry	2.0 Mbit average per 12-hour orbit about Mercury
Time correlation	1 pulse per second time tick from the spacecraft along with announcement with <50 ms accuracy in real time and <1 ms following navigation data processing
Relative pointing	Determine laser output pointing direction with respect to the spacecraft axes over temperature to ±50 µrad peak to peak
Envelope	28 cm × 28 cm × 26 cm

3 MLA Instrument Design

3.1 Background

MLA builds on the experiences gained from the development of several space-based and airborne laser altimeter systems flown over the past two decades including the Mars Observer Laser Altimeter (MOLA-1; Zuber et al. 1992), the Mars Orbiter Laser Altimeter (MOLA-2; Smith et al. 1998), two Shuttle Laser Altimeters (SLA-1 and SLA-2; Garvin et al. 1998), the Geoscience Laser Altimeter System on the Ice Cloud and Land Elevation Satellite (GLAS/ICESAT; Zwally et al. 2002), and the airborne Microchip Laser Altimeter System Microaltimeter (Degnan 2002). The measurement scheme for MLA is similar to that of MOLA, in which the outgoing pulse starts a counter that is stopped by the detection of a received echo pulse. A significant change implemented in MLA is the ability to record several return pulses, process them onboard, and send the "most likely" signal returns to the ground for correlation analysis. This technique is similar to and derived from experience with the Microaltimeter (Degnan 2002).

3.2 MLA Functional Overview

An overview of MLA operation may be gained from the MLA functional block diagram (Fig. 3). A trigger pulse initiated by the range measurement electronics starts the optical pumping of the MLA laser. This trigger pulse also initiates a 5-MHz 23-bit counter, 16 bits of which are used for coarse range timing. After optically pumping the laser for approximately 150 µs the laser emits a 5-ns, 20-mJ pulse, which propagates along the instrument line-of-sight to the planet's surface. A small fraction ($<10^{-6}$) of the emitted pulse impinges on a four-segment photodiode that performs three functions. One output of this photodiode is fed to the laser electronics where it is used to terminate the laser diode pump array drive current. The second output goes to a pulse integrator used to measure emitted energy, and a third output is fed to a comparator, which generates a logic pulse synchronous with the transmitted optical pulse. The leading edge of this latter pulse starts the first of six fine-resolution time-of-flight counters, which is subsequently stopped by the next edge of the 5-MHz clock. These counters provide a relative time within each 200-ns coarse clock cycle. The coarse counter value is latched at this point, and the two counters provide the leading-edge start timing value (with respect to the trigger pulse) for the range measurement. The trailing edge of the start pulse is timed in an identical manner. These first pair of counts establish the start time of the range timing cycle. The pulse width is computed by subtracting the leading edge measurement from the trailing edge measurement.

A portion of the pulse energy reflected off the planet's surface is collected by MLA's four receiver telescopes and focused onto four optical fibers that relay the signal through an opti-

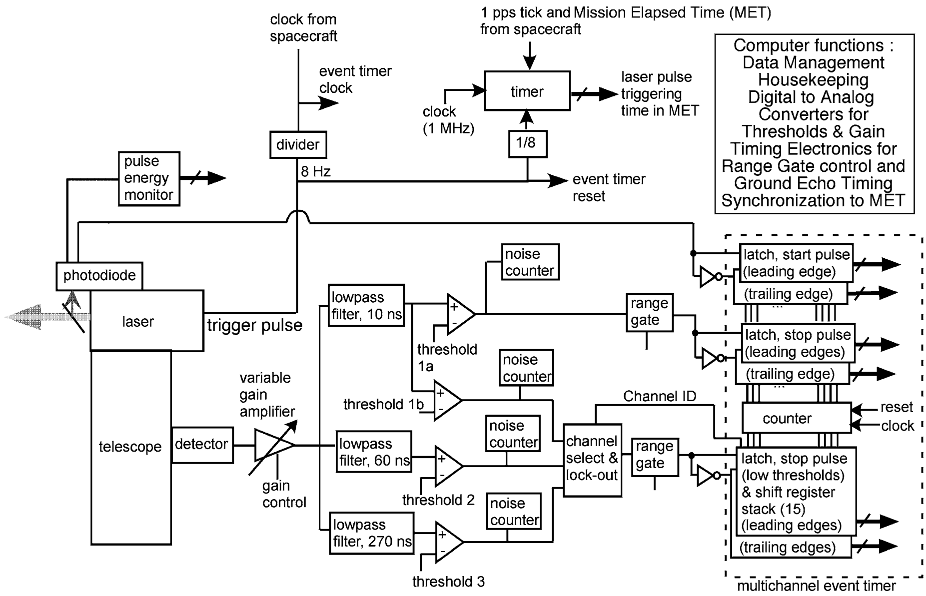

Fig. 3 MLA functional block diagram

cal bandpass filter to a silicon avalanche photodiode (SiAPD), which preserves to the extent of its bandwidth the deformation of the incident pulse caused by interaction with surface features. Slant angle ranging, surface roughness, or large-scale features on the surface can cause temporal pulse spreading. To maximize the probability of detecting spread returns, three matched filters are used after the detector amplifier. The first, a high-bandwidth filter output with a 10-ns impulse response, is split and fed to two comparators with independently programmable thresholds referred to as channel 1 high and low, respectively. The channel 1 high comparator signal is fed to the second pair of time-of-flight counters, which record the leading and trailing edge times of this pulse. The channel 1 low comparator and the other filter outputs with 60-ns and 270-ns impulse response, referred to as channels 2 and 3, respectively, are fed to the third pair of counters. For this last pair of counters the first received pulse leading edge to cross its corresponding threshold will stop the counter and lock out the other channels for approximately 1 μs in order to prevent a different channel from stopping the trailing edge counter. The MLA Range Measurement Unit (RMU) can collect and store up to 15 signal pulse returns from this last set of counters.

The nominal operational timebase for MLA event sequencing and range measurement is the MESSENGER spacecraft's oven-controlled crystal oscillator. The 5-MHz signal from either of the spacecraft's redundant oscillators can be used. The laser trigger operating at 8 Hz is also synchronized to the spacecraft 1-pulse-per-second (1-PPS) timing reference. A third backup 5-MHz crystal oscillator on the MLA RMU board can also be used.

To maximize the probability of return signal detection in MESSENGER's dynamic operating environment, MLA uses a real-time embedded algorithm to monitor background noise and adjust comparator threshold levels to minimize false signals. The MESSENGER spacecraft also provides MLA with once-per-second updates of estimated line-of-sight range to Mercury based on spacecraft attitude and orbit data. This information is used to dynamically set the range-gate time delays and gain levels for the detector amplifier.

For altitudes greater than 800 km on the inbound and outbound orbit trajectories the MLA signal-to-noise ratio becomes sufficiently weak that the "high" threshold channel is no longer detecting the return. In this situation the software collects and downlinks the multiple return pulses from the "low" channel timers.

The signal-tracking algorithm and the MLA command and data-handling software are implemented on a radiation-hardened 80C196 processor that, with a control and data communications field-programmable gate array (FPGA) and memory devices, make up the central-processing unit (CPU) electronics board. The RMU board is housed with this board in a box underneath the main instrument housing (shown in Fig. 2). The detector, amplifiers, and comparators are mounted on a separate printed wiring board and mechanically mated to the aft optics, which filter and focus the signal from the receiver fiber optics.

Housekeeping signal conditioning and data conversion functions are performed on another circuit board referred to as the Analog Electronics Module (AEM). Laser control and drive functions are implemented on two assemblies beneath the laser bench referred to as the Laser Electronics Assembly (LEA). All of the secondary voltages are converted in the Power Converter Assembly (PCA) located in the magnesium box bolted directly to the spacecraft deck adjacent to the main MLA housing.

Command and data communications to the MESSENGER payload Data Processing Unit (DPU) are through a low-voltage differential signal (LVDS) serial link using the RS-422 signal standard. An additional LVDS signal carrying the 5-MHz spacecraft reference clock is also provided to MLA and connects directly to the RMU board. The MLA instrument has single-string components but can operate from either one of the redundant DPU, clock, and power connections.

MLA has two defined software modes, Boot and Application. Boot mode is entered immediately after power up. MLA will remain in Boot mode until commanded to execute its onboard code residing in electrically erasable programmable read-only memory (EEPROM), at which point it enters Application mode. Within Application mode there are three defined operational modes through which MLA will cycle every orbit. The lowest power mode is Keep Alive, in which only the CPU, AEM, and laser diode's thermo-electric cooler (TEC) are powered. Upon transition to Standby mode the RMU is powered on. Finally, in Science mode, the laser power supply is turned on and the laser fires.

3.3 Technology Advances Implemented in MLA

MLA has several new technologies which provide a compact and efficient laser altimeter to the MESSENGER mission. The most prominent is the miniaturized laser transmitter shown in Fig. 4, delivering 20 mJ of energy in a 75-μrad beam width from a compact 14 cm × 9 cm × 3 cm package to facilitate high-resolution sampling of Mercury's surface. Its unique breathable filter allows for simpler testing in vacuum environments, providing significant test time in a flight-like environment.

MLA also incorporates a multiple aperture refractive telescope receiver, which has proven easier and less costly to manufacture and test than reflector telescopes used on previous altimeters and is capable of performing at the extreme temperatures expected during this mission. The modular design can be scaled to match the aperture requirements for a variety of missions. Fiber coupling makes the alignment and integration process simpler and decouples the detector assembly from the optomechanical integration and test (I&T) flow.

The MLA Range Measurement Unit is another significant advancement, using a low-speed 5-MHz counter and time-of-flight Complementary Metal Oxide Semiconductor (CMOS) ASIC developed by The Johns Hopkins University Applied Physics Laboratory (APL) to achieve timing resolution equivalent to a 2-GHz counter with significantly less power. The overall timing accuracy of MLA and component contributions to timing errors are shown in Table 3.

