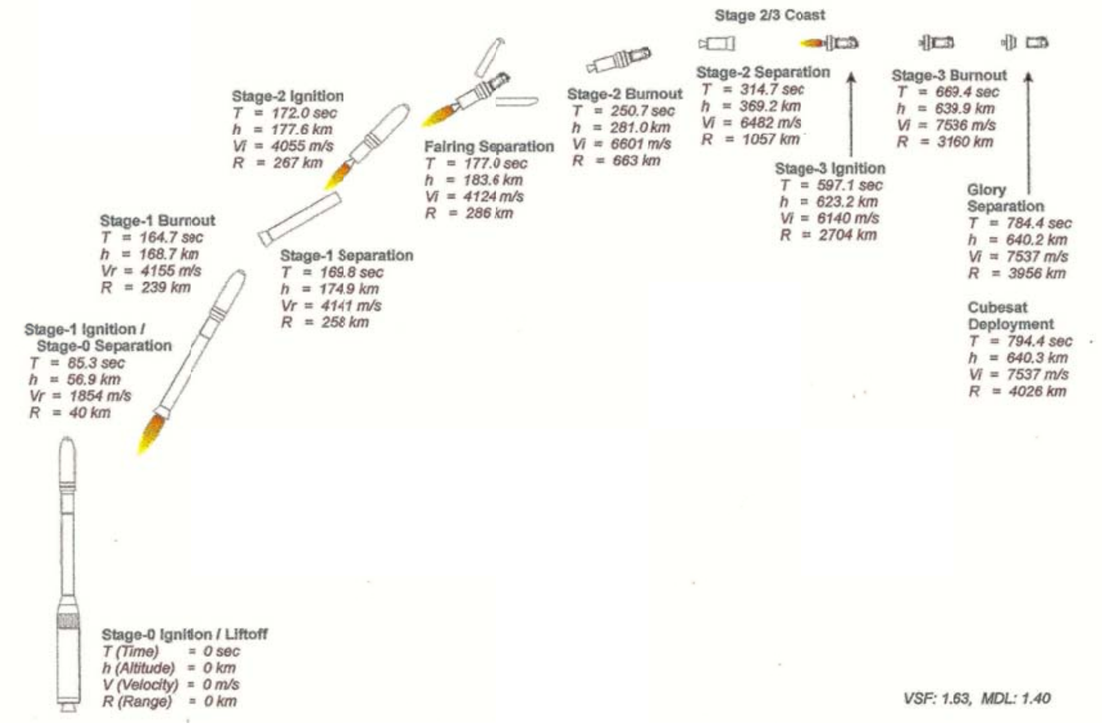
Overview of the Glory Mishap Investigation Results for Public Release

SUMMARY

The Glory spacecraft was a NASA satellite mission launched March 4, 2011, as the primary payload aboard an Orbital Science Corporation (Orbital) Taurus XL T9 launch vehicle from Space Launch Complex 576-E at Vandenberg Air Force Base (VAFB) in California. Liftoff was at 2:09:44.418 a.m. PST.



The Projected T9 Glory Nominal Trajectory

The mission proceeded nominally through Stage 2 ignition. Payload fairing separation was scheduled for 176.98 seconds after Stage 0 ignition. Fairings are a standard component of expendable launch vehicles, and they are always jettisoned as soon as possible after a launch vehicle has achieved an altitude where aeroheating is no longer a risk to the satellite but the fairing failed to separate as planned. The additional mass of the fairing caused the trajectory to deviate from nominal and the vehicle failed to reach orbital velocity. Telemetry data indicated subsequent Stage 2 burn and separation, Stage 3 ignition and burn, and spacecraft separation all occurred as sequenced, except that the payload fairing remained partially attached. The vehicle reentered the atmosphere and likely broke up or burned up, or both, because of reentry loads and aerodynamic heating.

The contingency was declared at 2:15:19.160 a.m. PST. No collateral damage or injury was reported as a result of this mishap. No physical launch vehicle or spacecraft debris was available for examination. The cost of the mission was approximately $388 million.

A NASA-led Taurus XL T9 Mission Glory Mishap Investigation Board (MIB) was formed by Mr. William Gerstenmaier, Associate Administrator for NASA's Space Operations Mission Directorate, March 8, 2011. The MIB was chaired by Mr. Bradley Flick, Director for Research and Engineering at NASA's Dryden Flight Research Center.

