# In-Flight Performance of the Mercury Laser Altimeter Laser Transmitter

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## ABSTRACT

The Mercury Laser Altimeter (MLA) is one of the payload instruments on the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft, which was launched on August 3, 2004. MLA maps Mercury's shape and topographic landforms and other surface characteristics using a diode-pumped solid-state laser transmitter and a silicon avalanche photodiode receiver that measures the round-trip time of individual laser pulses. The laser transmitter has been operating nominally during planetary flyby measurements and in orbit about Mercury since March 2011. In this paper, we review the MLA laser transmitter telemetry data and evaluate the performance of solid-state lasers under extended operation in a space environment.

**Keywords:** Lidar Instrument, Space Laser Instrument, Topography, Altimeter

## INTRODUCTION

The MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft, the first to orbit the planet Mercury, was launched on August 3, 2004. The MLA instrument is one of seven science instruments on MESSENGER [1,2]. The MLA instrument, shown in Figure 1, measures the time of flight (TOF) of laser pulses from the spacecraft to the planet's surface. The instrument contains a laser transmitter that generates the light pulse and a receive telescope that gathers the reflected light and focuses it to a detector. Combining the MLA TOF data and the MESSENGER orbit tracking data, a highly accurately topographic map of the Mercury surface can be generated. The objectives of the MLA instrument are to [3]:

- Provide a high-precision topographic map of the high northern regions of Mercury;
- Measure long-wavelength topographic features at mid-to-low northern latitudes;
- Determine topographic profiles across major geologic features in the northern hemisphere;
- Detect and quantify the planet's forced physical librations by tracking the motion of large-scale topographic features as a function of time; and
- Measure the surface reflectivity of Mercury at the MLA operating wavelength of 1064 nanometers.

The MLA laser was designed to support the instrument requirement of achieving a range resolution of less than 40 cm to the surface of the planet. The laser transmitter design is based on the Geoscience Laser Altimeter System (GLAS) laser instrument, previously developed by NASA Goddard Space Flight Center (GSFC) for the Ice Cloud and Elevation Satellite (ICESat) mission [4] with some design changes to accommodate the MESSENGER mission requirements. Both the GLAS and MLA laser transmitters used the master oscillator power amplifier (MOPA) architecture. The characteristics of Mercury's harsh environment drove several changes to the original GLAS master oscillator (MO). The MO design was changed from a Porro/Mirror configuration on GLAS to a cross-Porro MO design for the MLA to handle the large temperature excursion experienced by the MLA instrument. The energy requirement for MLA mission is less than that for GLAS and so is the electrical power allocation. Therefore, the second power amplifier stage was not included.

## MLA LASER TRANSMITTER

The MOPA approach has several advantages for this application: (1) The saturated loss of the passive Q-switch affects only the efficiency of the oscillator section, thereby enabling a reasonable overall efficiency with a passive Q-switch. (2) The small mode diameter (~1 mm) of the oscillator permits a compact and stable laser resonator with

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reasonable alignment tolerance. (3) The ratio of internal to external optical fluence is lessened relative to oscillator-only systems.

The MO is a crossed-Porro optical resonator with polarization output coupling, a Brewster's angle Cr:Nd:YAG slab pumped by a single two-bar stack (G2 package from Coherent, Inc.) of GaInAsP laser diode array (LDA), an air gap polarizer, a passive Q-switch saturable absorber ($Cr^{4+}$:YAG, 0.46 optical density), zero-order quartz wave plates for polarization control, and fused-silica Risley wedges for optical alignment. A thermoelectric cooler (TEC) is used to regulate the temperature of the LDA, which is heat sinked to the laser bench to keep the oscillator LDA at its design temperature and output wavelength. The 0.5% $Cr^{3+}$ co-doping of the Cr:Nd:YAG slab enhances the resistance to radiation darkening. The nominal MO mode diameter is 1.0 mm, and its output energy is 3.0 mJ in a 5-ns pulse [5].

The oscillator output beam undergoes a (2X magnification) beam expansion and is amplified ~7X by double passing through a power amplifier (PA) stage. The Cr:Nd:YAG PA slab is pumped by two, four-bar stacks of GaInAs LDAs (2 x G4 packages). The injected MO signal is double-passed through the PA to generate the required energy for the instrument. The isolation of the amplifier output beam from its input beam is accomplished by polarization. A 0.57-retardation wave plate together with the Porro-prism reflector provides a polarization change in the back-reflected beam to the orthogonal linear polarization. The PA amplifies the MO energy from ~3 mJ to a nominal laser pulse energy of ~20 mJ.