The detection scheme on MLA also makes possible operation and signal retrieval beyond the theoretical range limit of single-pulse detection electronics by acquiring and downlink-

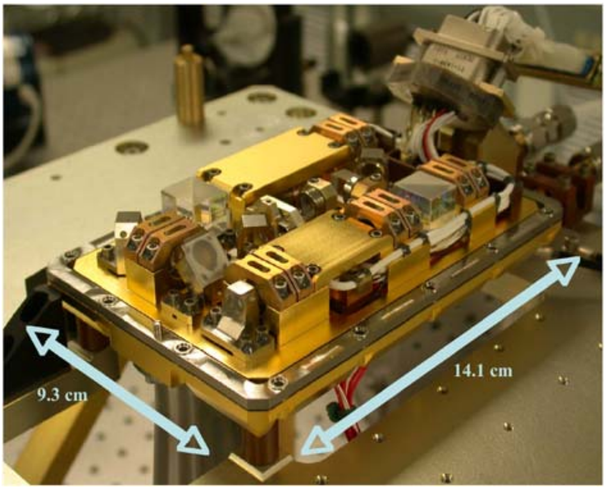

Fig. 4 MLA laser optical bench assembly

Table 3 Component contributions to MLA range error

Error source	Contribution
Leading edge timing	0.06 m
Clock frequency error (0.1 parts per million)	0.20 m
Measurement quantization (2.5 ns)	0.11 m
Pointing angle uncertainty (0.13 mrad)	0.68 m
Spacecraft orbit knowledge error	0.75 m
Total (root sum squared)	1 m

ing up to 15 returns per shot. Correlation processing on the ground will be used to extract valid range signals from these additional data points.

3.4 Laser Transmitter

The MLA laser transmitter is an evolutionary design building on the past 15 years of space-flight laser designs from MOLA to GLAS. There are common features shared among these and other space-based lasers, which include a semiconductor laser-pumped solid-state approach to the laser, "zigzag" slabs made of neodymium-doped yttrium-aluminum garnet that is chromium co-doped for radiation tolerance (Nd:Cr:YAG) with ends cut at Brewster's angle, and porro prism and mirror or crossed-porro prism laser resonators for stability against vibration and thermal stresses. The laser parameter requirements are enumerated in Table 4. The total number of shots required to complete the mission is on the order of 30 million, a relatively small number when compared with other laser altimeter experiments such as MOLA-2 (660 million shots) and GLAS. Salient parameters such as pulse energy and pulse repetition rate are also lower.

The MLA laser transmitter is also required to survive and operate occasionally (once or twice per year for a few hours) during the 6.6-year MESSENGER cruise phase as well as in the extreme thermal environment encountered in Mercury orbit. During the latter phase of the mission the laser will operate for 15- to 45-minute periods every 12 hours. During this operating time the laser bench temperature will climb from its initial heater-controlled temperature of 15°C at rates up to 0.5°C per minute. The thermal design of the instrument is described in greater detail in Sect. 3.12.

To meet these requirements the laser was implemented with an oscillator and amplifier design as shown in Fig. 4 and Fig. 5. The oscillator is a miniaturized version of the GLAS laser oscillator incorporating a zigzag Nd:Cr:YAG slab, GaInAsP laser diode pump arrays, a passive Q-switch, crossed porro prisms, and polarization output coupling. The laser diode arrays are temperature controlled with a TEC to maintain the optimum pump wavelength. The oscillator emits 3-mJ pulses that are then fed through a 2X beam expander and a second Nd:Cr:YAG laser diode-pumped single-pass amplifier slab, which provides approximately 7 to 9 dB of amplification resulting in an output pulse energy of 15 to 22 mJ. The gain of the amplifier stage is dependent on the temperature of the amplifier pump diodes and slab, which are not actively controlled (Krebs et al. 2005).

The output of the amplifier stage is coupled into a 15X Galilean beam expander, which reduces the final beam divergence to approximately 75 microradians. Since the beam expander output face is exposed to the surface of Mercury during operations, a sapphire window is used to minimize IR coupling through its glass elements.

The MLA laser electronics assembly delivers a 100-A current pulse to the semiconductor laser diode pump arrays. The oscillator and amplifier diode arrays are connected in series and are driven from a capacitor bank charged to approximately 35 volts direct-current

Table 4 MLA laser transmitter design requirements

Parameter	Requirement
Wavelength	1,064.5 nm ± 0.2 nm
Pulse energy	20 mJ ± 2 mJ
Pulse width	6 ns ± 2 ns
Pulse repetition rate	8 Hz
Beam divergence ($1/e^2$)	less than 80 µrad

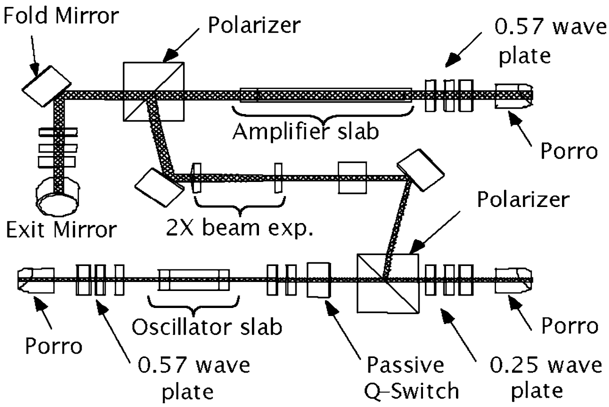

Fig. 5 MLA laser optical layout. The *bottom portion* shows the passively Q-switched crossed-porro master oscillator, and the *top portion* shows the amplifier path

(VDC) generated as a regulated secondary supply by the MLA Power Converter. When triggered from the MLA timing electronics, current is switched through the diode arrays by redundant metal-oxide-semiconductor field-effect transistors (MOSFETs). Current flowing through the laser diode arrays generates the 808-nm optical pump pulses for both the oscillator and amplifier Nd:YAG slabs. When the Q-switch, a saturable absorber in the oscillator, becomes transparent or "bleached," the 5-ns, 1,064-nm laser pulse is emitted. A photodiode in the laser detects the emitted pulse, and this signal is used to terminate the current pulse. The diode pump pulse is nominally 150 µs in duration and is limited by the electronics to 255 µs. As the diode lasers age and emit less power the pump pulse will last longer, allowing constant 1,064-nm pulse energy output for the duration of the mission.

The laser electronics also implement a control loop to maintain the oscillator pump diode lasers at 17 ± 0.1°C via thermoelectric cooler. The photodiode used to terminate the pump pulse is a quadrant detector that is placed behind a diffuser and views residual energy transmitted through the final turning mirror prior to the laser beam expander. Three segments of this detector are used for timing functions, and the fourth segment output is used to monitor the energy.

One breadboard, one engineering model, and one flight model laser were fabricated at the Space Lidar Technology Center operated by the NASA Goddard Space Flight Center (GSFC). Laser fabrication was performed in a Class-100 clean room. The engineering and flight units underwent vibration and thermal-vacuum cycling tests at the subassembly level during which all parameters were verified.

3.5 MLA Receiver Optics

The MLA receiver telescope design is a significant departure from prior telescopes used for MOLA, SLA, and GLAS. These altimeters all used Cassegrain reflector telescopes made

Table 5 MLA receiver optics design requirements

Parameter	Requirement
Aperture	417 cm^2
Field of view	400 µrad full angle, circular
Bandpass filter	0.7 nm pass band centered at 1,064.5 ± 0.2 nm
Detector	0.7 mm diameter silicon avalanche photodiode

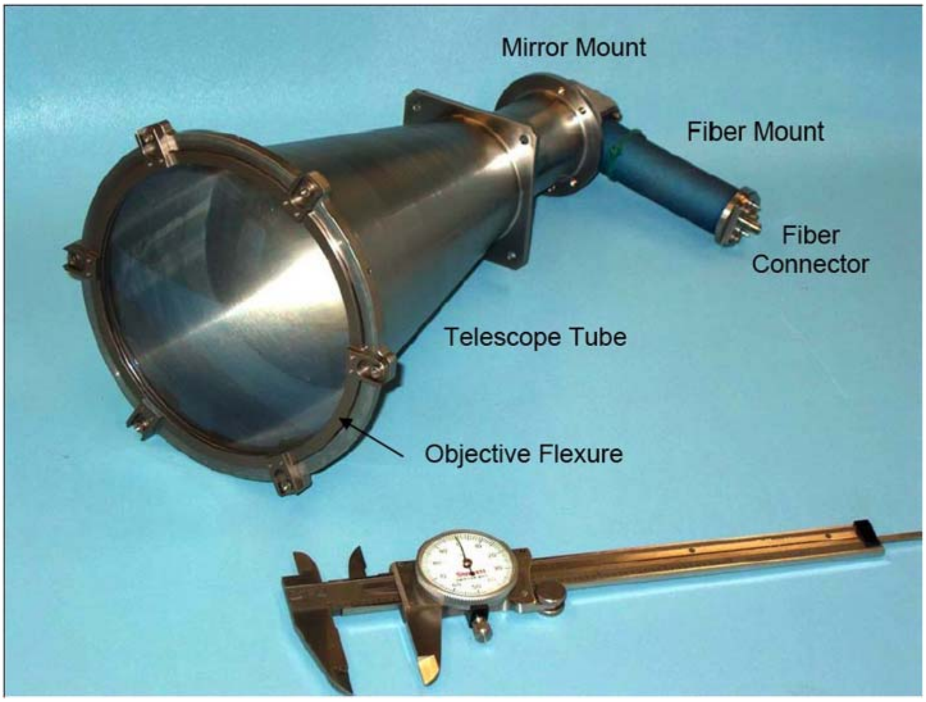

Fig. 6 One of the four MLA receiver telescope assemblies

with beryllium in the cases of MOLA and GLAS. The original design for MLA was a beryllium reflector similar to these, but once the MESSENGER thermal environment was understood it became apparent that the Cassegrain reflector would not perform adequately with the significant thermal gradients resulting from viewing Mercury's surface. The requirements for the MLA receiver are listed in Table 5.

