National Aeronautics and Space Administration

SYSTEM FAILURE CASE STUDIES

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The Tour Not Taken

The Comet Nucleus Tour (CONTOUR) mission is a story of lost opportunities and incomplete communication. The spacecraft was developed to gain insight into the nature of comets. While in orbit, CONTOUR fired its motor to put itself on the trajectory toward its first comet. During this time, the team did not schedule telemetry coverage, but they expected to regain contact once the burn was over. After many attempts to reestablish communication with CONTOUR, the project team officially declared the spacecraft lost.

BACKGROUND

The Discovery Program

CONTOUR is the only mission in NASA's Discovery Program that has not returned any science data. The Discovery Program is a series of low-cost, highly focused missions orchestrated by NASA's Solar System Exploration Division (SSED). The program seeks to use new technology to expand scientific knowledge; the model depends on developing relationships with industry and universities to operate within a low-budget, short timeline framework. Discovery Program mission teams include representatives from NASA, small businesses, government laboratories, and industry. A principle investigator (PI) directs the scientific objectives and instrument payload for the mission, then manages the mission to ensure the team stays on schedule and meets performance objectives.

Under the auspices of the Discovery Program, Cornell and John's Hopkins's Applied Physics Laboratory (APL) collaborated to build and run CONTOUR. The PI at Cornell developed the scientific objectives, while APL constructed and managed the spacecraft itself. NASA's role in the project was minimal; the PI reported directly to NASA's Associate Administrator for the Office of Space Science and to the Discovery Program Manager. APL was responsible for certifying CONTOUR mission readiness through the Discovery Program Office.

CONTOUR's Objectives

CONTOUR was a small spacecraft designed to help scientists understand the composition of comets. The mission plan called for CONTOUR to take high-resolution pictures

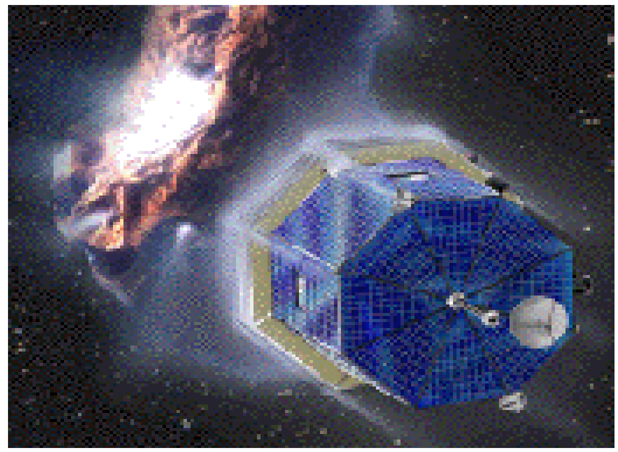

Figure 1: Artist's conception of the CONTOUR spacecraft

of the largest and most active comets in the Jupiter family: Encke, Schwassmann-Wachmann-3 (SW3) and possibly d'Arrest. CONTOUR would also do a compositional analysis of the comets it visited and determine their precise orbits. Scientists hoped the mission would be particularly informative because SW3 had split into pieces in 1995 and researchers expected to have access to exposed subsurface materials.

CONTOUR's signal disappeared during a solid rocket motor (SRM) burn on August 15, 2002. Mission control never regained contact with the spacecraft.

Probable Proximate Cause:

- The SRM was nested too far into the body, and heat from the motor's exhaust destroyed the spacecraft

Underlying Issues:

- Inadequate project team SRM expertise
- Insufficient rigor in contracting and design reviews
- Significant reliance on subcontractors who were not integrated into the project
- Reliance on heritage designs
- Focus on project goals at the expense of programmatic objectives

Spacecraft Design

CONTOUR carried various instruments to track and analyze comets, including two dual imagers, a mapping spectrometer, and a dust analyzer. Solar cells on the surface of its octagonal shell powered the scientific instruments, and a hydrazine propulsion system controlled spacecraft orientation. A STAR 30 BP solid rocket motor (SRM) that accounted for more than half the spacecraft's weight was included to boost the craft from its elliptical earth orbit into an interplanetary trajectory. CONTOUR used four antennas to communicate with the ground using a two-way non-coherent Doppler technique.

WHAT HAPPENED?