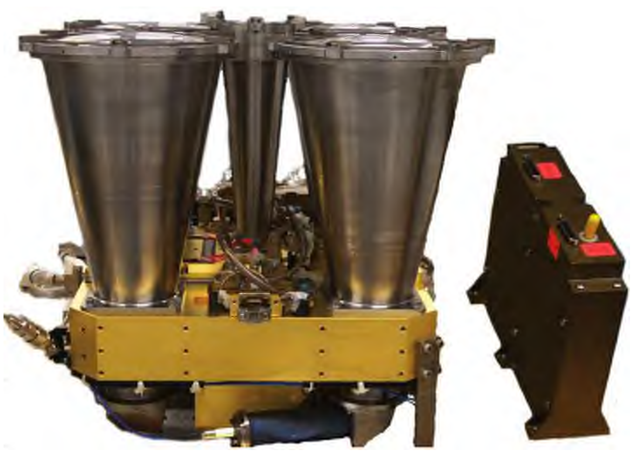

Figure 1. Photograph of MLA at GSFC prior to delivery to MESSENGER. The diameter of each of the four receiver telescopes is 14 cm.

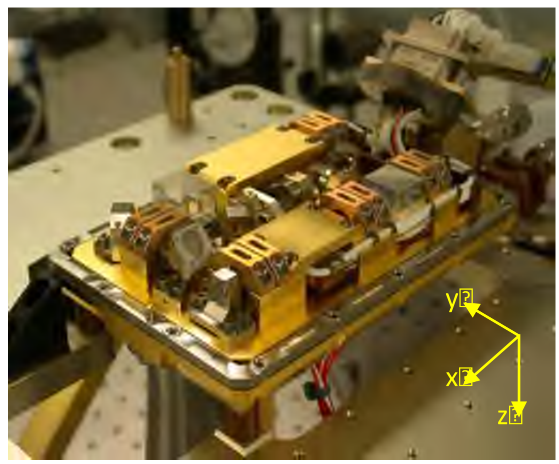


Figure 2. Photograph of the MLA laser transmitter.

An output beam expander is mounted to the underside of the laser optical bench. A quarter-wave plate is used between the beam expander and the laser to generate a circularly polarized output beam to prevent back-reflected energy from entering the amplifier. On the backside of the optical mount for the exit mirror, a diffuser plate was attached to intercept the leakage through the exit mirror. A quadrant photodiode (UDT Sensors, SPOT-4D) staring at this diffuser plate provides (1) a timing signal for terminating the laser diode pump pulse, (2) laser energy monitoring, and (3) a start signal for the ranging electronics. To provide a greater signal level for the critical function of triggering the ranging system, the signals from three quadrants of the detector are summed to provide the ranging start signal. The remaining quadrant of the detector provides the signal for terminating the laser pumps and energy monitoring.

The MO and PA LDAs are operated in series, electrically, driven with a 100-A peak current. The laser electronics provide a current pulse that ramps up slowly (taking ~ 45±3 s) at turn on; the pump pulse is limited only by the maximum width setting (255 µs) until the detector pulls it in after detection of a Q-switched pulse. As configured, the oscillator Q-switches at ~160 µs (beginning of life, or BOL), and the signal from the quadrant photodiode terminates the laser diode drive pulse at that time. As the laser ages the switch-out time increases, so this quantity is an indicator of laser health during in-space operation. Since the oscillator and amplifier are electrically in series, if the oscillator pump diodes start to age or the resonator Q-factor decreases, the pump duration increases to allow for a longer switch-out time for the Q-switch pulse to form. The oscillator is operating under constant power, so a longer switch-out time would not affect the MO output energy. The amplifier, on the other hand, would see a higher overall pump energy due to a longer pump pulse, so the MOPA energy output would increase as well if the amplifier diodes remain unchanged from BOL. The pump duration capacity (255 μs) of the electronics provides an approximate 35% (~160 μs at BOL, a margin of ~95 μs) specific gain margin to accommodate the pump array degradation and additional resonator losses at end of life (EOL).

