NASA's ICESat was launched on January 12, 2003 at 4:45 PST on board a Boeing Delta II expendable launch vehicle from Vandenberg Air Force Base, California. As the satellite passed over the ground station in Svalbard, Norway, on February 20th, the first of the Geoscience Laser Altimeter System's (GLAS) three lasers was activated. After Laser 1 activation, GLAS measurements of laser waveforms, surface elevations, clouds and aerosols were excellent. However, after several weeks it became apparent that data from Laser Profiling Array (LPA) sensors monitoring the energy emitted by Laser 1 began to show a greater than anticipated decline with increased operating time. Also, at least one large S-curve event (sudden energy rise followed by a drop) around operation day 23 occurred, followed by an energy shift from red (1064nm) to green (532nm) and the development of a second energy lobe as seen by the LPA at approximately operation day 27. These events and the timeline of actions are depicted in Figure 1.

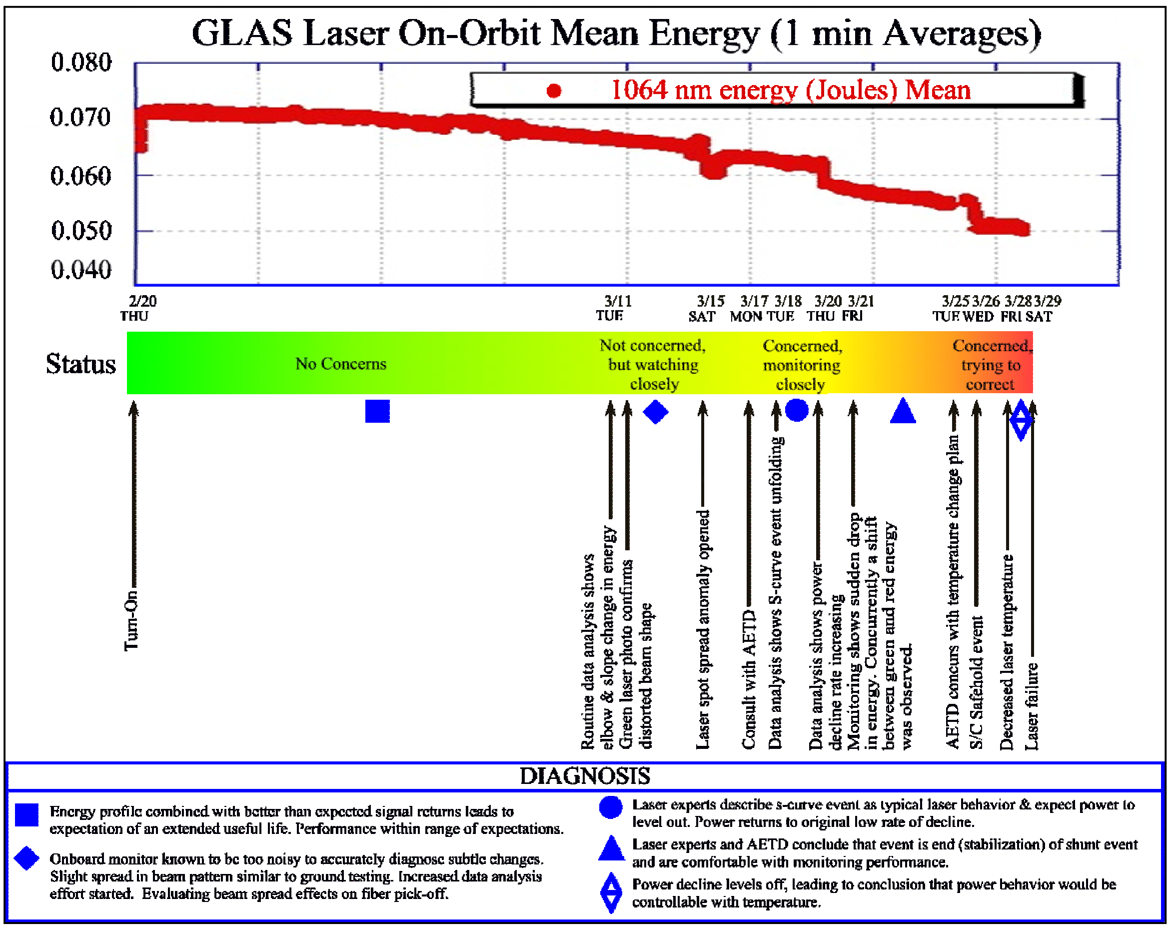

Figure 1, GLAS Laser 1 Anomaly Events Timeline

Following consultation with engineering, at approximately operating day 35 the laser reference temperature was lowered from 29.2 °C to 22.0 °C in two steps to extend the lifetime of the laser and reduce the energy degradation. About 50 hours later, on Saturday March 29th, 2003, at approximately 9:58 a.m. Eastern Time, the GLAS laser transmitter stopped emitting laser pulses; the two 40 Hz laser monitors (LPA and GLAS

