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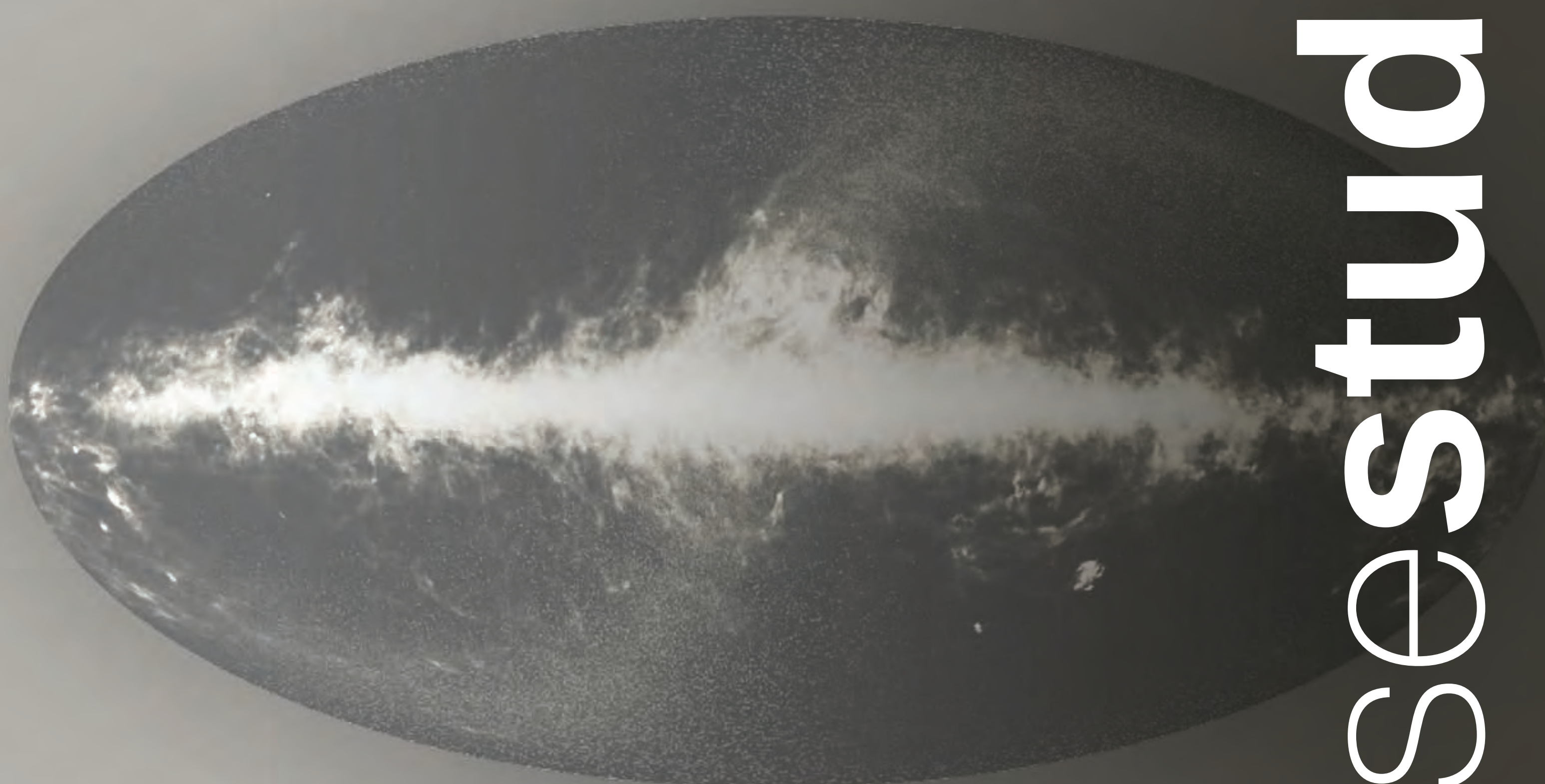
Redesigning the Cosmic Background Explorer (COBE)