The ensuing design shown in Fig. 6 is a set of four refractive telescopes with an aperture equivalent to a single 0.25-m diameter reflector with a 15% secondary obscuration. The objective lenses in each telescope are sapphire, chosen for its ability to withstand thermal shock, its lower absorption in the infrared, and its resistance to radiation darkening. At the back of each telescope is a dielectric fold mirror which reduces the total height of the assembly and reflects only a narrow band about 1,064 nm, allowing protection against accidental direct solar viewing by passing most visible solar radiation through its frosted back. At the focal plane of each telescope is a 200-mm core diameter fiber, which limits the field of view to 400 µrad. Alignment of each telescope's field of view (FOV) to the MLA laser is accomplished solely by translating each fiber at the focal plane (Ramos-Izquierdo et al. 2005).

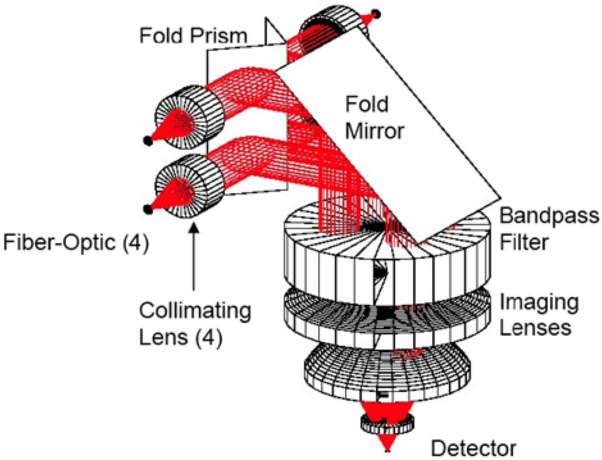

Fig. 7 MLA aft optics layout showing the four fiber optics from the receiver telescopes coupled through a common bandpass filter to one detector

Each fiber optic couples the received power to a single aft optics assembly (Fig. 7), which collimates the fiber output through a single optical bandpass filter with a 0.7-nm bandwidth. The center wavelength of the bandpass filter can be adjusted by tilting it to match the center wavelength of the laser pulse, which for MLA is 1,064.5 nm. After the bandpass filter the light from all four fibers is then focused onto a single silicon avalanche photodiode detector with a 0.7-mm diameter.

Five engineering model (EM) telescopes and an EM aft optics assembly were fabricated out of aluminum to validate optical, mechanical, and thermal performance models. These EM units also served to develop the integration procedures and ground test equipment needed for the flight model telescopes. Four of the telescopes and the aft optics with fibers were also integrated with an aluminum MLA EM housing and laser beam expander assembly. This approach provided a complete optomechanical EM that also served to validate models and develop instrument-level alignment verification tests, which were used successfully on the MLA flight instrument.

3.6 Receiver Electronics

The detector hybrid, shown in Fig. 8 was first developed during in the 1980s by then EG&G Optoelectronics Canada for optical communication programs. It consists of a SiAPD chip, a low-noise preamplifier, and a high-voltage bias circuit, all contained in a hybrid circuit housed in a one-inch-diameter hermetically sealed package. These devices were used in SLA, MOLA-1, and MOLA-2, the latter of which operated in space from 1996 until the end of the Mars Global Surveyor mission in 2006 with little performance degradation. Additional development of this device by the manufacturer in the 1990s improved the bandwidth from 50 MHz to more than 100 MHz. The higher bandwidth version was used for GLAS and MLA.

The electronics for received pulse detection duplicates in concept subsets of the circuits used for MOLA and GLAS and includes the same SiAPD detector hybrid and variable gain amplifier (VGA) stage as GLAS. The output of the VGA is split three ways that define the MLA “channels” 1 through 3. Channel 1 is the highest bandwidth version of the signal and has a 10-ns matched filter. The next two splits feed into the 60-ns and 270-ns matched filters. These latter two filter outputs are gain compensated for the filter loss. Channel 1 has two comparators, each with separately programmable thresholds (channel 1 “high” and

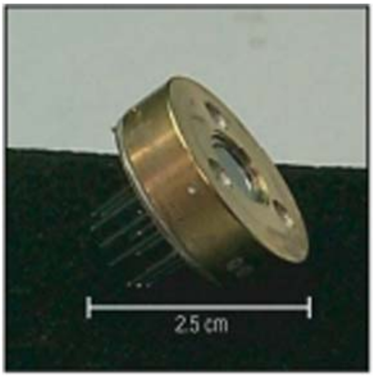

Fig. 8 MLA detector hybrid package

channel 1 "low"). The remaining channels have single comparators. When the signal level crosses a programmed threshold voltage, the high-speed comparator switches a logic level, which is transmitted to the RMU via low-voltage differential signal (LVDS) interface for signal timing.

3.7 Range Measurement Electronics

Conceptually the MLA range timing circuitry builds on the basic pulse edge timing technique used for MOLA and SLA. The timing cycle for each laser pulse is shown in Fig. 9. Rather than using the laser pulse emission to start the counter, as was done with MOLA, the trigger pulse to the laser is itself used as the start time and the laser pulse is the first event in each cycle. The important change is the implementation of a low-frequency counter operating at 5 MHz coupled with a tapped delay line ASIC to determine the intra-cycle timing within the coarse counter resolution, providing much better resolution without the need for a high-frequency counter.

The receiver event timers consist of a set of time-to-digital converters (TDCs). The TDCs are based on the tapped delay line technique, and each channel is implemented in a silicon ASIC specially designed for space applications, designated TOF-A by their APL developers (Paschalidis et al. 2002). The tapped delay lines consist of a series of logic gates with precise and uniform propagation delay times. An on-chip delay-lock-loop is used to self-calibrate the delay time against an external reference clock signal. The TOF-A can perform subnanosecond timing without the need for high-frequency logic circuits and clock oscillators yet has limited full-scale range; thus a coarse-resolution 5-MHz counter is synchronized with each TOF-A to provide a full-scale pulse time-of-flight. Digital logic circuits are implemented in an FPGA, an Actel RT54SX72S. The combined circuit can time the leading and trailing edges of the transmitted laser pulses and the received echo pulses to better than 500-ps accuracy with 13-ms dynamic range.

Six of these circuits make up the MLA RMU. A signal edge designated T0 starts the coarse counters. Each edge of the LVDS comparator signals from the detector board starts a corresponding TOF-A, and this circuit counts until the next leading edge of the 5-MHz clock stops it, providing subcycle timing. The start pulse and channel 1 "high" pulse TDCs record one event per edge (leading and trailing). The "low" threshold pulse TDCs can store multiple events from each shot; therefore a lockout circuit (as described in the overview) and a means to associate the source of the pulse (channel 1, 2, or 3) are implemented. This circuit records the times of up to 15 events for every transmitted pulse with a dead-time of

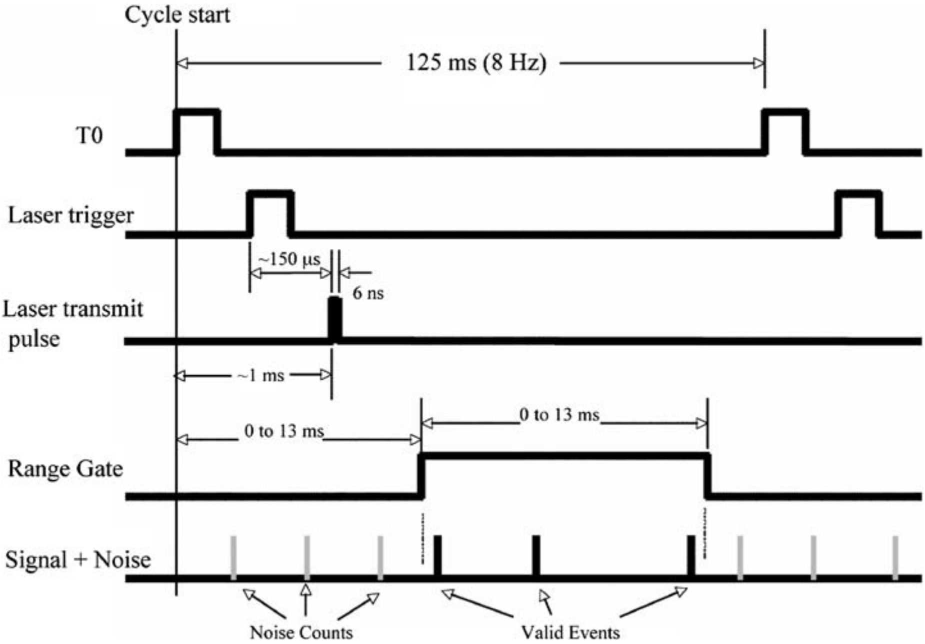

Fig. 9 MLA range measurement timing diagram. Events are referenced to an internal signal (labeled T0) that is synchronized to the spacecraft's 1-Hz mission elapsed time (MET) reference signal

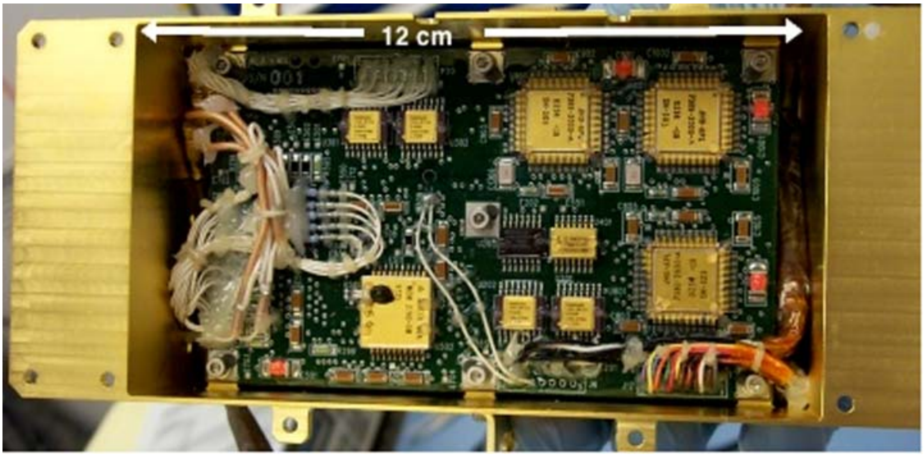

Fig. 10 MLA Range Measurement Unit (RMU) assembly shown mounted in its beryllium housing

several hundred nanoseconds. A separate set of event counters totalizes pulses received on each channel inside the range gate. These counters are read and reset after every shot.