## LASER TRANSMITTER PERFORMANCE DURING GROUND TESTING

The laser transmitter was designed, built, and tested at NASA GSFC prior to delivery to the MESSENGER project. Table 1 summarizes the requirement for the MLA laser. The laser was environmentally tested prior to delivery to the project for integration with the spacecraft.

Table 1. Summary of the MLA laser transmitter requirements.

| | | | |
|---|---|---|---|
| Design Lifetime! | Operational! | 2 years! | Based on 5 yr. Cruise, 1 yr. mission operation! |
| | Power Cycles! | ³ 2000 ! | ~720 on orbit! |
| | # Shots! | ³ 30 Million | ~12 Million on orbit |
| Laser Output! | Wavelength! | 1064.5 ± 0.1 nm! | Diode pumped Cr:Nd:YAG! |
| | Pulse Energy! | 20 ± 2 mJ! | |
| | Rep. Rate! | ³ 8 Hz! | |
| | Pulsewidth! | 4 – 8 ns! | |
| | Divergence! | 50 ± 10 μrad! | After 15X beam expander! |
| | Shot-shot Jitter! | £ 10% of Beam divergence! | |
| To Beam Exp.! | Angular dev.! | ± 2 mrad! | |
| | Centration! | ± 0.10 mm! | |
| Temperature! | Op. in spec.! | +15 to +25 °C ! | |
| | Op. w/o damage! | +5 to +35 °C ! | |
| | Survival! | -20 to +40 °C ! | |
| Radiation! | Total exposure! | £ 30 krad! | MESSENGER predicts! |

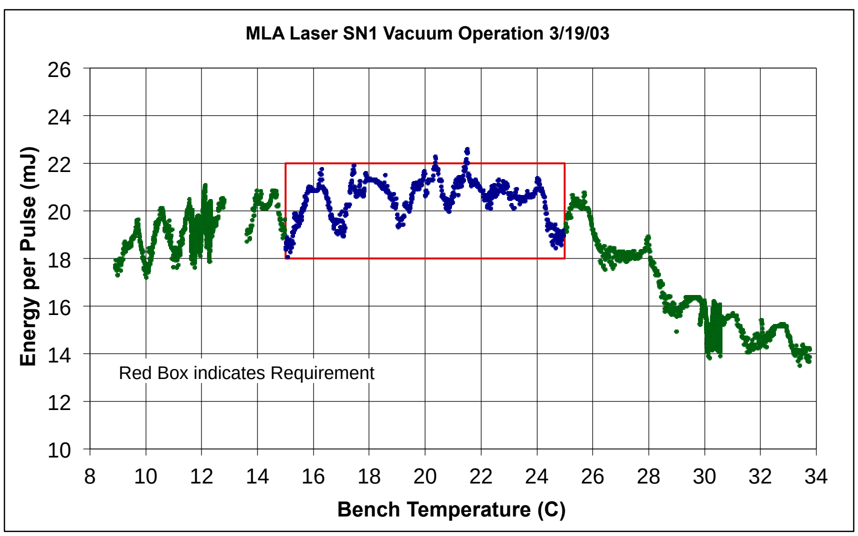


Figure 3. Laser output energy versus bench temperature, measured in vacuum.

The environmental tests of the laser subsystem consisted of vibration and thermal vacuum (TVAC) testing. Vibration testing consisted of three-axis random vibration to a root mean square (rms) acceleration of 8.0 *g* (where *g* is Earth's surface gravitational acceleration) in x and y, and a rms of 10.7 *g* in z, with a full evaluation of the laser pointing, power, and divergence before and after each test. The body axes are as shown in Figure 2. The TVAC testing involved a nonoperational warm soak at 40°C, and a nonoperational cold soak at 5°C, followed by a cold start, a hot start at 35°C, and four operational thermal sweep cycles, all in vacuum conditions. During this testing the output power, divergence, beam pointing, and pointing stability were measured continually [5].