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REDESIGNING COBE

In the Beginning…

How did the universe begin? Humans have asked the question for millennia. In the modern age, scientists have focused on determining the physical origins of the universe. The designers of the Cosmic Background Explorer (COBE) satellite proposed to provide hard evidence to support some longstanding hypotheses about the nature of the early universe. COBE's instruments were built to measure two types of radiation—diffuse infrared and microwave radiation—that many physicists, including COBE Project Scientist John Mather, believed to be artifacts of the Big Bang, the moment when the universe burst into existence.[1]

The proposal that NASA approved called for COBE to carry three instruments: a Diffuse Infrared Background Experiment (DIRBE) to search for cosmic infrared background radiation, a Differential Microwave Radiometer (DMR) to search for fluctuations in the brightness of the cosmic microwave background (CMB) radiation, and a Far Infrared Absolute Spectrophotometer (FIRAS) to compare the spectrum of the cosmic microwave background radiation with a precise blackbody. (A blackbody is an object that absorbs all electromagnetic radiation that reaches it; none passes through it and none is reflected.) Designing these instruments and a spacecraft that could provide the proper operating conditions to gather reliable measurements would prove extremely complex.

NASA established COBE at Goddard Space Flight Center as an "in-house" project, meaning that the engineering work was done by civil servants rather than contractors. "We did not feel there was any way to write a contract to do what these instruments had to do," said Mather. The opportunity to work on important science in a hands-on environment made COBE an attractive project for new NASA employees. "We were a training program; we helped to recruit bright young people."

A Shuttle Launch

As initially proposed in the mid-1970s, COBE was to be launched into space by a Delta rocket, an expendable launch vehicle (meaning it could only be used once). Before the spacecraft was designed, however, NASA adopted the Space Shuttle as its standard launch vehicle. Shuttle supporters pinned great hopes on the Shuttle serving as a largely reusable vehicle that would fly monthly, leading to cost savings for the agency over time. Its payload bay could accommodate large satellites and up to 20 tons of mass.

Senior management at NASA moved the agency's science missions, including COBE, on to the Shuttle schedule. It was not a perfect launch vehicle for all missions—it could not,

[1] In addition to personal interviews conducted in 2006 and 2007, this case study makes extensive use of John Mather's first-person account of the COBE project. See John C. Mather and John Boslough, *The Very First Light* (London: Penguin Books, 1998).

for instance, insert COBE directly into the orbit that its experiments required—but it also offered capabilities that a Delta or Atlas rocket did not.[2]

COBE was slated to launch on the Shuttle in 1989 from Vandenberg Air Force Base. The Shuttle would place the satellite at an altitude of 300 kilometers, and an on-board propulsion system would then raise it to a circular 900 kilometer sun-synchronous orbit.

Fighting the Matrix

By the time Deputy Project Manager Dennis McCarthy joined Project Manager Roger Mattson's team in 1983, the scheduled launch was a full six years away. There was little question in McCarthy's mind that the science team would need that much time, if not longer. The instruments were all based on new technology, there was no guarantee that they would perform as expected, and they were already behind schedule.

While COBE was an in-house project that could hypothetically draw on Goddard's significant resources, it was treated as a low priority by branch managers in the center's various engineering divisions, who would pull their most talented people from COBE whenever a need arose elsewhere. This "matrix management" system, which gave authority to the branch managers, gave the project the sense that it never really controlled its personnel. As Mather put it, "If you're fighting the matrix, there's no way to win."

As a result, McCarthy found that his team members kept disappearing at a moment's notice. "They (Goddard senior managers) would use it as a pool of resources – they would take people off COBE and use them on the latest crisis," McCarthy said. "So we couldn't manage the budget or the schedule very well."

Grounded

In spite of the unwelcome demands on his resources, the team that Mattson and McCarthy managed made significant progress. By the beginning of 1986, the COBE spacecraft was all but complete and proceeding smoothly toward its planned launch on the Shuttle. The instruments were not ready—they would be the last piece of the puzzle—but the other elements had fallen into place as expected. The project team had built a wooden mockup of the Shuttle and completed most of the electrical harness and electronics that would power and monitor the spacecraft and its instruments.

