NASA SAFETY CENTER

SYSTEM FAILURE CASE STUDY

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# All Shook Up

## The LADEE Spacecraft Vibration Mishap

May 3, 2012, Bay Area, California: Vibration testing was commencing for the Lunar Atmosphere and Dust Environment Explorer (LADEE) spacecraft Engineering Test Unit (ETU). LADEE's purpose was to orbit the Moon's equatorial region for approximately 1 month to collect data on the lunar dust conditions to help guide the possible design for lunar outposts and future robotic missions. The LADEE mission also studied the fragile lunar atmosphere before further human activity contamination occurred. However, during vibration testing, an anomalous sine burst test at a contractor test facility damaged the spacecraft.

### PROXIMATE CAUSE

- High pre-existing frictional force from misaligned and seized bearings caused the control system for the vibration test sliptable to compute an abnormally high voltage to achieve the initial test level.

### UNDERLYING ISSUES

- Missed Opportunities
- Sine burst testing and unforeseen costs

### AFTERMATH

- Revision of NASA Standard 5001A, Section 4.1.2.1, Test Methods to include a warning related to sine burst testing hazards to test articles
- Recommendation that ARC develop and implement a Safety System and Mission Assurance (SS&MA) Technical Authority process that ensures issues pertaining to the Project and Center SS&MA requirements are elevated, reviewed, and resolved at an appropriate level

## Background

### LADEE

Launched September 7, 2013, LADEE supported NASA's Science and Mission Directorate lunar exploration endeavors as part of Marshall Space Flight Center's (MSFC's) Lunar Quest Program. The mission was a cooperative project between the Ames Research Center (ARC) and the Goddard Space Flight Center (GSFC), with ARC tasked with mission management, spacecraft construction, and mission operations and GSFC tasked with payload development and launch vehicle integration. Beyond the scientific value, the mission reestablished ARC's in-house spacecraft development capability. LADEE launched on a Minotaur V rocket from Wallops Flight Facility (WFF).

The Class-D LADEE spacecraft was built with a low-cost, composite frame that was modular and configurable for multiple mission types. The Class-D designation was assigned because of the mission's low priority and high risk considering factors such as criticality to the Agency Strategic Plan, national significance, availability of alternative research opportunities or reflight opportunities, and magnitude of investment.

### Scheduled Testing

Although ARC possessed strength testing facilities, it did not have the capacity to perform sine burst vibration testing—a method of applying a quasi-static load, using a vibration shaker and shock-testing software

Figure 1. The LADEE spacecraft ETU on the vibration sliptable. Source: NASA

to qualify the strength of an item and its design for flight. Sine-burst testing, developed by GSFC, is often used in lieu of acceleration (centrifuge) or static loading tests, due to cost. To complete sine burst testing, project management chose an off-site contractor based on competitive cost, experience, and proximity to ARC.

## What Happened

On Thursday, May 3, 2012, the LADEE spacecraft ETU (Figure 1.) was fully configured for testing and was securely mounted on the vibration shaker sliptable. The entire test system consisted of a shaker (with a 65,000-pound force peak sine force and a 2-inch stroke), amplifier, and sliptable, coupled to a control system. The system was successfully demonstrated weeks prior on April 17, 2012 with a non-representative test article simulator at sine burst levels of 16 Hz and 9.4 g's to envelope the loads being finalized for the LADEE tests.

The procedure called for tests on each of the spacecraft's three axes, a sweep from 5-100 Hertz at 0.1 g's to identify the structural fundamental frequencies, burst test in three increasing increments, culminating at 6.5 g's in the lateral axes and 12.8 g's in the vertical axis, and finally, another sweep to compare post burst integrity.

Instrumentation consisted of 74 channels of strain gauges and 79 channels of accelerometers. The ARC team, using its own data acquisition system, acquired and monitored the strain gauge data. The vibration contractor team monitored the accelerometers using a separate data acquisition system. The structure also had four shipping (trip) accelerometers mounted on interior panels, two with 10 g thresholds and two with 15 g thresholds.

The sweep was performed and a fundamental bending mode of 31 Hz was measured. From this, a 10 Hz sine burst test frequency was selected with an initial target level of 2 g's (approximately one third of the full level 6.5 g test). The test plan called for one-third and two-thirds test levels to be accomplished to check for linearity in the test data before performing the full level tests.

As the 2 g test was being programmed, the NASA Test Director and the vibration contractor Test Engineer discussed the starting level for the system calibration phase of the test. The control system software default start level was -12 dB, which would have resulted in pulses to the test article in 3 dB steps of -12 dB, -9 dB, -6 dB, -3 dB, and 0 dB (or full level). The Test Director wanted to minimize the loading cycles on the structure and asked that the lower level increments be deleted. This resulted in an intended start level at 0 dB, or 2 g's. Unbeknownst to either the Test Director or the Test Engineer, the control system for the shaker requires several low-level, wide-band random pulses to calibrate for a sine burst test. The calibration phase of the test was initiated without the low level pulses, and shortly thereafter, the sliptable with LADEE attached moved violently, emitting a loud bang, and was automatically shut down by the control system. The sliptable did not return to the neutral centered position.