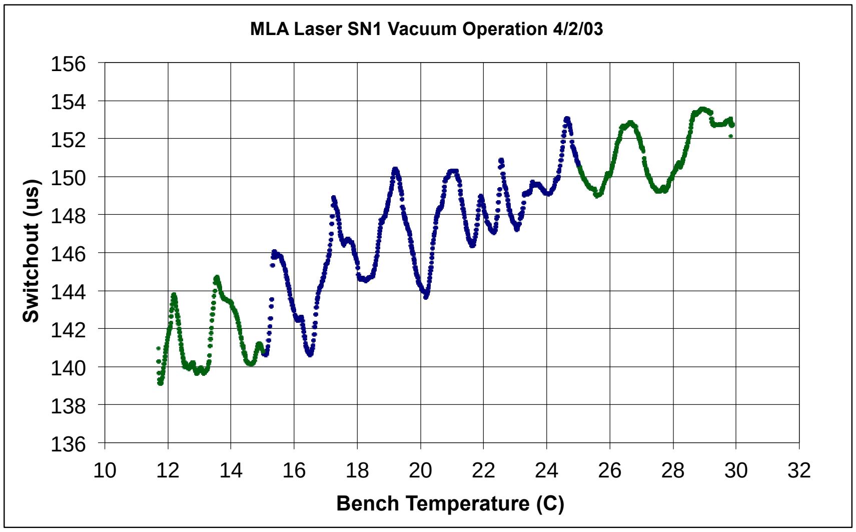


Figure 4. Switch-out time of the passively Q-switched laser as function of bench temperature, operated in vacuum.

The output energy of the laser subsystem is shown in Figure 3 over a temperature sweep between 10 and 34°C. The overall shape of the curve is due to changes in the output wavelength of the amplifier pump array and consequent changes in absorption efficiency. The 0.8–1.5°C oscillations seen in the data are likely related to the Fabry-Perot resonances of the oscillator. Figure 4 shows the switch-out time of the Q-switched pulses with the laser operated in vacuum over a temperature sweep between 10 and 32°C.

## LASER PERFORMANCE DURING SPACE OPERATIONS

The MLA laser transmitter was first powered on briefly 17 days after launch, and all the telemetry data were nominal. However, ranging performance could not be verified because of a lack of ranging targets. Two more opportunities arose to perform in-space ranging from MLA to Earth. The first was in May 2005 during MESSENGER's Earth flyby. The 1.2-m telescope facility at the Goddard Geophysical and Astronomical Observatory (GGAO) was used as the ground station for the ranging experiment. The ranging precision was shown to be ~10–20 cm [6]. A second ranging experiment was conducted on June 5, 2007, during MESSENGER's second Venus flyby [7].

On January 14, 2008, MLA became the first instrument to measure the distance between a spacecraft and the surface of Mercury during a flyby. The instrument acquired the surface at a slant range of about 600 km (about 370 miles) and tracked the surface through closest approach near 200 km (about 125 miles) and out to a distance of about 1500 km (about 930 miles). During the Mercury encounter, the instrument met or exceeded all performance specifications [8].

Since MESSENGER's insertion into orbit about Mercury in March 2011, the MLA instrument has successfully measured Mercury's surface topography and acquired measurements of surface reflectance at the laser wavelength. MLA began collecting science measurements from orbit on 29 March 2011 and is still operating as of this date. As of January 2014, MLA has fired more than 30 million laser shots over the course of 7 Mercury years [9]. MLA has produced a topographic map of the northern hemisphere of Mercury during the MESSENGER primary science mission and the first extended mission [10, 11]. Despite large thermal transients, constant thermal cycling, and power cycling (>2,000 on the laser transmitter), the MLA laser cavity and optics appeared to remain aligned and in focus. The maximum ranging distance achieved by MLA is 1600 km in the nadir direction and 600 km at a 60° slant angle [9]. MLA measurements have extended to the equator and, in many places, southward of the equator during MESSENGER's primary mission despite the spacecraft's eccentric orbit and high northern periapsis. A map of surface slopes has been generated from topographic measurements that distinguish volcanic smooth plains from older cratered terrain [12]. MLA measurements of surface reflectance included areas in permanent shadow in Mercury's north polar region [13]. MLA measurements of Mercury are continuing during MESSENGER's second extended mission [14].

As described above, the pulsed laser transmitter generates a pulse train at 8 Hz with pulse width of ~5 ns for the TOF measurement. The switch-out time of the Q-switched pulses is an indicator of the health of the MO. Factors that can affect the switch-out time include aging of the pump LDAs, higher loss on resonator optics due to contamination, optical damage, and misalignment of the MO cavity. These factors all contribute to higher loss in the resonator and thus a lower effective gain, causing the switch-out time for the Q-switched pulses to increase to compensate for the higher loss. If the switch-out time remains constant but the laser transmitter energy is lowered, then this is most likely due to aging of the amplifier pump LDAs or damage to the optical components that are in the amplifier optical path. In Figure 5 we show the laser parameter trending graphs for the pulse energy, pulse width, and switch-out time. The laser energy decreased steadily by about 35% from ~20 mJ to ~13 mJ from the beginning of the science measurements in March 2011. As observed from Figure 5, the laser began to degrade from day 250 of 2011. The switch-out time increased from a nominal 150 μs to around 220 μs.