Laser Altimeter Detector Start Pulse) indicated that this occurred over a single shot. Ground controllers at the Laboratory for Atmospheric and Space Physics (LASP) subsequently turned off the power to Laser 1. Following turn off, review of the housekeeping telemetry showed that the final laser pulse had been accompanied by a sudden rise in temperature of ~9 ^{o}C in the oscillator, and the shutdown of the Boost Converter (main laser power supply).

The ICESat Project designated an Anomaly Tiger Team on March 30, 2003, and appointed an Anomaly Review Board on April 8, 2003. The Independent GLAS Anomaly Review Board (IGARB) began activities on May 7, 2003. It includes experts from several NASA Centers and private industry and was chartered to report to the GSFC Deputy Director and the Goddard Program Management Council (GPMC). The IGARB was requested to investigate the Laser 1 anomalous performance and identify probable root cause, recommend future options for Laser 1, provide recommendations concerning the turn-on and operations of Lasers 2 and 3, and disseminate any lessons learned to related programs and activities.

A Blue Ribbon Panel was convened at the direction of the Earth Sciences Enterprise to evaluate the results of the IGARB. This panel includes non-NASA experts with extensive ground and space flight laser development and test from academia, other government agencies, and private industry. The Panel convened once for a full day review of the IGARB's initial results on June 24, 2003, and continues to follow developments.

The IGARB has concluded that the most likely cause of failure of GLAS Laser 1 was an unexpected failure mechanism in a pump diode array that resulted in excessive power degradation and catastrophic failure. Manufacturing of the laser diode arrays introduced excessive indium solder that resulted in a metallurgical reaction that progressively eroded the gold conductors through the formation of a non-conducting gold-indium intermetallic, gold indide, at a rate dependent on temperature. The second necessary factor contributing to the catastrophic failure was the development of a current shunt in a diode array bar that combined with the relatively high current requirements (compared to MOLA) in the gold wire bonds. The current shunt forced the redistribution of current, which accelerated gold indide formation and wire fatigue through increased thermal stresses and ultimately contributed to open bond wires. At some point the remaining wires were unable to handle the stress and fused open. An arc then formed a short to ground that overstressed other diodes, and fused them open as well.

It is likely that the same problem that affected Laser 1 may also exist in Lasers 2 and 3. However, it is impossible to predict with certainty the performance of Lasers 2 and 3 since it is not possible to determine the exact condition of their diode arrays. Laser 1 operated for approximately 74 days of pre-launch operations plus 36 days of on-orbit operations. Lasers 2 & 3 pre-launch operations were 44 & 37 days, respectively.

The IGARB has recommended that science operations be structured with the expectation of substantially reduced life from Lasers 2 and 3, and that Laser 2 be activated first with on-orbit spacecraft and instrument operations structured to minimize the thermal stresses to which the laser diodes are subjected. This includes disabling pulsing rather than turning off laser power, and safe mode recovery changes. To reduce temperature-related effects of any indium contamination, the IGARB has recommended that Lasers 2 and 3 be operated at a 25 ^{o}C reference temperature rather than the 29 ^{o}C initially used for Laser 1. The IGARB recommends use of the existing operations plans regarding turn-off as they apply to laser operations, but revision of the survival mode recovery procedures to control the rate of warm-up prior to turn-on to minimize thermal stresses and strains in the diode array solders. Also recommended is more frequent processing of telemetry data with appropriate filtering, with regular assessment and reporting. Lastly, the IGARB has recommended that a restart of Laser 1 not be attempted until Laser 2 and 3 have been expended, because of the small risk that the failure could propagate. Laser 1 should have re-started on its own if the failure had cleared following cessation of pulsing and prior to turn off, but this did not occur.