The loss of the Space Shuttle *Challenger* 73 seconds after liftoff on January 28, 1986 changed everything. *Challenger* was a tragedy for the nation as well as for NASA. For the agency, the implications were vast. Above all, the loss of the seven-person crew was unspeakably painful. The accident led to the immediate grounding of the Shuttle fleet

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[2] As Mather noted in *The Very First Light*, the move to the Shuttle enabled the COBE team to employ a more advanced technology for Differential Microwave Radiometer (DMR) than would have been possible if the instrument had been designed initially for a Delta rocket. See *The Very First Light*, p. 173.

and the establishment of an independent commission to study the accident and make recommendations. The Shuttle program's future was far from certain. This had dramatic consequences across NASA, and not just for its human space flight program. The Shuttle was NASA's primary means of delivering payloads to space—the agency had stopped relying on expendable launch vehicles such as Delta or Atlas rockets—and as a result the supply of alternatives had dwindled.

The morning after the accident, the COBE team was forced back to the drawing board. "We were abandoned," said McCarthy. "This was the worst possible thing that could happen."

McCarthy called a meeting of everyone involved with the project. "I pulled everybody together, and we decided to keep going. My job was to get this into space, whatever the way."

A Drawing on a Napkin

The team spent the spring looking at every possible launch vehicle in the world. On the wall of the project management office, Mattson and McCarthy posted a comprehensive matrix of all the possible launch vehicles in the world that might be suitable for COBE. "We found that an Ariane or Proton could've launched COBE as it was currently designed – about 14 feet across, and 12,000 pounds. We could launch from French Guyana and put it in the exact same orbit as the Shuttle would from California," said McCarthy.

He went on an unauthorized trip to meet with the Ariane team in Washington. The Ariane offered a solution that would not require a change in the spacecraft design, but it was far from ideal. The politics of using a French launch vehicle for one of NASA's top science missions were prohibitive. Within weeks of mentioning the Ariane to colleagues, McCarthy received a phone call from an official at NASA Headquarters instructing him to drop the idea.[3]

After months of careful analysis and consideration, inspiration struck. While driving home one night, McCarthy found himself asking if COBE could be folded up to fit on a Delta rocket. After all, he thought, the project had been proposed on a Delta. He sketched the folded spacecraft on a napkin, and realized that his idea was a possibility. "I knew physically we could do it."

In the meantime, the team kept looking at all options. In early summer, McCarthy had a meeting with Goddard Center Director Noel Hinners. "Dennis, could this fit on a Delta?" Hinners asked.

"As a matter of fact, it can," McCarthy said.

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[3] For a more complete account of this controversy, see *The Very First Light*, p. 204.

While Mattson was on vacation in August, McCarthy faced the same question at NASA Headquarters from Sam Keller, Deputy Associate Administrator in the Office of Space Science and Applications. It was no secret to McCarthy that NASA's leadership was eager to see a successful, high-profile science mission fill the void that the agency faced since *Challenge*r had grounded the science program. Keller asked McCarthy if he could deliver a COBE spacecraft that would fit on a Delta launch vehicle in 24 months. McCarthy asked for 36 months. They settled on 29 months. A launch date was later set for February 1989. There was no time to waste.

Skunkworks

McCarthy returned to Goddard to discuss this effort with Noel Hinners. He and Mattson would need control of their project team and access to every resource Goddard could offer. Hinners gave him the green light to do what he needed to do. "The only way we were going to be able to do it fast was if we had control over the employees. That's the golden rule," McCarthy said. "The line organizations did not like this at all."

McCarthy and Mattson set up a "skunkworks," an organizational concept based on the legendary success of the Lockheed team that built the XP-80 fighter in record time during World War II. Project engineers and scientists would work elbow to elbow in a bullpen without cubicles until the job got done.[4] The project management office became the "war room." McCarthy taped a master project schedule to the wall with names of the individuals responsible for all the elements of the schedule. "I'd say psychologically that made a big difference," McCarthy said.

They needed top talent, and with Hinners's blessing, they brought in three of the best mechanical, electrical, and Delta launch vehicle engineers at Goddard. "There were a lot of young engineers on this program, because they had to work a lot of hours," McCarthy said, "But the key was to have these three senior engineers reviewing everything daily, and that assured that the project design would work. That made a difference." Those three veterans stayed with the project for the next 36 months.

McCarthy also got help from Center management in streamlining the procurement process. Hinners authorized a green piece of paper with a skunk on top of it, "and anything we wanted procured went on this sheet," McCarthy said.