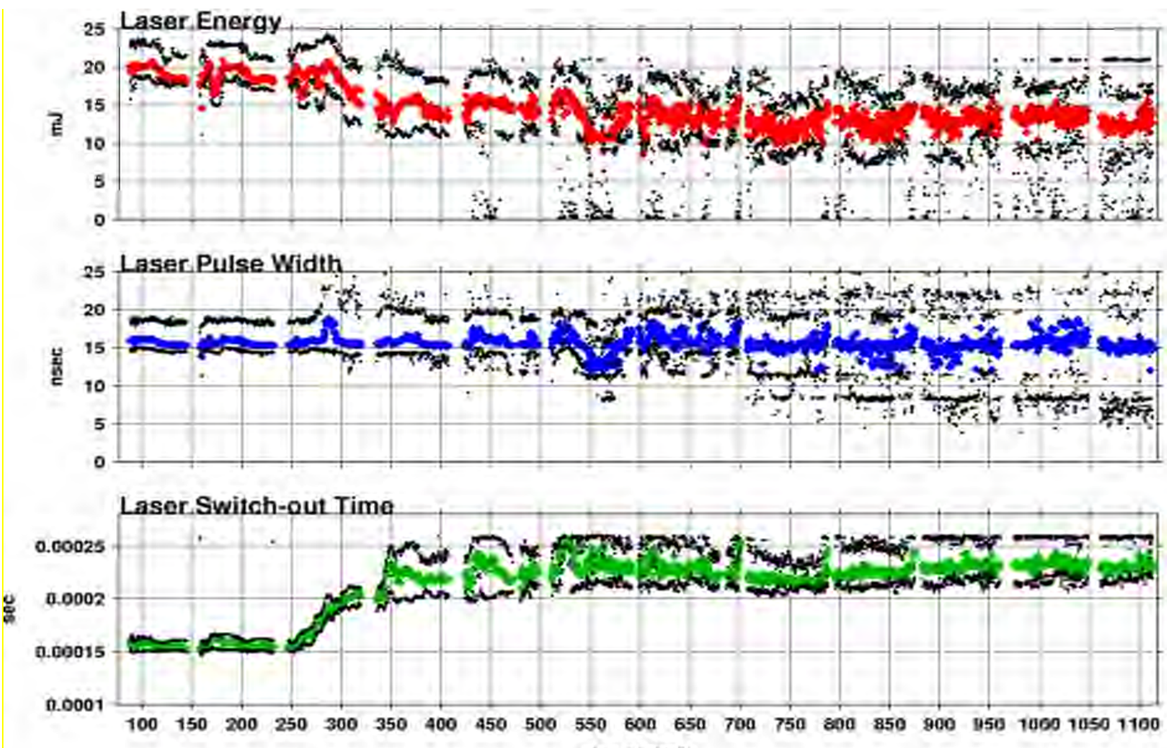


Figure 5. Trends in MLA laser transmitter parameters since the instrument began science measurement in March 2011. The top graph shows the laser energy steadily decreasing from ~20 mJ to ~13 mJ over the course of 1100 days. The middle graph shows the pulse width trend for the MLA laser, and the bottom graph shows the switch-out time of the Q-switch pulses for the MO. The black bands on each of the graphs show the minimum and maximum values for each parameter.

The leading hypothesis for the observed changes is the following. From day ~180 to 250 of 2011, as shown in Figure 5, the instrument was powered off during a spacecraft off-nadir pointing period to prevent payload overheating by the hot planet. The instrument was turned on in early September 2011 while the temperature was still relatively high. A few days after this event, the switch-out time began to increase, and the overall energy decreased about one month after that event. The hot start could have accelerated the aging process of some of the emitters within the LDA bars. On the basis of this hypothesis, we modeled the performance of the MOPA laser using a coupled rate equation laser energetic model for the master oscillator as described in [4] and the formalism for the amplifier gain and stored energy as presented in [15].