Aware of a serious problem with the test, the team checked for external damage to the LADEE structure. Having found no obvious external damage, and without removing LADEE from the test stand, the team conducted borescope inspections that revealed damage on the composite cruciform panels of the propulsion structure within the spacecraft (Figure 2). In addition, two of the vertically oriented shipping accelerometers on the cruciform panels had tripped.

The incident was officially declared a mishap: management was notified and a LADEE Incident Response Team (IRT) secured the area, gathered and impounded evidence, obtained written witness statements, and entered the case into the NASA Incident Reporting Information System (IRIS). NASA HQ management formed the Investigation Authority, and the NASA mishap investigation began in parallel with the contractor's internal Failure Review Board (FRB).

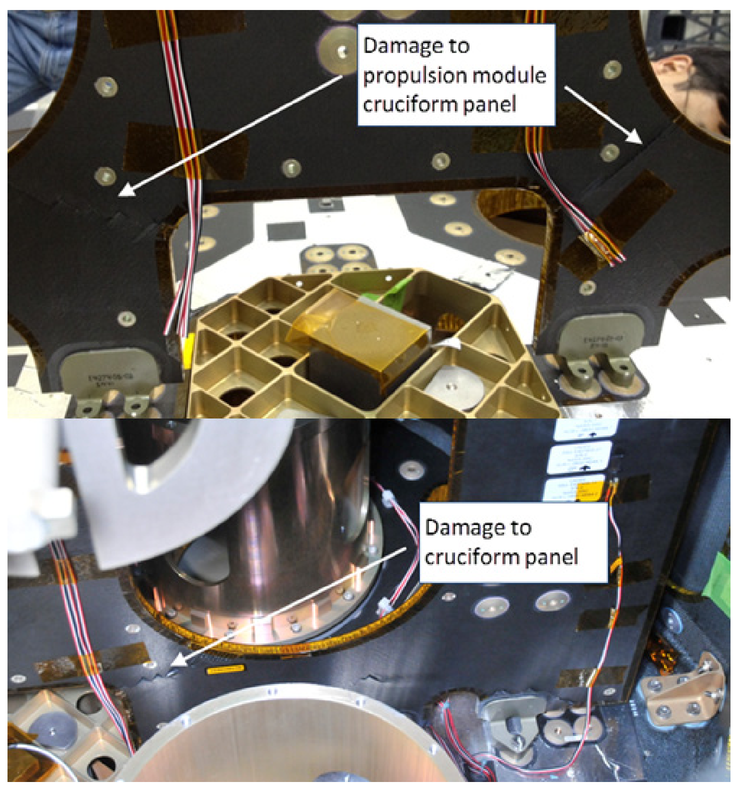


Figure 2. Stress damage on the composite cruciform panels of the LADEE spacecraft's propulsion structure. Source: NASA

The ARC team removed solar array panel mockups while the ETU was still on the vibration table. Damage appeared to be isolated to the X-direction cruciform panel (direction of loading/motion) and the team determined it was safe to remove the LADEE structure and transport it back to ARC for further disassembly and inspection. All fasteners, except for those attaching the cruciform panels to the lower propulsion deck, maintained torque and structural integrity. Although extensive damage occurred to the X-direction propulsion module cruciform panel, no damage was observable to the composite modules, radiator deck, solar panel substrates, or any of the mass simulators.

## Proximate Cause

Test facilities were controlled by the contractor including the design, build, and maintenance of the sliptable facility. NASA did not have the purview to extend this investigation to include the sliptable facility. Without the scope of authority to extend the investigation to include that facility, NASA investigators could not, in its analysis, continue to a root cause.

Although no irregularities were found in the manner the spacecraft was secured, extensive damage was found with the sliptable and the amplifier modules that powered it. Upon inspection, one of the journal bearings that allow the sliptable to move freely was found partially seized, while additional journal bearings were found out of alignment. This explained why the sliptable did not return to a neutral position after the anomaly. Of the 42 amplifier power modules used by the testing apparatus, 10 had blown fuses and 6 had damaged electronics.

The most likely reason for the mishap was that high pre-existing frictional force from the misaligned and partially seized bearings caused the control system for the sliptable to compute (from the initial calibration pulse) an abnormally high voltage to achieve the initial test level. The late decision to override the nominal control system -12dB start pulse value likely exacerbated the problem. Since sine burst tests are short duration and open loop, they have no capacity for correctional feedback from the control accelerometers.