Goddard managed to track down the last Delta I rocket ever manufactured. It was not a pretty sight: it was corroded in spots, and its aluminum skin was covered with patches, leading to gallows humor among the engineers about its shoddy appearance.[5] But it was a launch vehicle nonetheless.

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[4] For more about the original skunkworks, see:
http://www.lockheedmartin.com/aeronautics/skunkworks/index.html

[5] *The Very First Light*, p. 222.

A Crash Diet

Every element of COBE had to be reconsidered, from how its solar panels would deploy to how the instruments would be affected by the vibrations they would encounter on the new launch vehicle. The first and most obvious challenge was reducing the size of the spacecraft. In its Shuttle configuration, it weighed 10,959 pounds. The Delta I could only launch 5,025 pounds. The spacecraft's launch diameter also had to be reduced from 15 feet to 8 feet. The goal was to achieve these reductions without touching the science instruments.

One piece of hardware on the spacecraft that could not be altered was the dewar, a giant Thermos bottle that would be filled with liquid helium and cooled to a temperature of almost absolute zero. (See Figure 1.) This cooling process transformed the helium into a "superfluid" state so it could serve as a completely uniform thermal conductor. The dewar was critical to the operation of the Far Infrared Absolute Spectrophotometer (FIRAS) and the Diffuse Infrared Background Experiment (DIRBE).

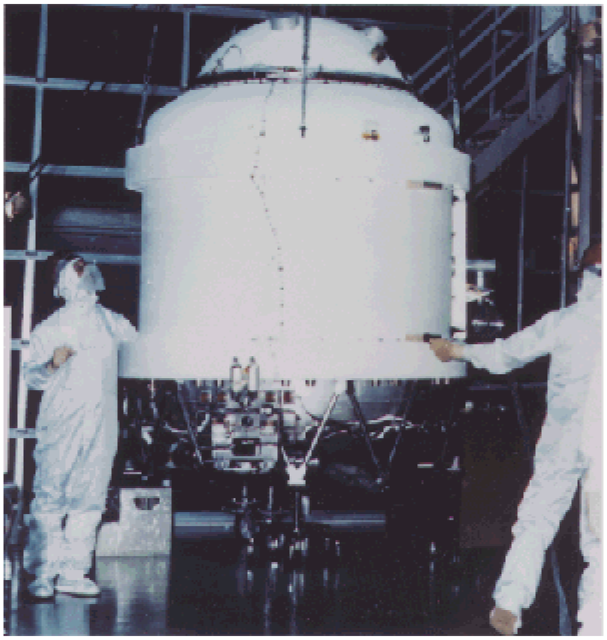

Figure 1. The COBE dewar, a 660 liter liquid helium cryostat, provided a stable 1.4 Kelvin environment for the Far Infrared Absolute Spectrophotometer (FIRAS) and the Diffuse Infrared Background Experiment (DIRBE). (Source: NASA)

The dewar weighed 1,426 pounds, and was considered so sensitive that it was transported across country from manufacturer Ball Aerospace's facility in Denver to Goddard on a truck in a suspended container equipped with shock-detection equipment to measure the *g*-forces that it encountered on the cross-country journey.

A lot of the mass of the COBE system on the Shuttle was in support structure that was not needed on the Delta. The first reductions in weight came from scrapping the propulsion system, which was no longer necessary since the Delta could insert COBE directly into the proper orbit. The propulsion system accounted for 2,060 pounds. The system was sold to the Department of Defense.

Since the diameter of the spacecraft was being reduced by nearly half, the smaller and lighter structure enabled a reduction of 3,800 pounds. A smaller electrical harness and smaller solar panels saved additional weight.

The only change to the instruments was the positioning of the Differential Microwave Radiometer (DMR), which was mounted directly on top of the dewar.

The new spacecraft weighed 4,828 pounds. The team had cut away 5,766 pounds, leaving a 197-pound margin, and trimmed its dimensions so that it would now fit on the Delta rocket.

Ticking Clock

Beyond the reduction in size, the redesign posed numerous other challenges. There were myriad problems with electrical interference among the instruments, which were now packed much more closely together than in the earlier configuration. The smaller electrical harness played a part in this as well. Testing also revealed that the vibrations from the Delta might cause damage to the DIRBE instrument. Solutions had to be found for these and scores of other critical issues if COBE was to yield the scientific data that John Mather and his colleagues had spent more than a decade preparing to collect.