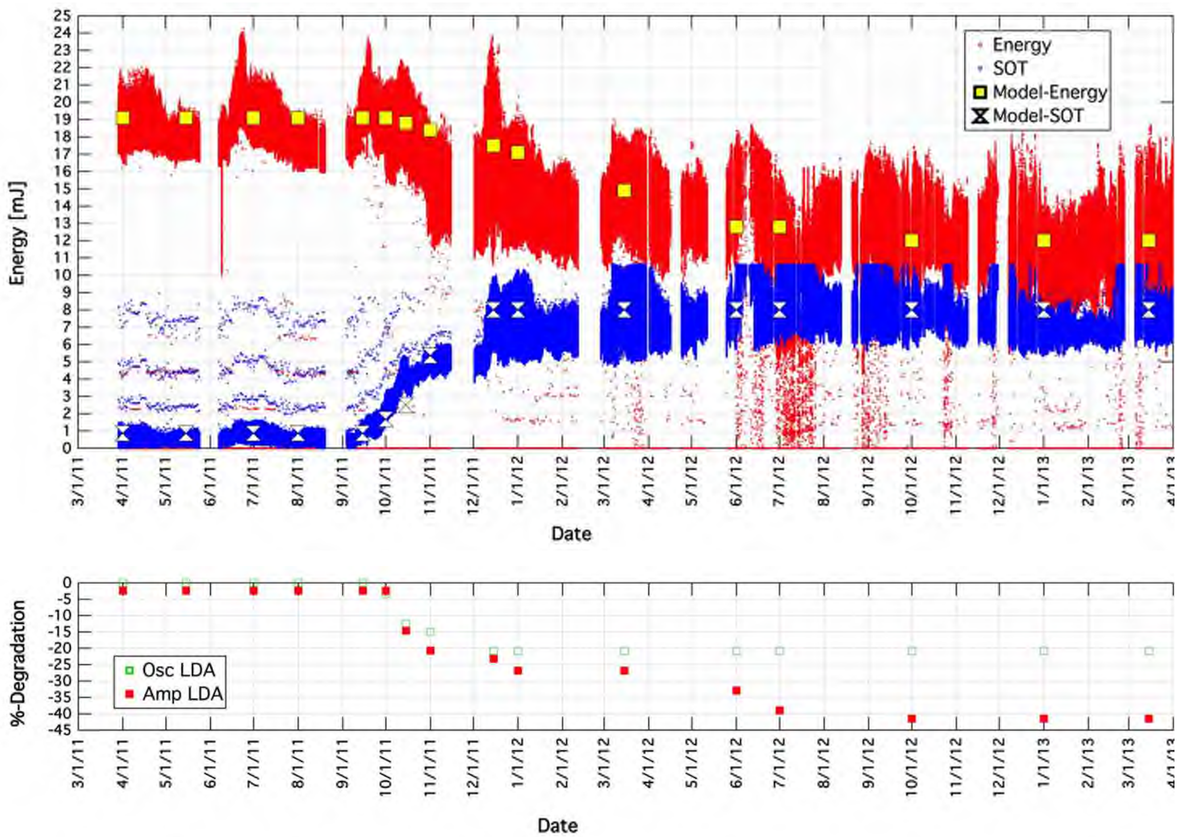


Figure 6. Modeling results showing the increase in switch-out time of the Q-switch pulses for the MO and the overall energy degradation from the MOPA laser. The bottom graph shows the percent-degradation of pump diode energy to the slabs that were used to model and match the increase in switch-out time and decrease in MOPA output energy. The model used a single heat-sink temperature of 18°C.

In Figure 6, the degradation or increase in switch-out time is modeled by decreasing the oscillator LDAs pump energy by the percentage shown for a particular switch-out time. The energy decrease is modeled by appropriate degradation in the amplifier pump LDAs as well.

The same graphs shown in Figure 5 are plotted in Figure 7 along with the housekeeping telemetry data at the MLA housing, the top of the beam expander, the electronics board, and the laser amplifier. The temperature variation during the first 500 days seemed to be fairly consistent, so the changes in pulse energy and switch out time over days 250–350 of 2011 are most likely not caused by temperature.

For days 500–600, there seemed to be a larger temperature excursion. Such an excursion could lead to more frequent mode beating in the MO. The pulse width would then see a larger variation and there would be a larger change in laser pulse energy and switch-out time.

