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# MERCURY LASER ALTIMETER
# INSTRUMENT DESIGN, TESTING, AND PERFORMANCE VERIFICATION

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## ABSTRACT

We report the design, testing, and performance verification of the Mercury Laser Altimeter, which is one of the payload science instruments on the MErcury Surface, Space ENvironment, Geochemistry, and Ranging mission, scheduled to be launched in July-August 2004. The altimeter will provide measurement of the Mercury surface topography via laser pulse time-of-flight. The instrument is capable of ranging to greater than 800km distance at a ranging error standard deviation of 0.15-m.

## 1. INTRODUCTION

The Mercury Laser Altimeter (MLA) is one of seven scientific instruments on the MErcury Surface, Space ENvironment, GEochemistry and Ranging (MESSENGER) spacecraft under NASA's Discovery Program [1]. MESSENGER is scheduled to be launched in July-August 2004, enter Mercury orbit in 2011, and perform scientific measurements for a period of one earth year, which is equivalent to four Mercury years. MESSENGER will be in a highly elliptical and near-polar orbit around Mercury with a periapsis of 200 to 400 km, an apoapsis of 15,000 km, and an orbit period of 12 hours. 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 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 instruments deck to point at the ecliptic south pole with MLA ranging at a slant angle as high as 53 degrees.

Fig. 1 shows the MESSENGER orbits and MLA measurement geometry. Fig. 2 shows the coverage of the MLA measurement over the planet over the entire mission. Figure 3 shows the MESSENGER payload instruments and the location of MLA.

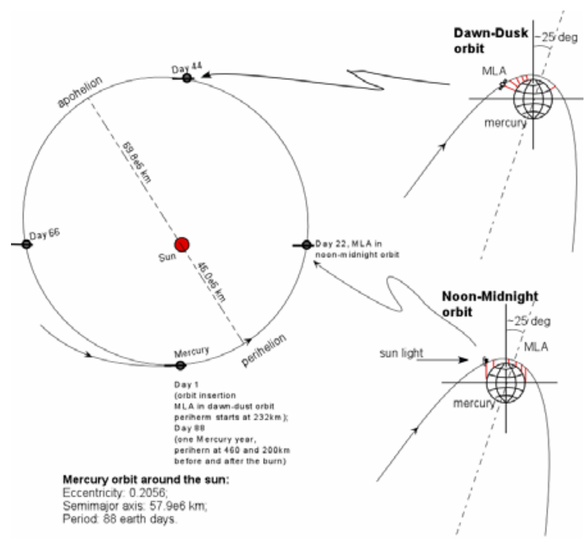


Fig. 1. MESSENGER orbits around Mercury and MLA measurement geometry in dawn-dusk and noon-midnight orbits.

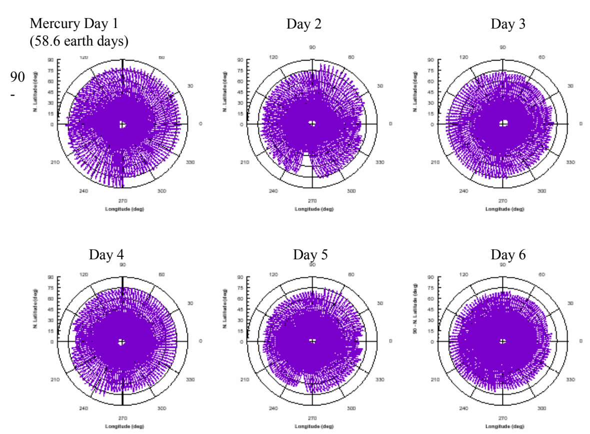


Fig. 2. MLA measurement coverage on Mercury northern hemisphere over the mission lifetime, which is equivalent to four Mercury years (about 88 Earth days/year). The coverage is divided into the six Mercury sidereal days (58.6 Earth days each).