The flight RMU is shown in Fig. 10. An engineering unit is integrated into the instrument EM. Subassembly testing of the RMU demonstrated range precision capability under 1 ns. Standard deviation of the error signal was approximately 250 ps with a mean error of 480 ps.

3.8 Command and Data Handling Electronics

The MLA command and data-handling (C&DH) electronics are assembled on one printed wiring board referred to as the MLA CPU board. The unit was custom built for MLA but uses components with extensive heritage. The CPU itself is a 80CRH196KD device from United Technologies Microelectronics Corp. operated at a 16-MHz clock frequency. All control and interface functions are implemented in an Actel RT54SX72S FPGA. Two each 64-kB programmable read-only memories (PROMs), 256-kB EEPROMs, 512-kB static random-access memories (SRAMs), an oscillator, and LVDS transceivers round out the board. A block diagram of the CPU is shown in Fig. 11. The CPU board is shown in Fig. 12.

All command and data interfaces flow through the FPGA on the CPU board. Each MLA subsystem's control and data lines tie into this device. The FPGA therefore has a functional block for each MLA subsystem, two universal asynchronous receiver/transmitter (UART) blocks for communications, and one block for address control and reset functions. The subsystem functional blocks are mapped to 80196 data memory space and defined for the PCA, AEM, and RMU. An interrupt controller is also implemented in the FPGA for interrupts

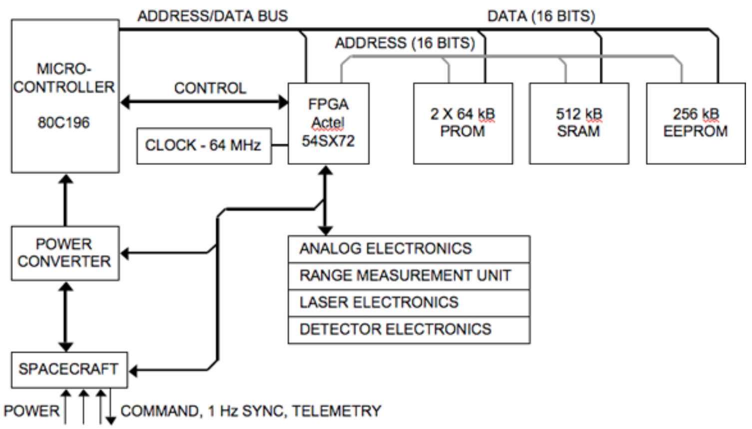

Fig. 11 MLA CPU block diagram

Fig. 12 MLA CPU board

from the RMU, AEM, address decode, and UART. All transfers to and from the subsystem and UART blocks are byte-wide only. Each UART is connected to one of the redundant MESSENGER DPUs (A and B). All command and data transfer to the MESSENGER DPU passes through the UARTs. An additional UART integrated into the 80196 CPU was used for development. The 80196 timer function is also used to provide a reference to the phase of the spacecraft 1-PPS signal and for flight software timing.

MLA operational modes (Keep Alive, Standby and Science, described in Sect. 3.2) are defined by which subsystems are powered, so all mode changes are implemented by setting bits in the PCA block to enable secondary voltages. The RMU block transfers all range data and control functions. This block must function when the RMU is powered off as is the case in Keep Alive mode. The AEM block executes an autoconversion sequence to acquire laser energy and diode current monitor samples each time the laser fires without software intervention. All other analog-to-digital and digital-to-analog conversions are done under software control.

PROM memory contains the bootstrap code. One EEPROM device is permanently write protected and contains the last fully ground-tested version of the flight software. The second EEPROM can be overwritten via ground commands to allow updates to the flight software during the mission.

One breadboard, two engineering models, and one flight unit were fabricated for MLA. The breadboard CPU was used for flight software development and testing, and one EM was used in the instrument EM.

3.9 Power Converter Electronics

The MLA PCA is shown in Fig. 13.

The PCA generates all the secondary voltages on MLA. Requirements for secondary voltages and the subsystems that use them are enumerated in Table 6. The 2.5-V, 35-V, and 550-V converter outputs are all switched on or off by control bits from the CPU FPGA to control power consumed by MLA. The 12-V, 5-V, and 2.5-V sources are forward converter topology DC-DC converters. The negative 5-V source is produced from the positive 5-V

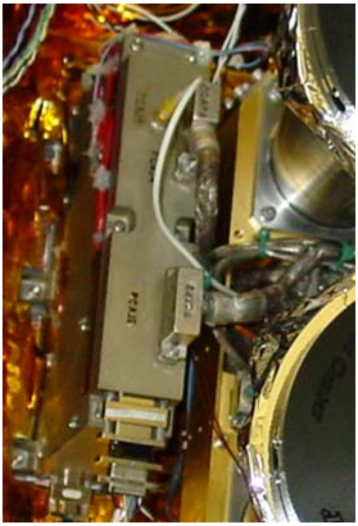

Fig. 13 MLA Power Converter Assembly, shown mounted on the MESSENGER instrument deck adjacent to the MLA main housing

Table 6 PCA power requirements for each subassembly and secondary supply

Subsystem	Power required (W)					
	+2.5 V	+5.0 V	−5.0 V	+12.0 V	35 V	+550 V
CPU	0.275	0.87	0	0	0	0
RMU	0.088	0.25	0	0	0	0
RMU heater	2					
Detector	0	0.775	0.47	0	0	0.01
Analog board	0	0.157	0.073	0.019	0	0
Laser electronics	0	0.26	0.11	0.324	5.54	0
Laser thermo-electric cooler	0	2.5	0	0	0	0
Laser amplifier heater	0	0	0	2	0	0
Load totals	2.36	4.81	0.65	2.34	5.44	0.01
	1.11	1.44	0.35	0.91	0.74	0.20
Power requirement				20.37		
Schottky diode loss				0.370		
Average prime power required				**20.75**		

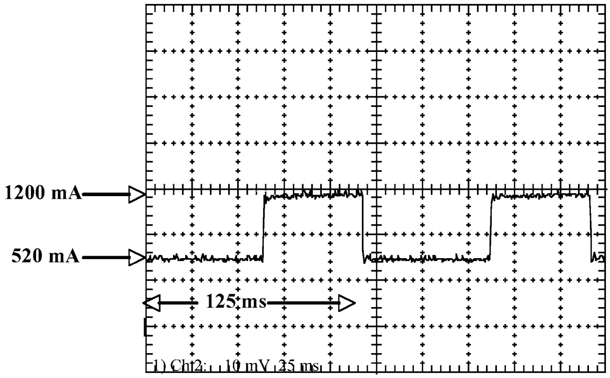

Fig. 14 Oscilloscope trace showing MLA PCA current waveform captured with a current probe placed on the 28-V input power line

supply by a flyback converter. The 550-V SiAPD bias voltage is also converted from the positive 5-V supply by a resonant converter. A 35-V source used solely for charging the capacitor bank that powers the laser pump diodes is implemented in a flyback converter.

The laser, operating at an 8-Hz pulse rate, discharges the capacitor bank by switching 100 A through the laser pump diodes in a 150-µs current pulse. The capacitor bank must then be recharged in time for the next pulse. The resultant charge current, drawn through the 35-V converter, is reflected on the spacecraft power bus current in the form of an 8-Hz square wave with approximately 700-mA amplitude and duty cycle from 25% at maximum bus voltage to 80% at minimum bus voltage as shown in Fig. 14. Since the MESSENGER general electromagnetic compatibility (EMC) requirements specified that current ripple be less than 500 mA, a waiver was granted for MLA allowing up to 800 mA ripple. Subsequent cross-compatibility tests showed that this ripple did not affect other spacecraft subsystems.

All secondary voltages are monitored, scaled, and sampled once per second with an 8-bit analog-to-digital converter, and these values are reported in the MLA Status telemetry packet. To reduce circuit board area, secondary supply current monitors were not implemented. Only the laser pump diode current is sampled during every shot 50 µs after being triggered. This value, along with a counter value indicating the duration of each pump pulse, is stored in the MLA Science telemetry packet.

The 8-Hz laser trigger is synchronized to the spacecraft 1-Hz timing reference. Since the spacecraft C&DH samples the power bus current synchronously with this reference the MLA current is always sampled at the peak of 8-Hz square wave described earlier.

The PCA is housed in a magnesium box, which is bolted directly to the spacecraft deck. A thermal gasket allows conduction of dissipated power to the deck. The spacecraft power and communications connectors are on the PCA box. Command and data signals are simply routed through the PCA to the MLA CPU board.

One engineering model and one flight model PCA subassembly were delivered to GSFC by Space Power, Inc., the contractor for the PCA design and fabrication. The units as delivered were functionally tested over the specified temperature range.

3.10 Software

The MLA flight software consists of multiple tasks running under a real-time executive. The two main groups of tasks are the C&DH set comprised of timing, communications, and system maintenance, and the Science tasks that acquire, process, and compress the critical science data. Code for MLA was developed in the C programming language and operates under a Real Time Operating System (RTOS) from CMX Systems. The MLA Flight Software Tasks are depicted in Fig. 15.