Figure 3. The LADEE spacecraft undergoing laboratory testing. Source: NASA

## Underlying Issues

### Missed Opportunities

Post mishap forensics revealed that the sliptable had indications of damage prior to the mishap. Contractor sine burst testing experience was limited to a few hours embedded in a 10-hour training and test preparation activity with the controller software vendor 2 weeks prior to the mishap. Further interviews revealed that the contractor Test Engineer that had direction over the table operator did not fully understand the operation of the vibration table control system, and the reasons for the different buildup points required for table calibration. A more comprehensive understanding of vibration shaker operation, along with thorough collection and analysis of system performance trend data may have prevented the mishap.

Additionally, the NASA mishap investigation revealed that the LADEE team did not properly execute certain aspects of the LADEE System Safety and Mission Assurance Implementation Plan (SMAIP) and the LADEE Risk Management Plan. Furthermore, personnel responsibilities in the LADEE Sine Burst Test Plan were not established in advance of the test, and were not fully understood and accomplished. Formal contractor surveillance was not accomplished and sine burst testing risks were not being tracked in the NASA risk-tracking database.

The investigators also found that the ARC Internal Audit Program lacked the independence and adequate staffing to thoroughly review the LADEE Project.

### Sine-Burst Hazards and Unforeseen Costs

Beyond the LADEE Project not reviewing the Agency's Lessons Learned Information System (LLIS) for sine burst testing, investigators determined that sine burst methods were not required to complete strength qualification testing of the spacecraft. The Investigating Authority did note the similarity between this mishap and others that have occurred NASA-wide while conducting sine burst testing.

Sine burst test methods, especially those involving sliptables, have an elevated risk of test article damage. Other methods to accomplish strength qualification testing with less risk of damage to the test article were available to NASA. However, these other methods have a cost and schedule tradeoff for this reduced risk. Static loading or acceleration (centrifuge) test methods can accomplish the same test objectives.

Sine burst testing is a short duration test conducted open loop (i.e., a burst of energy into the test article). Because of the short duration of the open-loop load, it is difficult to implement effective hardware protection schemes (abort circuitry). Sine burst testing also requires more rigorous pre-test evaluation than other types of vibration tests to verify the test equipment is in good operating condition and is capable of running the test safely prior to installing the test article. While sine burst testing is used fairly extensively within NASA, it is not as commonplace in the aerospace industry. For this reason, many testing houses

Figure 4. An Orbital Sciences Corporation Minotaur V expendable launch system. Derived from the land-based LGM-118A Peacekeeper ICBM, its maiden flight carried the LADEE spacecraft payload. Source: NASA

do not have experience or the appropriate understanding of the risks and mitigation strategies to control those risks. Instrument and spacecraft engineering development teams typically lack specific knowledge related to vibration test equipment, which can compound the problem.

## Aftermath

The mishap investigators recommended that the Agency revise NASA Standard 5001A, Section 4.1.2.1, Test Methods, page 12 to include the following caution:

"Sine burst testing, while an effective test method for strength verification, carries an elevated risk of unintended test article damage due to the short duration, open loop nature of the energy input. See LLIS entry 0903 High Energy Spectroscopic Imager Test Mishap. (http://www.nasa.gov/offices/oce/llis/0903.html)"

In addition, the mishap investigator recommended that ARC should develop and implement a System Safety and Mission Assurance (SS&MA) Technical Authority process that ensures issues pertaining to the Project and Center SS&MA requirements are elevated, reviewed, and resolved at an appropriate level of SS&MA Authority, citing that "the Center Director (or designee) is responsible for establishing and maintaining Center Technical Authority policies and practices, consistent with Agency policies and standards."

The LADEE mission was executed successfully. After all objectives were completed, LADEE was intentionally set on a collision course on the far side of the Moon.

## Relevance to NASA

Although this mishap occurred at a contractor facility, it could still have been avoided if NASA personnel were better trained and educated in the intricacies of sine-burst testing and general test discipline. The High Energy Solar Spectroscopic Imager (HESSI) mishap—and now LADEE mishap—had fairly high visibility, but there have also been a number of lower visibility subsystem level sine burst test mishaps at GSFC and perhaps elsewhere that have gone unreported. Despite the various knowledge-transfer means used at NASA and across the aerospace industry, the awareness level of this testing risk needs to improve. It is the intent of this case study to help meet that objective.

Historically, numerous NASA projects have used dynamic tests to ensure that payloads and launch systems function reliably despite extremes in temperature, pressure, vibration, shock, radiation, and other stressors. Examples of test failures that improved vehicle reliability and odds of mission success include the Spirit and Opportunity landing tests; test failures on simulated Martian terrain showed how to protect both landers when they bounced onto Mars itself. Such effort represents "needful risk," when lessons pay off with the engineering of tough, capable vehicles. In the LADEE sine burst test, demonstrations of risk imposed by one choice of test type among options and risk imposed by unlearned yet available lessons from the past are palpable. Going forward, improved capture of and access to test failure analyses at the right time in their lifecycles can pay dividends beyond those gained through project failure analysis.

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