The Taurus XL Mission T9 MIB was commissioned to:

- Obtain and analyze whatever evidence, facts, and opinions it considers relevant.
- Conduct tests and any other activity it deems appropriate.
- Interview witnesses and receive statements from witnesses.
- Impound property, equipment, and records as considered necessary.
- Determine the proximate cause(s), root cause(s), and contributing factors related to the mishap.
- Develop recommendations to prevent similar mishaps.
- Provide a final written report.

No physical evidence from the T9 mishap was available for examination. The T9 MIB tested hardware, performed engineering simulations, analyzed simulation data, and reviewed telemetry data (including telemetry obtained after the T8 mishap). The MIB also obtained technical knowledge on the Taurus XL launch vehicle using information and evidence gathered from interviews, technical interchange meetings, and document and data reviews with the NASA Launch Services Program; NASA's Glory Project; Orbital’s Dulles, Virginia, and Chandler, Arizona Divisions; and Ensign-Bickford Aerospace and Defense Company, the manufacturer of the fairing frangible joint assembly. It was from these sources that the T9 MIB then developed the fault, event, and causal factor trees.

Using this data, the MIB was able to analyze and determine that the proximate cause of the mishap was the failure of the payload fairing system to separate. Detailed analysis determined one of the side rails of the payload fairing system failed to fully fracture near the fairing’s nose cap. However, no root cause for the fairing’s failure to separate was able to be determined. The board also analyzed telemetry comparing the T8 telemetry data with T9 telemetry data and concluded that the post-fairing separation failure configurations of both vehicles were similar.

NASA has completed the Agency’s assessment of the Glory T9 MIB report. NASA is not making the report public because it contains information the company considers to be proprietary and information restricted by International Traffic in Arms Regulations. Instead, NASA is providing this overview of the mishap and the investigating board's findings and recommendations regarding the Glory mishap.

BACKGROUND

Mission Overview

The Glory mission, with a three-year operational prime lifetime, was intended to accomplish two scientific objectives: collect data on the properties of natural and human-caused aerosols in Earth's atmosphere as agents of climate change, and measure the total solar energy entering Earth's atmosphere to determine its long-term effects on Earth's climate record.

Determining Earth's energy balance and climatic effects requires measuring black carbon soot and other aerosols as well as the total solar irradiance. Glory was a scientific research satellite designed for launch into low Earth orbit as part of the Afternoon Constellation, also known as the A-Train. The A-Train is a series of Earth-observing satellites flying in close formation in a 438-mile altitude, Sun-synchronous, circular orbit inclined at 98.2 degrees. Glory’s data would have enhanced existing Earth science analysis through correlation with data from instruments located on other satellites orbiting in the A-Train. Its prime mission operations period was designed for three years.

The Glory project was managed by NASA's Goddard Space Flight Center for the Agency’s Science Mission Directorate. The spacecraft was built by Orbital Sciences Corporation in Dulles, VA.

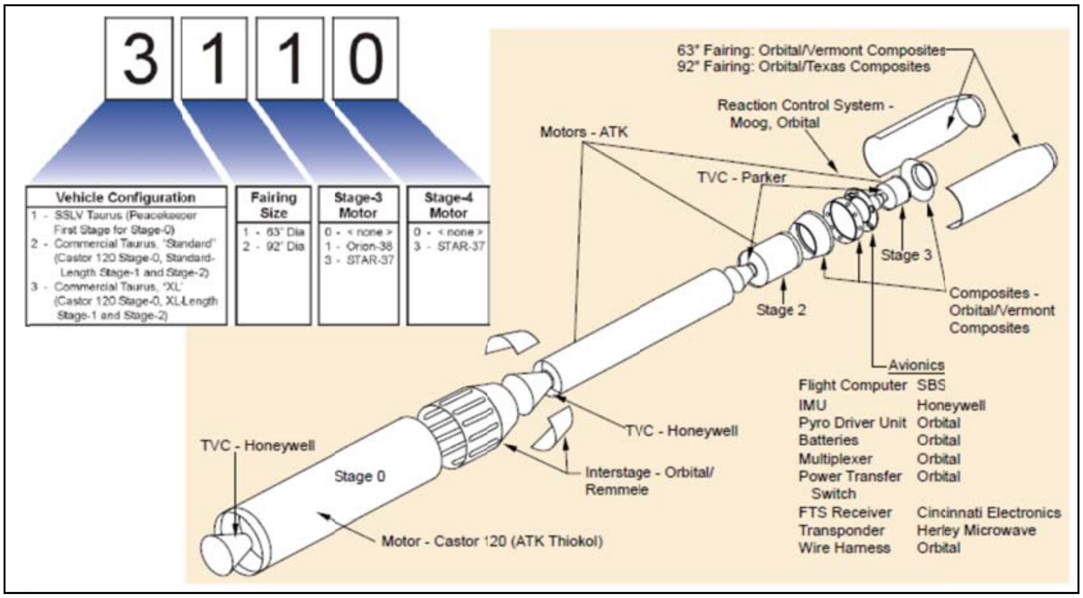
Artist’s Conception of the Glory Spacecraft In Orbit

Selection of Launch Vehicle

The Glory launch service was procured under the small expendable launch vehicle services contract in October 2003.