The Kennedy Space Center launched CONTOUR on July 3, 2002 from a Delta II launch vehicle. Over the next 43 days, the mission operated nominally. At 4:49 am EDT, on August 15, 2002, 44 days after launch, the mission control team initiated the SRM burn to steer CONTOUR out of earth orbit and onto the trajectory toward the comet Encke. Ground control could not communicate with the spacecraft during the burn, but they expected to regain contact 46 minutes later, at 5:35 am; they never received a signal. The team worried that something had happened to the spacecraft but hoped it was just an antenna malfunction. They waited for the spacecraft to initiate alternative communication methods, which it was programmed to do if it did not receive ground commands for a period of 96 hours. The system would cycle through the spacecraft's antennas, trying to reestablish contact with earth. Ground control waited a week for the signal to reappear, but on August 22nd CONTOUR was still silent.

Outside data supported the team's growing belief that the spacecraft was lost. Two or three seconds before the scheduled end of the SRM burn, the U.S. Air Force observed a flare in the same location as the spacecraft. Shortly afterward, a space watch laboratory at the University of Arizona noticed and recorded three objects on the same trajectory CONTOUR would have entered, had the SRM burn been three seconds too short.

Despite these discouraging signs, ground control attempted to communicate with CONTOUR once each week until early December, 2002 when it expected the spacecraft to be in a favorable viewing geometry. When the spacecraft did not respond, the team officially ended attempts to recover CONTOUR.

PROXIMATE CAUSE

CONTOUR's break-up remains a mystery because the team had no telemetry data from the SRM burn. However, later thermal analysis suggests some components experienced temperatures high enough to melt aluminum. The most likely explanation is that the exhaust from the SRM burn overheated the spacecraft because the motor was nested too far into the spacecraft body. If this is what happened, the material around the motor probably weakened in the excess heat. Investigators found that, in hindsight, the design's assumptions about SRM plume heating effects did not incorporate adequate error margins.

UNDERLYING ISSUES AND CONCERNS

Project Element Integration

CONTOUR's development team at APL was largely unfamiliar with solid rocket motors. One APL employee had experience working with SRMs, but he was assigned to another project and did not work on CONTOUR. To make up for their inexperience, APL relied on recommendations from the SRM manufacturer, Alliant Techsystems Tactical Systems (ATK), in determining whether the SRM was flight-worthy and acceptable for CONTOUR. The STAR model's successful history of only 2 failures in 86 missions lent credence to APL's decision to apply earlier, successful designs. However, some of ATK's modeling used a generic model rather than models that matched CONTOUR's specifications. Since ATK generally worked with clients who were familiar with SRMs, they were accustomed to clients who would already know how to integrate the generic motor into their design. If APL had formally stated ATK's integral role in providing SRM expertise, ATK might have become more involved in the specifics of the SRM design and provided advice on how to integrate the SRM with the rest of the spacecraft.

Figure 2: The Solid Rocket Motor (SRM)

To further compensate for APL's lack of in-house SRM expertise, APL relied on a consultant's dynamic analysis for the SRM firing. The consultant operated under several misconceptions that the project team did not scrutinize. For example, the consultant assumed the spinning spacecraft was a stable system, without accounting for fuel slosh effects. The consultant also presumed mass would decrease at a fixed rate, not realizing that spacecraft inertia dropped rapidly near the end of the burn and that the center of mass moved away from and then back towards the SRM nozzle. Later modeling that took these effects into consideration showed that the spacecraft operated under acceptable margins, but the consultant still should have been working with validated approximations rather than assumptions; the project team had much of the data the consultant needed. Separation between the contractors and subcontractors meant that information and expertise in one group was not shared with other groups on the project team.

Given APL's lack of expertise in SRM applications, they should have more fully integrated their subcontractors into the project team and provided them with the design specifics necessary to complete thorough analyses. APL should also have established clear communication channels and specifications with its subcontractors. The lack of integration and communication suggests that APL was not sufficiently involved with its subcontractors to ensure they had the information they needed to perform their tasks.

Systems Management and Reviews

Part of the reason the team did not recognize weaknesses in CONTOUR's design was because, rather than following NASA's typical approach of meticulous requirements definition upfront, APL relied on a robust test program to refine design specifications. APL's routine included thorough tests followed by design modifications and further tests to finalize the design. Unfortunately, testing the spacecraft with the SRM assembled was impractical, and the APL team was not able to complete testing with their typical rigor. Neither NASA nor APL recognized the weaknesses in APL's design-test-design strategy for CONTOUR's specific configuration.