The science algorithm builds on heritage primarily from MOLA and Microaltimeter experience. Like the MOLA software, the MLA algorithm integrates background noise counts (detector events outside the range gate) and sets comparator thresholds to minimize false detections within the range window. MLA also uses line-of-sight range information from the spacecraft attitude control system (ACS) to update the range gate delay, width, and detector gain based on altitude and descent or ascent rate. More significantly the MLA algorithm takes in the multiple returns from the RMU low channel and maintains a histogram of range

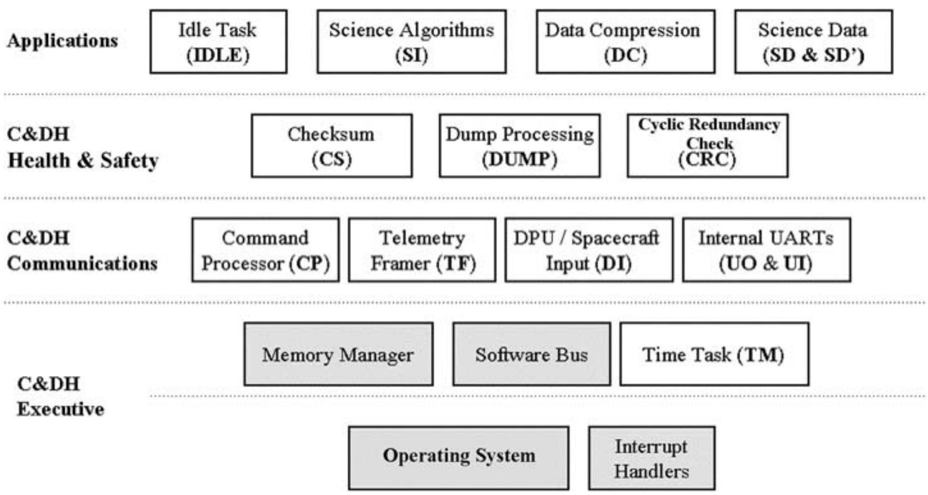

Fig. 15 MLA flight software task hierarchy. Tasks in *gray boxes* comprise the kernel; tasks in *white boxes* are interrupt-driven. Within the latter category the Time Task has highest priority and schedules execution of all other tasks

measurements within the window. If a valid return is detected on the high threshold channel, then the three low returns closest to it are downlinked to the ground. If there is no high channel return, then all the low returns (up to a preset limit) are downlinked to the ground to be processed using correlation techniques.

The flight software timing is handled by the RTOS and interrupt service routines (ISRs). The RTOS is a preemptive, priority-based scheduler with semaphore and delay functionality. The processor immediately branches to the ISRs when their associated interrupt is generated, except when they are masked off, in which case the interrupt is pending but no action is taken by the processor.

The base cycle period of the flight software is 1 s. The spacecraft demarcates this period with the 1-PPS signal. All telemetry for that second is required to be packaged in an Instrument Transfer Frame (ITF) and sent to the spacecraft. During each second the flight software runs an entire pass through all of its code. There are some tasks that have counters that enable them to do different things on different seconds, but those counters are always maintained locally to the task.

Three scheduled sequences occur in each second. The first is the internal flight software timing sequence, the second is the RMU laser firing sequence, and the third is the purely data-driven, low-priority tasks that are scheduled either from command packets or the time message. The first two sequences are independent and can run asynchronously, but they are both configured to synchronize with the 1-PPS and therefore, in effect, synchronize with each other. The execution of the last sequence is dependent on the content of the command input and the spacecraft time message.

Every time the CPU board is powered on or reset, the Boot Loader executes. A command is required to signal the software that the Boot Loader should load the flight software out of EEPROM and into SRAM for execution.

There are three ways to reset the MLA instrument: a processor reset, an FPGA watchdog timeout, and a spacecraft power cycle. All three ways can be commanded. There is, on the other hand, only one way to go from the PROM Boot Loader code to the EEPROM flight software code, and this is by processing a load directive. A load directive is a structure in memory used by the Boot Loader that contains instructions on where and how to initialize SRAM, as well as where to copy sections of EEPROM code and data into SRAM to be executed. There are only two commands that cause the Boot Loader to process a load directive.

Bench testing was performed on three separate platforms. First, the MLA flight software was executed on a PC-based simulator. Second, the MLA CPU breadboard was used as a stand-alone test bed. Finally, before loading the software to the flight instrument EEPROM it was tested on the MLA engineering model instrument. Once software was loaded to the flight instrument, additional orbit simulation testing was performed during spacecraft I&T that included inputs from the spacecraft attitude control system and simulated optical signals to mimic the expected return signal from the Mercury surface.

3.11 Mechanical Design

MLA's optomechanical structural elements, like those of MOLA and GLAS, are made primarily of beryllium, which was selected for its superior stiffness-to-weight ratio and high thermal conductivity. The PCA box, fabricated from magnesium to minimize mass, is located off the optomechanical structure. This was done to reduce power dissipation and thermal gradients in the alignment-sensitive portion of the instrument. A significant departure from previous altimeters is the use of four refractive telescopes, also made with beryllium.

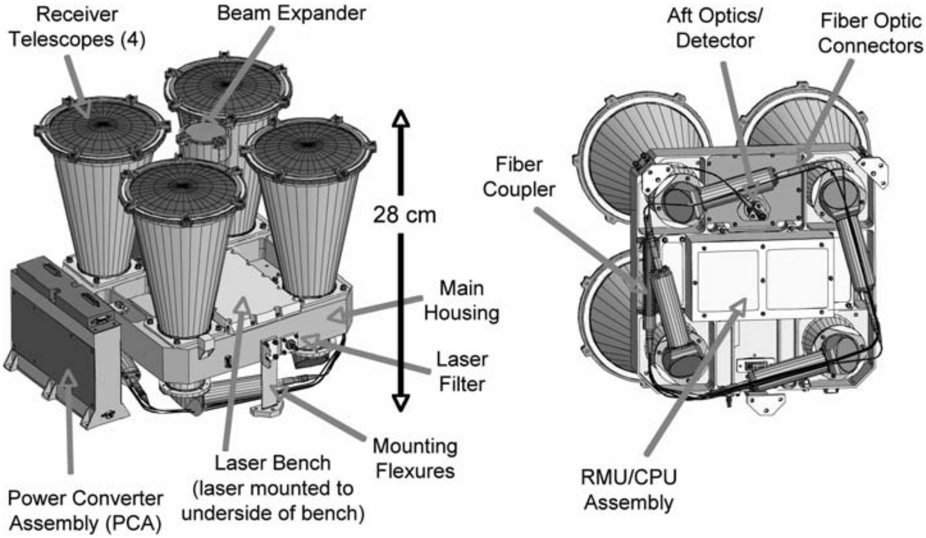

Fig. 16 MLA mechanical subassemblies

Previous altimeters have used reflective telescopes, but in this case a refractive telescope design was deemed less costly and better suited to the expected thermal environment. The main mechanical elements of MLA are depicted in Fig. 16.

The primary metering structure that maintains the boresight alignment is the MLA main housing. This beryllium structure supports the four telescope tubes, the beam expander, and the laser bench. The detector, aft optics, and housekeeping electronics also occupy the housing, and a separate box with the RMU and CPU is bolted to the housing. The main challenge in the design of this structure is to keep the telescope tubes coaligned with the beam expander over the extreme temperature swings to be seen on orbit. Tight assembly tolerances were required to bring all four telescope tubes to within 2 mrad of the beam expander output at initial assembly. The fiber optic couplers could then be adjusted to align the receiver and transmitters to within 10 µrad. The main housing bolts to the spacecraft deck via kinematic mounts using three titanium flexures to minimize thermal conduction to the deck and avoid mechanical distortion of the housing.

The laser bench is a 14-cm by 9.3-cm slab of beryllium to which the laser resonator and amplifier components are mounted. The beam expander bolts directly to this bench and comprises the laser subassembly. The housing has a cavity to contain the laser, which was precision cleaned and kept sealed until laser integration. This cavity has a breathable filter that allows the laser to vent during vacuum testing and after launch. The laser bench is bolted to the housing with 14 bolts around the perimeter. The four beryllium telescope tubes also bolt directly to the housing with four bolts each. The lens mounts for the beam expander and telescope tubes are titanium and hold the BK7G18 glass optics for the beam expander and the sapphire objective lenses in the telescopes.

The main housing, laser bench, and electronics housing were all gold plated for thermal performance. Most of the beryllium used is instrument grade (I-220-F) save for the telescope flanges, which are structural grade. All beryllium parts are nickel plated to prevent oxidation and personnel exposure. Phosphor-bronze helicoils were used for all bolt holes. Aluminum engineering models of all components were fabricated to develop assembly and integration procedures and to validate structural models.

3.12 Thermal Design

MLA will operate under a harsh and highly dynamic thermal environment due to the large variation in heat flux from the Mercury surface from daytime, nighttime, and deep space views. Figure 17 shows the predicted temperatures during the hottest mission orbit. As the spacecraft approaches orbit periapsis the MLA laser is turned on, increasing power dissipation by approximately 10 W, and the instrument view transitions from seeing the cold of deep space to viewing the 700-K surface of Mercury. During this period the transmitter and receiver optics undergo a rapid and uneven temperature rise at a rate of tens of degrees per hour in the laser-beam expander and the receiver telescope.

MLA acquires data for 15 to 45 minutes of each 12-hour orbit during which time it fires the laser, resulting in maximum power dissipation. This data acquisition period takes place near periapsis, where radiative input from Mercury's surface is also at a maximum. These factors result in a rapid temperature rise through the instrument during the data pass. The remaining 11 hours of the orbit are used to radiate the absorbed heat into deep space. The primary radiators are the telescope tubes and the laser beam expander. MLA, as with the rest of the spacecraft, never reaches thermal equilibrium during operations and will see temperature excursions similar to those shown in Fig. 17 during every 12-hour orbit, resulting in more than 700 thermal cycles during the 12-month mission.