Taurus Launch Vehicle System Description

The Glory mission used the Taurus XL 3110 configuration which uses motors adapted from Orbital's Pegasus Program. The rocket's first stage is composed of a Castor 120 booster and an Orion 50SXL-G for Stage 1. The second stage uses an Orion 50XL and the third stage uses an Orion 38. The payload fairing for the Glory mission was 63 inches in diameter.



Taurus XL Launch Vehicle

Taurus 63-Inch Fairing System Description

The Glory mission was lost when the Taurus payload fairing, the clamshell-style cover that encloses and protects a payload on the pad and during early flight, failed to separate during ascent. One half of the fairing clamshell consists of the nose cap, pyrotechnic separation systems, and the environmental control system ducting for payload ground processing. The other half of the clamshell contains the majority of the telemetry sensors. The fairing provides environmental control during ground processing, integration operations, and ascent. The two fairing halves are joined lengthwise during the payload encapsulation process using frangible joints called side rails. There is an additional frangible joint around the circumference of the base of the fairing, known as the "base ring," to attach the fairing to the third stage assembly. The frangible joints consist of pyrotechnically activated mild detonating fuse (MDF) contained in a stainless steel expanding tube, with a silicon rubber charge holder to transfer the detonation wave energy to the expanding tube.

The 63-inch payload fairing system was used on both Orbiting Carbon Observatory (OCO) and Glory missions. The Glory Taurus XL T9 mission was the first Taurus launch following the failed OCO Taurus XL T8 launch. Like the Glory T9 mission, the OCO T8 mission failed to deliver its payload to orbit because of the failure of the payload fairing to separate. The OCO T8 mishap investigation could not identify a root cause but did identify four potential intermediate causes:

1. Failure of the base ring frangible joint to completely fracture.

2. Failure of the electrical subsystem preventing ordnance from firing.

3. Failure of the fairing's hot gas generator pneumatic system to pressurize resulting in a failure to push the fairing halves and/or side rails apart.

4. Snagging of the flexible confined detonating cord (FCDC) on one of the payload fairing side rail's nut plate.

A Taurus XL Return-To-Flight activity took corrective actions against these potential causes for the T9 Taurus XL flight, including replacement of the hot gas generator pneumatic system with a cold gas system (with added pressure sensor telemetry to verify thruster activation), and installation of room temperature vulcanizing silicone to eliminate the potential for FCDC snagging.

During a normal flight separation, a pneumatic system would pressurize the fairing deployment thrusters. The fairing's frangible joints (both side rails and the base ring) would be broken using MDF, and the thrusters then would push the fairing halves outward on external hinges and separate the fairing halves from the stage. Sensors mounted in the fairing would provide telemetry on temperature, pressure, and acoustic environments. The fairing base ring has separation break wires on each half and is monitored in telemetry.

MISHAP CAUSES AND RECOMMENDATIONS

Using information and evidence gathered from interviews, technical interchange meetings, documents, data reviews, and testing, the T9 MIB developed a timeline of events, performed a detailed Fault Tree Analysis, and a Root Cause Analysis. From these analyses, the T9 MIB identified the proximate cause and possible intermediate causes for the failure. As a matter of explanation, a proximate cause, also known as the direct cause, is the event or condition that directly resulted in the occurrence of an undesired outcome. In this case, the proximate cause was that the fairing did not separate from the launch vehicle. An intermediate cause is an event or condition that created the proximate cause and that if eliminated or modified would have prevented the proximate cause from occurring.

Proximate Cause: Fairing separation failed

Flight telemetry data strongly suggested that the payload fairing did not separate as planned. The T9 MIB hesitated to declare this as the sole and obvious proximate cause and, instead, elected to conduct a comprehensive investigation of potential causes. Comparison of modeled structural behavior based on analysis and ground test to flight data provided through telemetry showed the only reasonable scenario was that the fairing system failed to separate. The detailed analysis pointed to a failure to fracture near the forward end of one of the fairing side rails, which prevented full separation. The extra pressure sensor added to the installation of the cold gas pressurization system, in place of the hot gas generator system as part of the response to the T8 MIB report, provided valuable data to the T9 MIB. This sensor data verified the cold gas pressurization system performance was satisfactory and that the T9 payload fairing's base ring indeed had separated. As a result, the T9 MIB could eliminate the cold gas pressurization system and the base ring as a cause and focus on the scenario in which the forward end of the payload fairing side rail failed to fracture.