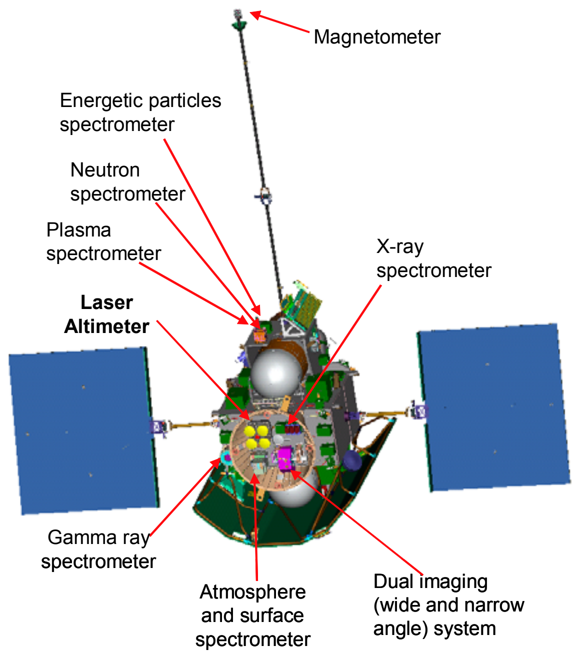


Fig. 3. MESSENGER spacecraft and payload instruments

MLA will measure the topography of the Mercury northern hemisphere via laser pulse time-of-flight data and spacecraft orbit position data. The primary science measurement objectives are to provide a high-precision topographic map of the polar region, measure the long-wavelength topographic features of the mid-to-low latitude region, and detect and quantify the planet's forced librations.

MLA will operate under a harsh and highly dynamic thermal environment due to the large variation in the heat flux from the Mercury surface from daytime, nighttime, and deep space background. The transmitter and receiver optics undergo a rapid and uneven temperature rise during the science measurement (tens of degrees over an hour at the laser beam expander and the receiver telescope). It is a major challenge for the instrument opto-mechanical design to maintain optical alignment when the instrument is always undergoing large and rapid thermal transitions.

Another major challenge is the relatively long distance for which the instrument has to provide accurate range measurement and shallow slant angles during the noon-midnight orbits. The pulse spreading caused by the slant angle greatly reduces the signal-to-noise ratio and makes it difficult for the pulse to be detected. The instrument mass, power, and size allocations also impose severe constraints in the choices of the transmitted laser pulse energy and the receiver collecting aperture size.

## 2. MLA INSTRUMENT DESIGN

The MLA instrument consists of a laser transmitter, receiver telescopes, aft optics, detector, electronics, and microprocessor for instrument control and data processing. The basic instrument design concept was inherited from the Mars Orbiter Laser Altimeter (MOLA) [2] and the Geoscience Laser Altimeter System (GLAS) [3], with major differences in the following design and operation areas:

(a) Four refractive telescopes were used instead of a single reflective Cassegrain-type telescope, with multimode optical fibers coupling the optical signal from the focal point of the telescopes to a single detector. The major advantage of this design is the ease of maintaining optical alignment compared with a larger Cassegrain telescope under an uneven and asymmetric thermal gradient.

(b) The detection threshold was lowered and multiple received pulses are recorded, including the echo signal and several false alarms. The onboard software algorithm then filters out the false alarms and selects the likely ground echoes for downlink. The false alarm pulses arrive randomly, while the ground echoes are likely to be continuous and become distinguishable after histogramming.

(c) The laser and the electronics power profiles and duty cycle will be variable during each orbit in order to achieve and maintain the desired operation temperature range. The instrument is thermally isolated from the spacecraft to avoid additional heating influx from the spacecraft.

Fig. 4 shows a line drawing of MLA, and Fig. 5 shows a photograph of the as-built instrument. Table 1 lists all the key instrument parameters.

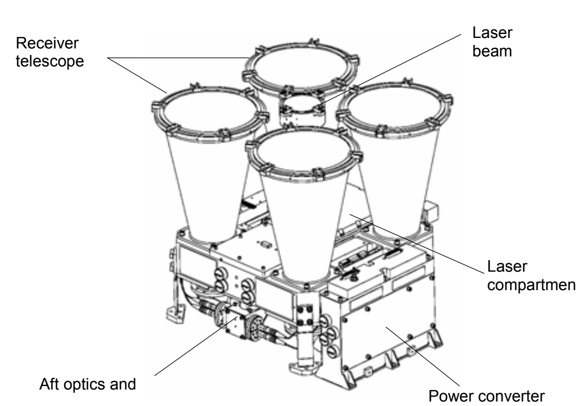


Fig. 4. MLA mechanical layout

Fig. 5. Photograph of MLA prior to delivery to the spacecraft for integration and testing