The potential problem with gold-indide formation had not been uncovered during GLAS ground testing. The GLAS Instrument used a standard protoflight qualification regime, which included thermal-vacuum and vibration environmental tests. Also, an Engineering Test Unit (ETU) had been constructed and tested, and accelerated life tests were successfully performed on similar laser diode arrays. The detrimental effect of indium contamination is the major factor that had not been anticipated, detected, or accounted for. Laser 3 and the Engineering Test Unit (ETU) had experienced catastrophic failures of diode arrays during ground testing that had been analyzed and repaired with part replacement. Failure analyses conducted at the time had not uncovered the gold indide issues, and concluded that the likelihood of failure reoccurrence was extremely rare. Also, Lasers 1 and 3 had experienced small power output drops during unit level testing that were believed to be diode bar shunts. Similar shunt events had been observed previously on MOLA, and were known to cause diode bar darkening. The GLAS design incorporated extra diode arrays to allow for the darkening of individual bars by shunts.

The manufacturer of the laser diode arrays was apprised of the IGARB findings. They were helpful and cooperative in providing the IGARB specific manufacturing data relevant to the parts that are being used for space flight. The manufacturer had already discontinued the specific laser diode array design that was used on GLAS.

The GLAS laser diode arrays are complex, high technology and high performance assemblies that were procured as Commercial Off the Shelf (COTS) products for space flight applications. Unlike other types of Established High Reliability Parts, such as some military grade resistors, capacitors, transistors, and electronic microcircuits, these parts were not manufactured to highly controlled processes, drawings, or with significant reliability testing. To prevent recurrence of the problem in the future, the IGARB recommended a more extensive laser diode array flight qualification program for future space flight applications that incorporates rigorous manufacturing controls, extensive testing, and characterization to ensure reliable performance. The IGARB also concluded that hardware designated as having heritage from previous flight missions requires a rigorous analysis to ensure that it is the same as previously used and that it meets the requirements of the new mission. Heritage cannot be applied when there is a general lack of knowledge of the fabrication and assembly process, which is the general case for COTS products and the GLAS laser diodes in particular. MOLA heritage and on-orbit experience was considered to be relevant for GLAS by similarity, despite what has now been found to be significantly larger stresses in use and modified manufacturing processes. The IGARB also recommends a rigorous focus on root cause determination for failures or off-nominal results in testing, particularly for new technology. Acceptance of known, observed phenomena associated with a specific technology, where the root cause is not yet understood, leaves the user vulnerable to future problems. Catastrophic bond wire open events occurred in the GLAS ETU laser and in Laser 3 during test and may have been related, but the failure investigations conducted at the time led to the conclusion that the probability of recurrence was unlikely. Current shunts in Lasers 1 and 3 were accepted and presumed benign based on prior MOLA experience, although not fully understood. Lastly, the treatment of Commercial Off The Shelf (COTS) parts requires special attention in excess of current activities. An independent parts qualification assessment should be done. Vendor qualification of the GLAS laser diode array was considered acceptable when experience has shown it was not. Careful attention must be paid to the potential for process variability since process changes occurred without NASA knowledge or visibility. Spares or reserve units should be purchased for critical components to anticipate potential requirements for DPA, life testing, and shelf life issues.

A final IGARB briefing was given to NASA Senior Management on August 20, 2003. It was noted by the Project that a significant factor in the anomaly was that GLAS was developed as Class C instrument, with Grade 3 parts (utilize manufacturer's processes and controls). A modified science plan and strategy to achieve optimal science return from limited life lasers has been developed and implemented. The plan assumes that Lasers 2 and 3 will perform similarly to Laser 1. However, the plan also has flexibility to take advantage of extended laser life as compared to Laser 1 if it occurs, and will optimize science return in the event of shorter life than Laser 1. Mission operations procedures will be altered to best protect Lasers 2 and 3. Remaining GSFC activities are to disseminate the failure review findings to the community via the Laser Risk Reduction Program (LRRP), and to conduct a GSFC "Case Study" Review Board evaluating how effective the GSFC processes were in supporting the GLAS development effort. A laser diode vacuum test has been initiated and results will be reported through the LRRP, and a Life Test of flight spare Laser 4 is planned and will likewise be reported through the LRRP. The Blue Ribbon Panel was in agreement with the IGARB findings and recommendations, and reported to NASA senior management on August 22, 2003, with the added recommendation of additional laser modeling for future designs.

Robert A. Kichak

Robert A. Kichak

Chairman, Independent GLAS Anomaly Review Board