The entire instrument is covered with a ten-layer multilayer insulation (MLI) blanket as shown in Fig. 18. The outer layer of the blanket is vapor-deposited gold (VDG), and the inner layers are vapor-deposited aluminum (VDA). During spacecraft I&T a layer of

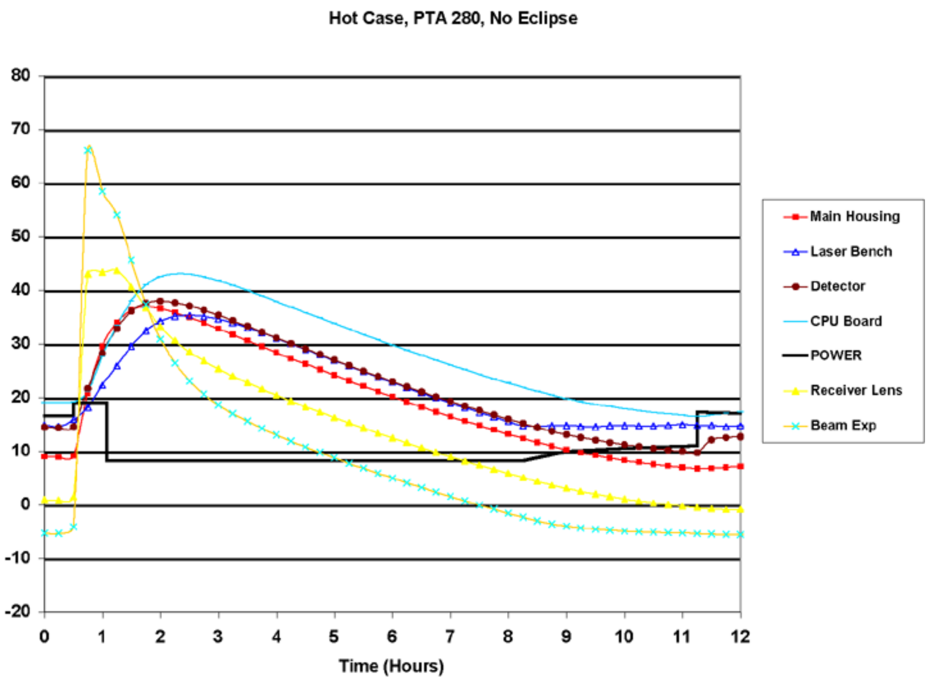

Fig. 17 Predicted temperatures of MLA subsystems during the hottest expected orbit. The plot time starts approximately 30 minutes before firing the laser. The laser beam expander output window temperature (*orange line*) swings from −5°C to +65°C in less than 30 minutes

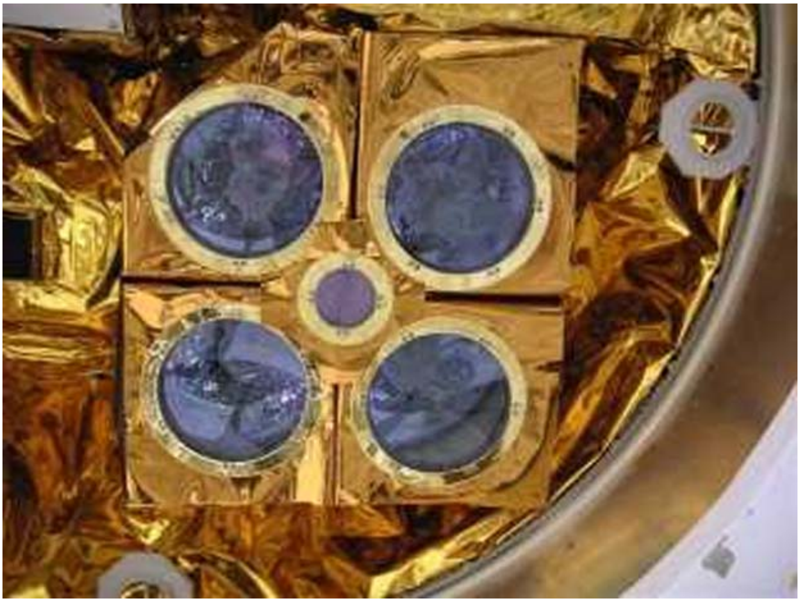

Fig. 18 The MLA instrument shown mounted to the MESSENGER payload deck with thermal blankets installed

aluminized Kapton was added to the nadir-facing surface to alleviate concerns about solar illumination of the VDG layer. A thin strip of black Kapton was also added to minimize reflections on the side facing the MESSENGER Dual Imaging System, MDIS (Hawkins, III et al. 2007). The PCA box conducts its dissipated power directly to the spacecraft deck and is enclosed in another MLI blanket to avoid radiative coupling to the rest of the instrument. Titanium flexures minimize conduction from the main housing to the deck, and another MLI blanket underneath the instrument provides radiative isolation from the spacecraft. The sapphire objective lenses have excellent thermal conductivity compared with other transparent materials, and while they absorb about half of the infrared radiation from the planet's surface they can withstand the resultant thermal shock. A sapphire flat is also used on the beam expander output to improve its thermal properties.

Two sets of 17-W survival heaters powered by separate spacecraft circuits are used. The "B" side circuit has a −20°C thermostat, and the "A" side trips at −15°C. During operations the "A"-side heaters will be used. The "B"-side heaters are needed during cruise and orbit eclipse cases.

Laser transmitter performance is dependent on the laser bench temperature. Optimal operating temperatures for the laser bench range from 15 to 25°C, so to maximize laser energy during the data acquisition part of the orbit the laser bench should be at 15°C just prior to entering Science mode. To achieve this objective an operational heater is located on the laser bench and is powered by the 12-V supply when MLA enters Standby mode. The duration in Standby mode may be modulated through the mission to achieve this starting temperature under varying orbit conditions. Currently the predicted time in Standby mode ranges from 15 minutes for the hot case to 480 minutes for the cold case.

4 MLA System Integration and Test

4.1 Instrument Assembly

The MLA assembly sequence was driven primarily by the cleanliness requirements for the laser. Prior to any assembly activity the main housing was precision cleaned, and the cavity that enclosed the laser was sealed during integration of the electronics with the housing. Laser bench integration was performed in a Class-100 clean room. Once the laser was sealed in the housing, a ground-support equipment (GSE) air filter was attached in series with the built-in flight filter to provide additional protection during I&T.

The receiver telescope tubes and aft-optics were assembled on a Class-100 laminar flow bench in a Class-1000 clean room. The MLA housing with the laser and electronics was delivered to this area, and the telescope tubes were attached. The assembled instrument was then attached to its handling fixture. Before the fiber optics were connected, a series of free-space tests with the laser were performed to establish baseline performance and to calibrate the GSE power measurements that would be used throughout ground testing to monitor laser performance.

MLA was then mounted to an optical bench that contained the alignment optics for bore-sighting. The optical axis of the alignment fixture was coaligned with the MLA laser's optical axis. Each receiver's fiber optic was then aligned to the fixture's axis. As a final post-assembly check each fiber was back-illuminated while the laser was firing, producing an image at the alignment fixture's focal plane showing the laser image with the receiver's illuminated FOV. Since the alignment was done in the lab at one atmosphere, shims on the fiber optic connectors positioned each fiber at the vacuum focus of each telescope, causing the image to blur but allowing for accurate evaluation of the centered images. Subsequent evaluation of the alignment in vacuum was performed during environmental testing. The fibers were then attached to the aft optics, completing the assembly sequence prior to instrument-level testing.

4.2 Contamination

After assembly of MLA the particulate contamination requirements were relaxed to Class-10 000 level since the most sensitive optics were sealed. All optical surfaces, particularly the beam expander output window, were visually inspected prior to firing the laser. MLA GSE that came in close contact with the instrument was cleaned and inspected prior to each use. GSE covers were made for each telescope objective and the beam expander window. These were attached when the instrument was not under test. After MLA was installed on the spacecraft with the thermal blankets, a sheet of lumalloy was taped over the receiver objectives when not testing. Final inspection and cleaning of all optical surfaces was performed prior to encapsulation using bright white and ultraviolet light sources.

The GSE air filter remained attached to the laser housing until final closeout at the spacecraft level save for mass properties testing during which a small plug was installed. A gaseous nitrogen purge was applied to the spacecraft payload area during integration up to launch. This purge line was filtered, and a manifold distributed the purge gas to each instrument. The purge line for MLA was attached near the laser filter snout at final closeout after the GSE air filter was removed.

Table 7 MLA optical alignment allocations and margins. These parameters could be verified to within 10 µrad during testing with the MLA alignment GSE

	Specification
Integration margins	
Laser beam axis parallel to receiver telescope axis	<2 mrad
Laser beam axis perpendicular to mounting plane	<5 mrad
Alignment margins	
Receiver telescopes to laser beam axis (boresight)	±50 µrad
Laser beam axis to MLA reference cube (knowledge)	±50 µrad
Stability	
Laser beam axis to MLA mounting plane	±50 µrad
Receiver telescopes to laser beam axis (boresight)	±100 µrad

4.3 Performance Testing

Table 3 and Table 7 show the MLA ranging and optical alignment error budgets associated with the performance requirements listed in Table 1. A suite of tests was designed to verify MLA performance at the instrument level and during spacecraft testing. Subsets of this suite were used for Aliveness and Functional testing, and the entire suite comprised the Comprehensive Performance Test. Ancillary tests such as boresight alignment verification and timing tests were used at key points during integration and test as calibration points and to demonstrate compliance with the MESSENGER Component Environmental Specification.

4.3.1 Bench Checkout Equipment

The set of test equipment used to verify performance was in itself a system of electronic, electro-optic, and optomechanical subsystems referred to as the Bench Checkout Equipment (BCE). The BCE hardware is composed of three subsystems. One equipment rack contains the main data acquisition system, spacecraft interface simulator, timing references, and electro-optic sources. A second rack contains the alignment data acquisition and control system. An optomechanical target assembly is used for functional and alignment testing. Several hundred meters of fiber optic cable were also used to couple signals and provide constant time-delay paths.

During instrument-level testing the BCE used the MESSENGER-supplied spacecraft interface simulator to provide power and transfer commands and data to and from MLA. After integration with the spacecraft the BCE acquired real-time telemetry via the MESSENGER ground data system network. During all phases of testing the BCE captured and time-stamped each and every laser pulse emitted by MLA and provided simulated return signals and noise at the MLA receiver telescope. Laser pulse energy was continuously monitored.