Table 1. MLA Instrument Parameters

| | |
|---|---|
| Laser pulse energy | 20 mJ |
| Pulse repetition rate | 8 Hz |
| Pulse width | 6 ns FWHM |
| Wavelength | 1064.30 ±0.05 nm |
| Beam divergence (full angle at $1/e^2$ points) | 80 microradians (TEM00) |
| Receiver aperture | 11.5 cm diameter, X4 |
| Receiver field of view | 0.4 mrad |
| Receiver optics transmission with bandpass filter | 77% |
| Receiver optical bandwidth | 0.7 nm FWHM |
| Detector active area | 0.7 mm diameter |
| Detector quantum efficiency | >35% |
| Detector photomultiplication gain | 100 |
| Preamplifier noise equivalent power (NEP) | 0.04 pW/Hz$^{1/2}$ |
| Detector electrical bandwidth | 100 MHz |
| Receiver timing electronics | 5 channel event timers |
| Receiver timing accuracy | <1 ns (standard deviation) |
| Instrument duty cycle | Average 30 minutes per 12 hour orbit |
| Instrument design life time | 5 year cruise, 1 year operation |
| Data rate while in operation | 2.4 kbits/s |
| Weight | 7.4 kg |
| Size | 30 cm (W) 30 cm (L) 30 cm (H) |
| Electrical power consumption while in science measurement | 23 W |

The laser transmitter is a diode-pumped two-stage Nd:YAG slab laser with passive Q-switching. An external 15X beam expander is used to obtain the required beam divergence. The laser cavity is sealed but has a venting hole with a special breathing filter to prevent contaminants from getting into the laser cavity during ground testing and in orbit. A photodiode is placed at the back of the exit laser beam turning mirror to detect the laser pulse emission through the residual passage of laser light through the mirror. The photodetector output serves to start the receiver timing electronics and to terminate the pumping laser diode current. A schematic of the laser optics layout is shown in Fig. 6. A photograph of the as-built MLA laser is shown in Fig. 7.

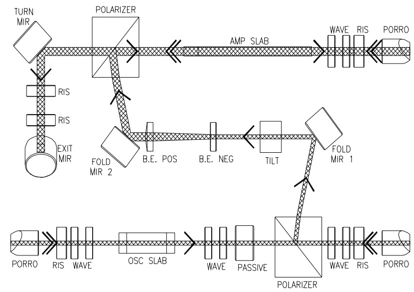


Fig. 6. MLA laser optics layout

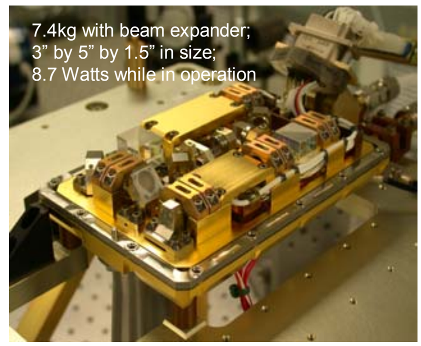


Fig. 7. Photograph of the as-built MLA laser

The MLA receiver consists of four 11.5-cm diameter refractive telescopes and 4 equal-length 200-μ core optical fibers to couple the received optical signal onto a single silicon avalanche photodiode (APD). The interference of the partially coherent light from the four telescopes will cause the addition and redistribution of laser speckles, but the basic function of the receiver as a ‘photon bucket’ is not affected.

The Si APD and pre- and post- amplifier designs are similar to those in GLAS [3]. A variable gain amplifier (VGA) is used to accommodate the wide signal dynamic range resulting form the constantly changing spacecraft altitude during science measurements.

There are three receiver channels, each with a different match filter, 10-, 60-, and 270-ns Full Width Half Maximum (FWHM) impulse response, respectively. The channel that is the closest match to the input pulse has the highest signal to noise ratio and has the highest probability of being detected. Channel 1 also has two comparators, one with a higher threshold and one with a lower threshold. For strong echo signals that cross both thresholds, the two comparator outputs give four samples of the received pulse waveform, which may be used to estimate the received pulse energy assuming a Gaussian pulse shape.