The CONTOUR Mishap Investigation Board expressed concern that NASA and APL's major milestone reviews were not detailed enough to understand the risk associated with APL's "non-typical" implementation strategy. The Discovery Program kept NASA out of the day-to-day details of the project and relied on high level independent review teams of space system experts to identify potential risks in a design or project plan. However, these reviews did not provide the same depth of information and insight that might

Figure 3: Assembling CONTOUR

have been uncovered by an independent technical peer review that dug into project's details or simply the presence of a NASA Project Manager involved in the daily routine of designing a spacecraft might have uncovered.

Programmatic Perspective

Investigators identified other concerns with the CONTOUR project that did not directly cause mission failure but were important for future missions. In particular, the Board pointed to the lack of telemetry data during the SRM burn in which CONTOUR disappeared. In programs that involve multiple missions, telemetry data during mission-critical events is crucial because it allows for causal analysis in the event of a failure. Referencing a similar decision related to the Mars Polar Lander, the CONTOUR Investigation Board wrote, "The decision not to have critical event telemetry was a defensible project decision, but an indefensible programmatic one." The CONTOUR team was focused on accomplishing their mission, not the larger goals of the Discovery Program, so they were willing to forego telemetry data when orbital geometry and spacecraft attitude made spacecraft communication impossible during the burn. NASA could have pointed the CONTOUR team to other resources such as U.S. Air Force facilities, but because CONTOUR was not required to monitor mission-critical events, these options were not seriously considered.

AFTERMATH

Of the seven Discovery Program projects completed to date, CONTOUR is the only failed mission.[1] Although no further missions have been scheduled to study comets Encke and Schwassmann-Wachmann-3, two other Discovery Program missions, Deep Impact and Stardust, have collected data about comet structure and composition. In 2004, Stardust flew within 149 miles of Comet Wild 2 and collected dust samples of the comet's tail while taking pictures of its surface. Deep Impact, launched in 2005, gathered data from Comet Tempel 1 that included the first definitive evidence of water and ice on a comet's surface. NASA has planned follow-on missions for both spacecraft that will further advance our understanding of comets.

As a result of the Mishap Investigation Board's recommendations, Science Mission Centers now routinely perform inheritance reviews early in the project life-cycle. NPR 8705.4 now recommends that all risk class A,B,C, and D missions have telemetry coverage during critical events.

NASA's Discovery Program office increased its personnel and resources, so that they can have better insight into discovery class projects that are not managed by NASA.

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[1] Genesis, another Discovery mission, experienced a partial-failure when its parachute did not deploy, but the spacecraft operated successfully and NASA recovered valuable data from the damaged return capsule.

APL made significant changes to their internal practices and went on to successfully complete later missions.

For Future NASA Missions

Although CONTOUR was largely a hands-off project for NASA, APL's struggle to successfully integrate work from several subcontractors is reminiscent of many NASA projects. CONTOUR's failure highlights a few key best practices that are applicable to any project involving multiple team members:

- Verify that contractors, manufacturers and consultants use models that are valid for the specific application; use independent validation to confirm conclusions. Identify the degree of uncertainty and its type (e.g., uncertainty related to the model).

- If you must rely on subcontractors for expertise, confirm that you have identified and communicated all essential information to the subcontractor; don't allow consultants to work from inaccurate assumptions.

- Make sure that design trades are properly vetted through all organizations responsible for impacted components and subsystems.

CONTOUR illustrates the value of integrating with contractors and other organizations on a project team. If NASA had played a more active role in the CONTOUR project, the team might have had access to the SRM expertise it needed or alternative telemetry data options. Being directly involved also helps ensure NASA requirements and standards flow down to contractors and subcontractors, so that engineering strategies like the design-test-redesign model are modified for a space design environment.

Finally, the lack of telemetry data during CONTOUR's SRM burn demonstrates the need to identify programmatic risks. NASA's work always builds on previous work and experience, and recognizing that today's missions will influence future missions shapes project design. Cost-benefit values shift when a project's scope is broad enough to include larger program objectives. Thanks in part to the CONTOUR Mishap Investigation Board, NPR 8705.4 recommends that NASA require that all projects identify mission-critical events and provide telemetry data for these events. Waivers should only be issued if telemetry tracking is truly impossible, as this information is critical for understanding a failed mission.

Questions for Discussion

- How well do the different groups working on your projects communicate?
- What areas would benefit from bringing in outside expertise?
- When you have to rely on other organizations for elements of your projects, how do you ensure that work meets NASA's standards and requirements for development?
- How are programmatic risks communicated to your Project? Are cost/schedule/technical risks integrated?

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