The project maximized its time by using the wooden Shuttle mockup to test the spacecraft's various electronic component boxes as they were completed. This kept the integration and test process moving during construction of the new structure and electrical harness for the Delta, thus avoiding costly delays. "We would bring the black boxes after they were done on the Shuttle mockup, and put them on the Delta structure," McCarthy said. "Everything was done in parallel."

The skunkworks approach paid dividends as the staff worked seven-day weeks in three around-the-clock shifts. The project team at Goddard ballooned from a core of three dozen employees when the redesign began to nearly 300 at the peak of activity in 1988. At some point it dawned on McCarthy and Mattson that they didn't need staff meetings. "Because of the fact that we were all co-located together, a lot of the work was done in the hallways, over coffee, during lunch," McCarthy said. "The scientists, the engineers, and the designers were all together, and just by assimilation we didn't need staff meetings. We had them once a month, but they weren't really necessary."

In September 1988, cryogenics experts filled the dewar with liquid helium and began the process of cooling it to a temperature approaching absolute zero, which took several weeks. Even after it had been cooled, maintaining its temperature was no simple matter. Above all, nobody wanted a last-minute surprise that would require reopening the dewar; it would take just as long to work the process in reverse.

The schedule began to slip, and the ballooning staff meant costs were up, eventually reaching $1 million per month. The pressure was on from NASA Headquarters: Congress had been told that COBE would launch by May 1989.

Endgame

COBE was not ready by the spring of 1989, but it was close. It had passed the major tests designed to ensure that it could withstand the rigors of spaceflight and the harsh space environment it would encounter. At the urging of a senior mechanical engineer, the spacecraft and its instruments were then to be tested in a horizontal position to simulate mission conditions; up to that point, all the tests had been conducted with the spacecraft vertically upright on the shop floor.

The test revealed a “showstopper”: the FIRAS instrument did not operate properly from the horizontal position. The dewar would have to be reopened, requiring weeks to warm it first. This was considered such a major undertaking that the COBE team had to get permission from NASA Headquarters before it could open the dewar to fix the instrument. The repair was successfully carried out in July. It then took several weeks to refill the dewar with liquid helium and cool it down to near absolute zero.

Once COBE had completed the formal flight hardware qualification process, there was one final test that experts urged McCarthy to perform. Technicians placed the satellite in a RF (radio frequency) clean room—a shielded environment where it would not pick up any radio extraneous signals—turned on the electronics, and left it to run for 2 weeks.

“We were encouraged to do this so the scientists would understand all the characteristics of the satellite, because what they were trying to measure was so minute and the measurements had to be so accurate that they needed to understand with certainty that their measurements reflected what they intended to measure, not ‘noise’ from the satellite,” McCarthy said. “This gave the scientists the opportunity to learn the idiosyncrasies of the satellite.”

The instruments passed the test without a hitch. After a last-minute fix to the spacecraft’s Earth scanners, which were designed to ensure that the spacecraft maintained the proper orientation with the Earth, the spacecraft was also ready.

Three years after Dennis McCarthy had met with Noel Hinners and Sam Keller to discuss his napkin drawing, COBE was set for launch.

COBE lifted off successfully from Vandenberg Air Force Base on November 18, 1989. The science data it collected would make history, earning Project Scientist John Mather and DMR Principal Investigator George Smoot a shared Nobel Prize for Physics in 2006.

Appendix 1. Teaching Notes

This case study has been designed to be delivered in a classroom setting. Participants should be given the full case to read prior to in-class discussion, preferably as a homework assignment or "read-ahead" that allows ample time for analysis and reflection.

The facilitator should then lead a guided discussion, focusing on the class's interpretation of the problem:

- What major issues did the project manager and his deputy face as they confronted the problem posed by the *Challenger* accident?
- What variables could the project management team control once work began on the redesign effort? Which ones were out of its grasp?
- What impact did the organizational changes have on the project team once the redesign effort began?
- What role did politics play at various stages of the case?

Participants should be encouraged to draw analogies to their own experience and develop as many options as possible.