Simulated return signals were generated by a diode-pumped Nd:YAG laser housed within the rack that produced 5-µJ 1-ns pulses when triggered by the timing electronics. These pulses were fed through an optical attenuator and fiber coupled to a holographic diffuser, which distributed the signal power in a 0.006-steradian cone to be collected by one of the MLA receiver telescope apertures. Optical background noise was simultaneously coupled in a similar manner using a continuous-wave (CW) Nd:YAG laser source.

The BCE used a Stanford Research Systems SR620 time-interval analyzer and two InGaAs photodiodes to independently measure the delay between each emitted MLA laser pulse and the corresponding simulated return pulse. The timebase for the SR620 is a rubidium-based oscillator. The drift of this oscillator is measured by recording the phase between its 1-Hz output to a 1-Hz tick generated by a Global Positioning System (GPS) receiver.

4.3.2 Laser Performance Testing

Two different laser beam termination schemes were used for monitoring the MLA laser. Both were designed to provide a "light-tight" seal to the MLA beam expander to prevent damaging levels of power from leaking into the receivers and afford an additional level of personnel safety. In addition both schemes were required to minimize back reflections into the laser itself.

One assembly is illustrated in Fig. 19. This scheme, known as the beam dump, was an integral part of the alignment test fixture and used a beam splitter to direct 90% of the laser pulse power into a holographic diffuser and then focused a portion thereof into a 0.22 numerical-aperture optical fiber for transmission to a Molectron JD2000 Joulemeter energy monitor and an InGaAs photodiode used for timing and temporal pulse width measurement. The remainder of the energy was transmitted to a charge-coupled device (CCD) camera used for beam diagnostics and redirected via retroreflector into one of the four MLA telescopes. Filter holders allowed for placement of volume-absorbing neutral-density filters to attenuate optical power to usable levels.

The second assembly, referred to as the beam stop, was used primarily for spacecraft-level testing and incorporated a Macor ceramic insert to diffusely reflect the incident laser power. The Macor transmits approximately 1% of the laser pulse, allowing for placement of an optical fiber on the back of the beam stop used with the BCE in the same manner as the beam dump fiber.

4.3.3 Boresight Alignment Verification

Two different methods were used to verify the MLA boresight alignment, or angular offset between the transmitted laser beam and each receiver telescope's field of view.

The initial boresight alignment was performed on a laboratory optical bench using a 2.5-m-focal-length collimator with a 400-mm-diameter off-axis parabola. The initial alignment described in Sect. 4.2 used this fixture. To verify the alignment with this fixture the MLA laser beam axis was aligned to the optical axis of the fixture. With the MLA laser turned off, a 1,064-nm continuous-wave point source at the focus of the fixture was mechanically swept across the MLA field of view while monitoring noise counts in MLA telemetry. MLA noise counts were then plotted against the point source offset to assess the receiver alignment. This method also enabled simultaneous alignment testing of all four receiver telescopes.

During MLA instrument environmental testing and spacecraft-level testing the laser beam alignment to the receiver telescopes was measured by redirecting a portion of the transmitted laser pulse back into one of the four receiver tubes using a lateral transfer hollow retroreflector (LTHR). At the output of the LTHR a pair of motorized Risley prisms deflected the beam at a programmable angular offset into the telescope. By sweeping the angular offset in orthogonal directions across each telescope's field of view and monitoring the power received at the MLA detector, a centroid was computed that indicated the relative

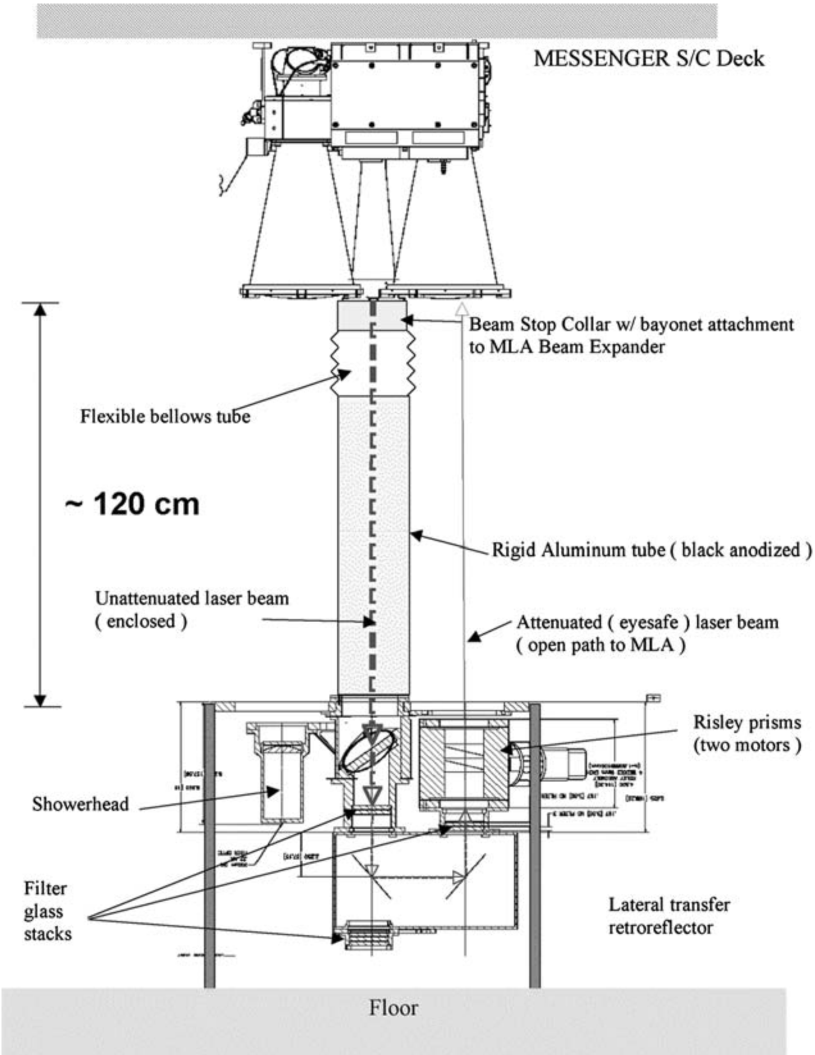

Fig. 19 MLA laser beam dump and alignment fixture shown in the configuration used to verify alignment after MLA was installed on the MESSENGER spacecraft S/C

angular offset of the laser beam to each telescope. Relative pulse power received was measured by computing the change in detected pulse width and normalizing for each tube. The setup used during spacecraft-level testing is depicted in Fig. 19.

4.4 Calibration and Characterization

4.4.1 Instrument Calibration

MLA provides three measurements: the laser-pulse time-of-flight, the echo-pulse width, and the echo-pulse energy, along with a precise epoch time. To calibrate these measurements the MLA BCE continuously monitored laser pulse energy and range timing over the entire dynamic range of the instrument at all detector gain settings and comparator thresholds.

Three methods were used to calibrate the range measurement. First, MLA and a calibrated time interval analyzer simultaneously measured a sequence of simulated range signals generated by the BCE. These simulated optical signals varied in time delay from approximately 1 ms to 13 ms after the transmitted MLA laser pulse, corresponding to the expected time delays to be seen in Mercury orbit from 200 km to 1,900 km.

Second, a series of closed-loop delay tests was performed by transmitting the MLA laser pulse via the beam dump described in Sect. 4.3.2 through five different lengths of fiber optic cable coupled back to the receiver using the holographic diffuser described in Sect. 4.3.1. The fiber lengths ranged from approximately 140 m to 270 m. Finally, the instrument range bias was evaluated using the boresight alignment fixture LTHR described in Sect. 4.3.3. This setup reflected the attenuated MLA laser pulse directly into the receiver telescope over an optical path length of 1 m.

To locate the measurement point on Mercury's surface a precise knowledge of the MLA boresight axis relative to the spacecraft frame is also needed. Pointing verification tests were performed during instrument thermal-vacuum (TVAC) testing, and on the spacecraft after integration, during TVAC, and prior to launch at the Astrotech integration facility in Titusville, FL.

Timing tests with the MESSENGER spacecraft were also performed after integration to verify that each laser shot was correctly time-stamped. All timing measurements were referenced to GPS-based Universal Time Coordinated (UTC) epoch time.

4.4.2 Environmental Testing

All engineering models of electronic, optical, and laser subassemblies were thermally cycled at ambient pressure. Optics were tested under vacuum to verify focus shift. The flight laser subassembly underwent full thermal vacuum testing while monitoring beam quality, pulse shape, and energy (Krebs et al. 2005).

A planet simulator target was also used during instrument-level thermal balance testing to provide a radiative input to MLA and measure the instrument's response to thermal transients. These tests provided valuable insight to the thermal performance during orbit conditions. The MLA thermal vacuum test setup is shown in Fig. 20. Cold plates were attached to the laser bench and main housing to achieve qualification temperatures.

During instrument TVAC testing the laser pointing was continuously monitored using a telescope and charge-coupled device (CCD) camera outside the chamber that imaged the

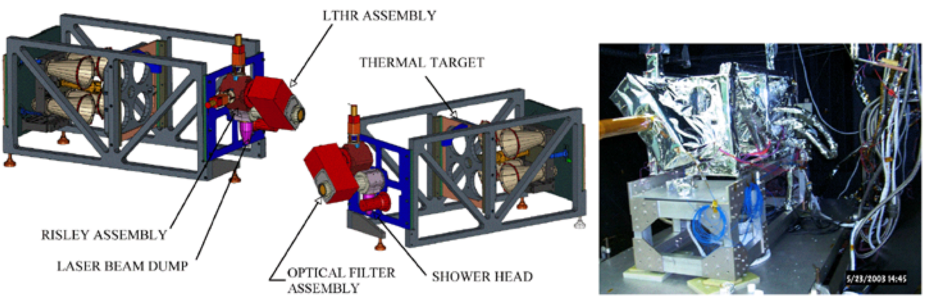

Fig. 20 MLA thermal vacuum test fixture used for instrument-level thermal vacuum testing. The fixture provided a stable platform to monitor alignment and inject optical signals during testing

MLA laser spot along with a reference cube on the instrument. Boresight verification was performed using the LTHR and Risley setup at each TVAC test plateau as well. After instrument TVAC testing the boresight was again verified using the optical bench setup.