Intermediate Causes

The T9 MIB examined all potential intermediate causes closely and concluded that the most likely intermediate causes were the two items listed below from the Event and Causal Factors Tree that were categorized as "possible:"

- ***Side rail charge holder slumped or compressed***
  Design analysis and ground testing of frangible joint components during the course of the investigation led the T9 MIB to conclude that the rubber charge holder, an internal component of the frangible joint, could have slumped due to the effects of launch acceleration and random vibration, resulting in incomplete fracture of the fairing side rails.

- ***Side rail system failed to operate correctly outside its evaluated environments***
  The second possible intermediate cause was an expansion of the first. Because the charge holder slumping scenario was identified early in the investigation process, considerable focus was placed on that component. It became clear to the T9 MIB that the lack of testing and analysis throughout the life cycle of the frangible joint applied not only to the charge holder, but to the other components comprising the frangible joint system. Consequently, while the first possible intermediate cause considers the charge holder alone, the second possible intermediate cause considers the rest of the joint system and the interaction between system components. There may be additional undiscovered failure modes due to untested environments within the joint system. Analysis and testing must be applied to the frangible joint system and not solely to the charge holder.

Root Cause Analysis

While the T9 MIB was able to identify the proximate cause and two possible intermediate causes for the T9 mishap, they were unable to identify the root cause for this failure. As a matter of explanation, an intermediate cause is between the proximate cause and the root cause in the causal chain. The root cause is the factor or set of factors that contributes to, or creates the proximate cause. Typically multiple root causes contribute to an undesired outcome.

The T9 MIB was unable to determine a root cause for the mishap mainly due to limited flight telemetry and the inability to recover the payload fairing hardware for analysis that would have enabled the determination of a definitive intermediate cause or causes. While the T9 MIB was unable to identify a root cause, they made several technical observations and findings which are summarized below:

- The T9 MIB determined that side rail charge holder slumping (compression) could possibly occur because of the following:

    1. The Side Rail assembly's susceptibility to (and the effects of) charge holder slump was not previously identified.

    2. The temporal distribution of acceleration, vibration, shock environments had changed over time.

    3. Orbital's fairing joint buildup process variability could affect charge holder slumping susceptibility.

- In addition, the T9 MIB noted a large percentage of potential causes rated as "possible, but highly unlikely" involved frangible joint components and also observed that Orbital's manufacturing processes were not as tightly controlled as those applied by NASA in other pyrotechnic hardware designs. The possibility exists that manufacturing process controls could allow variation in material properties and hardware dimensions that may impact system performance.

- The T9 MIB did not find evidence that a detailed failure analysis of the frangible joint design used on the Taurus was performed at any point in its life cycle. Details of the design had evolved since the genesis of the base ring application for the Pegasus launch vehicle, and the effects of those evolutionary design changes, including the potential for charge holder slump, were not discovered.

- The T9 MIB also discovered that the qualification activity for the frangible joint system was generally performed at the subscale level, using industry practices for the qualification of pyrotechnic devices. The effects of all flight environments, either individual or combined, were not always considered. As with the system design, the flight environments also have evolved over time, and the effects of these changes on system performance margins should be understood.

As a result of the analyses performed, the T9 MIB made the following technical recommendations:

1. Orbital should establish frangible joint system manufacturing process controls sufficient to assure that variability in materials properties and hardware component dimensions, within both maximum and minimum tolerances, will not invalidate design performance requirements.

2. An extensive failure analysis (for example, detailed fault tree or failure mode analysis) of the Taurus frangible joint design should be performed.

3. Design and implement a qualification and test activity for the Taurus frangible joint system based on the results of an extensive failure analysis (for example, detailed fault tree or failure mode analysis) and with consideration for the environments in which the joint is operated.

   > "*The MIB believes that if this recommendation were implemented, it could address all the possible frangible failure scenarios identified in the investigation*."

During the course of the mishap investigation, additional observations and recommendations related to Agency policy, special assessment procedures, and improved communications were noted by the T9 MIB. Although these items were not deemed causal to the launch failure by the T9 MIB, the MIB determined that they could be beneficial for future programs.