The receiver timing electronics consist of a set of custom silicon Application Specific Integrated Circuits (ASICs) that measure the time interval between a start and a stop pulse by delaying the former through a series of gates on the chip until it coincides with the stop pulse. The propagation times of the gates are constantly self-calibrated against an external clock signal. The ASICs can perform subnanosecond timing without the need for high-frequency logic circuits and clock oscillators. All other digital logic circuits are implemented in a silicon Field Programmable Gate Array (FPGA). The combined circuit can time tag the leading and trailing edges of the transmitted laser pulses and the received echo pulses to better than 1 ns accuracy. It is also capable of time tagging up to 15 events for every transmitted pulse with a 'dead-time' of a few hundred nanoseconds.

The onboard science algorithm software sets the range gate and the VGA gain, automatically adjusts the detection thresholds, and selects the likely ground echo pulse from a mixture of signal and false alarms. The range gate is set according to the slant range calculated by the spacecraft Guidance and Control system. The VGA gain is set according to the expected range. The threshold level is adjusted to give a constant false alarm rate over the given range gate.

## 3. SPACE QUALIFICATION AND PERFORMANCE VERIFICATION

MLA underwent a series of space qualification tests, including functional, temperature cycling, vibration, electro-magnetic compatibility, and thermal vacuum tests. The instrument performance was characterized during the thermal vacuum test. A special set of ground support equipment (GSE) was used to characterize the laser and to feed the test stimuli to the receiver. Fig. 8 shows a mechanical drawing of the GSE test fixture. The laser beam was first attenuated to an eye-safe level. Part of the beam is retro-reflected back to one of the receiver telescopes and part of the beam propagated out through a viewing port on the chamber for pointing jitter monitoring. A set of Risley prisms was used in the retro-reflected beam path to deviate the beam to verify the receiver field of view and the bore sight. A sample of the laser beam was coupled into a multiple-mode optical fiber and brought out of the vacuum chamber for laser pulse energy monitoring, time tagging, and test stimuli triggering. The test stimuli were generated by a pulse laser with programmable delay and fed to the MLA receiver through a collimating lens and a holographic diffuser. A continuous wave (CW) laser was also used to simulate the background from the sunlit planet.

To date, the instrument has passed all the space qualification tests and met all the design goals under the expected operation temperature range. The measured receiver sensitivity was 0.03 fJ per pulse (160 photons) at >90% detection probability for nadir

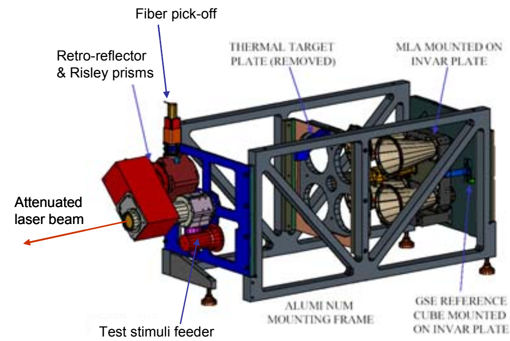


Fig. 8. MLA thermal vacuum test fixture

pointing and about 20% detection probability for 50° off nadir pointing angles. The measured laser pointing stability was about 20 microradians maximum relative to the payload deck.

An end-to-end ranging test was conducted with the MLA laser through a cascade of optical fiber spools and back to the receiver. The delays of the fiber spools were independently measured using a 1064-nm pulsed laser and a digitizing oscilloscope. The test results are plotted in Fig. 8.

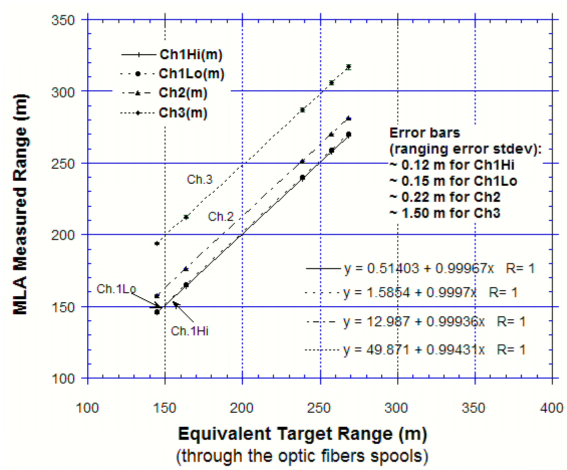


Fig. 8. MLA close-loop ranging test results.

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