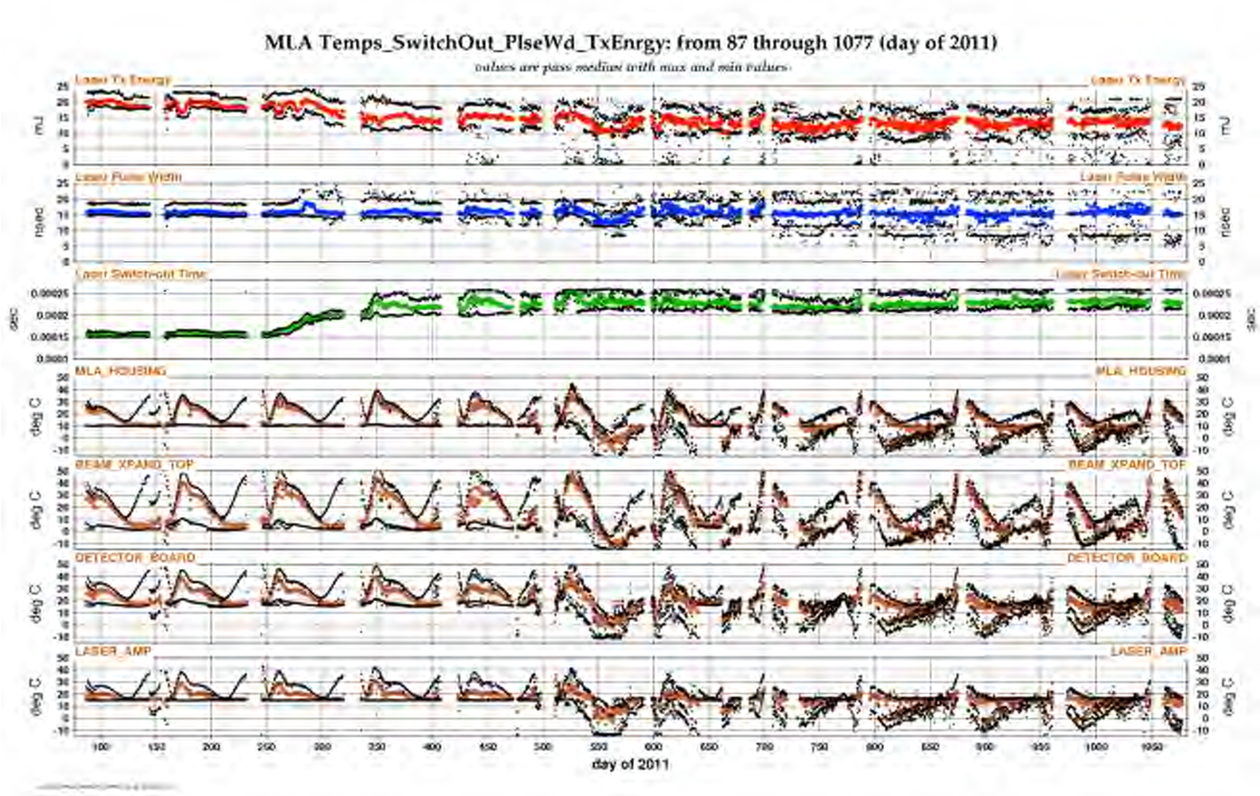


Figure 7. MLA laser pulse energy, pulse width, and switch-out time along with the temperatures of the MLA housing, beam expander (top), detector board, and laser amplifier as measured by the thermistors in each of these areas.

What has not been included in the model is the potential contamination of optical components inside the oscillator cavity (which would lead to an increase in switch-out time) or amplifier chain optics (which would lead to an overall decrease in energy). It is also likely that some combination of all of the potential causes (LDA aging/degradation, contamination, or misalignment) contributed to the current laser health. The laser performance has become more stable in recent months. We will continue to monitor the laser telemetry and recommend actions to extend the instrument life until MESSENGER completes its mission in early 2015.

## CONCLUSIONS

The MLA laser transmitter has been designed on the basis of the GLAS laser architecture. The laser has operated nominally since the MESSENGER spacecraft was launched in August 2004 and has accumulated more than 30 million shots. All other altimeter subsystems, including electronics, power supply, detector, and optics, are healthy. Laser performance has stabilized, and the instrument will continue to perform science measurements.

## ACKNOWLEDGEMENT

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