During spacecraft environmental testing cold plates were again attached to the MLA laser bench and main housing to provide additional temperature cycles. MLA testing on the spacecraft was limited to range timing with simulated signals. Pointing verification was done before and after spacecraft TVAC.

4.5 Postlaunch Checkout Results

MLA was first powered on August 19, 2004, 16 days after launch (L+16). It remained in Standby mode for approximately 24 hours to allow time for the laser bench to warm up. This warm up also allowed any contaminants (our primary concern was water condensate left as ice on the optics) to sublime. A detector noise characterization test was performed shortly after turn on. Noise levels were observed to be nearly identical to the values seen during ground testing. Another noise characterization was run on L+17 with a similar result.

On August 20, 2004 (Launch + 17 days), MLA was commanded to Science mode, causing the laser to fire. Laser performance was normal with the laser energy monitor reporting 19 to 20 mJ of energy. Figure 21 shows a plot of postlaunch laser energy with an equivalent cold turn-on during vacuum testing. The slightly lower energy ($\sim$0.4 mJ, or 2%) can be attributed to the lack of beam termination at the end of the beam expander. During testing it was observed that the laser energy monitor was sensitive to back reflection from either the beam stop or the beam dump. Since it was impossible to fire the laser unterminated on the ground this condition could not be verified, but the drop in the monitor reading was expected. The matching upward slope after several minutes of operation and the laser diode current pulse width indicate a healthy laser.

The need for additional power from the operational laser bench heater during this first cruise operation of the laser was unanticipated. As this heater was switching on for four

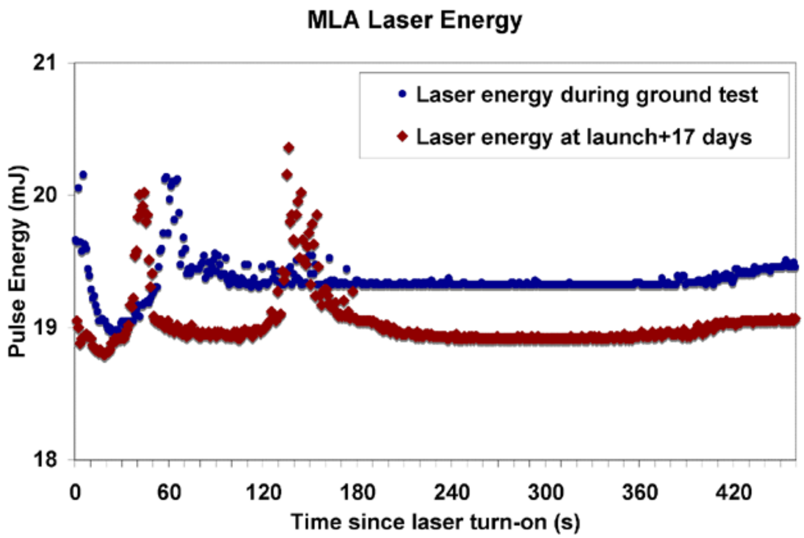

Fig. 21 MLA laser energy comparison showing pulse energy over a seven-minute window measured before launch and 17 days after launch

minutes during a nine-minute period it added approximately 250 mA to the total MLA current. Since the spacecraft C&DH computes power by multiplying the current monitor value times the bus voltage, and the MLA current is only sampled at the 35 ms peak (see Fig. 14), the computed power with the heater was 40.8 W. This apparent power draw violated a MESSENGER spacecraft autonomy rule that automatically shuts down any instrument drawing excessive current. This condition was realized just prior to the planned laser turn-on and the test proceeded with the agreement of the payload systems and spacecraft systems engineers. The autonomy rule executed as expected and turned off the instrument after approximately eight minutes. This rule was subsequently updated to account for this condition.

4.6 Cruise Calibration

In May 2005 MESSENGER successfully performed a sequence of Earth scan maneuvers to calibrate MLA pointing, radiometry, and laser pulse timing during cruise (Smith et al. 2006). Additional radiometric calibrations were performed during the two Venus flybys.

4.7 Data Products

The time-of-flight range data from MLA will be combined with MESSENGER spacecraft pointing knowledge and Radio Science range and range-rate tracking data obtained from the Deep Space Network to produce Digital Elevation Models (DEMs) of the planet's surface referenced to Mercury's center of mass.

MESSENGER's inertial measurement unit and star tracker provide the required pointing data. The radio frequency data link signals are used to determine the precise trajectory of the spacecraft with respect to the planet's center of mass. Once the spacecraft orbit and attitude determinations are initially made, the MLA time-of-flight measurements are used to determine the surface altitude. These surface measurements sample the planet's shape and are fed back into the precision orbit and pointing determination to improve these data sets. Crossover analysis identifies and correlates multiple range measurements of proximate surface features made during different orbits. Reiteration of this process produces the final data product in the form of a DEM. This DEM will be used to determine and track the planet's shape to refine the measurement of the amplitude of the forced physical libration.

Simultaneous pulse width data from the high- and low-threshold channels will be used to determine received pulse energy, which along with the transmitted energy measurement will indicate surface reflectivity at 1,064 nm. Pulse width measurements are also used to assess laser spot-scale, surface slope, and roughness.

4.8 Operation Plans and Observing Strategy

MLA will operate in Science mode, sampling the planet's surface, when the line-of-sight range to Mercury is less than 1,200 km under spacecraft nadir pointing or the slant range is less than 800 km. These limits result in an operating time of approximately 20 to 40 minutes during each 12-hour orbit. Over the life of the mission or approximately 700 orbits, MLA will make over 8 million range measurements at its laser pulse repetition rate of 8 Hz.

For the remainder of each orbit MLA will be commanded to Keep Alive mode to conserve power. In this mode the laser and range measurement electronics are powered off and the instrument dissipates the heat generated by the laser and absorbed from the planet during the brief measurement period. Depending on the orbit, MLA will then be commanded to Standby mode 15 to 480 minutes prior to the next Science mode pass. In Standby mode the laser and range measurement electronics are again powered without actually firing the laser to increase overall instrument power and ensure that the laser amplifier is at its minimum operating temperature of 15°C prior to entering Science mode. During eclipse periods when Mercury blocks the Sun from the MESSENGER solar panels the instrument is powered off.

5 Summary

The successful development, integration, testing, and deployment of MLA have demonstrated the practicability of its scalable, miniaturized laser transmitter, low-cost scalable receiver architecture, and low-power time-of-flight measurement electronics for future space flight missions. Scaling of laser transmitter power is achievable by either removing the laser amplifier (using just the oscillator section) to generate a laser pulse approximately one order of magnitude less powerful or by adding an amplifier to achieve higher laser pulse power. Scaling of the receiver aperture area may be accomplished by adding or removing individual telescopes. A scaled version of the MLA architecture has been used in the design of the Lunar Reconnaissance Orbiter (LRO) Lunar Orbiter Laser Altimeter (LOLA) instrument (Chin et al. 2007). LOLA will use the MLA laser oscillator design to generate 2.7-mJ laser pulses and a single receiver telescope to profile the lunar surface from a nominal altitude of 50 km above the Moon. LRO is scheduled to launch in October 2008.

MLA will provide the first precise laser pulse time-of-flight measurements of the surface of Mercury. This unique data set along with MESSENGER spacecraft pointing and Deep Space Network tracking data will be used to accurately determine the detailed topography of Mercury's northern hemisphere, measure topographic profiles across major geologic structures, track large-scale planetary shape to measure the planet's libration, and measure the surface reflectivity of Mercury at 1,064 nm.

Acknowledgements We wish to thank the following individuals for their significant contributions to the successful completion of the MLA instrument effort: Edward Amatucci, Adrienne Beamer, Pete Dogoda, Tom Feild, Ron Follas, Ame Fox, Jeff Guzek, Randy Hedgeland, Sid Johnson, Igor Kleyner, Steve Li, Steve Lindauer, Billy Mamakos, Dave McComas, Roger Miller, Tony Miller, Lou Nagao, Karen Pham, Steve Schmidt, Stan Scott, Nancy Stafford, Jon Vermillion, Ken Waggoner, Tony Yu, Ron Zellar, and the MESSENGER team at APL, in particular Steve Jaskulek, Eliot Rodberg, Chuck Schlemm, Stan Kozuch, Jack Ercol, and Ted Hartka.

References

J.B. Abshire, X. Sun, R.S. Afzal, Appl. Optics **39**, 2449–2460 (2000)
G. Chin et al., Space Sci. Rev. (2007). doi:10.1007/s11214-007-9153-y
J.J. Degnan, J. Geodyn. **34**, 503–549 (2002)
J. Garvin et al., Phys. Chem. Earth **23**, 1053–1068 (1998)
S.E. Hawkins, III et al., Space Sci. Rev. (2007, this issue). doi:10.1007/s11214-007-9266-3
D.J. Krebs, A.M. Novo-Gradac, S.X. Li, S.J. Lindauer, R.S. Afzal, A.W. Yu, Appl. Optics **44**, 1715–1718 (2005)
N. Paschalidis et al., IEEE Trans. Nucl. Sci. **49**, 1156–1163 (2002)
L. Ramos-Izquierdo et al., Appl. Optics **44**, 1748–1760 (2005)
D.E. Smith et al., Science **279**, 1686–1692 (1998)
D.E. Smith et al., Science **311**, 53 (2006)
S.C. Solomon et al., Planet. Space Sci. **49**, 1445–1465 (2001)
X. Sun, J.F. Cavanaugh, J.C. Smith, A.E. Bartels, *Proceedings of the 22nd International Laser Radar Conference (ILRC 2004)*. Special Publication SP-561, European Space Agency, Noordwijk, The Netherlands, 2004, pp. 961–964
M.T. Zuber et al., J. Geophys. Res. **97**, 7781–7797 (1992)
H.J. Zwally et al., J. Geodyn. **34**, 405–446 (2002)