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Saving SOHO
SPECIAL REPORT
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Saving SOHO

The problem with SOHO, the Solar and Heliospheric Observatory, began on a June evening in 1998. In the computer-packed control room at NASA-Goddard, ground controllers could not foretell that this was the start of nearly four months of unprecedented high-tech drama—a heroic international effort to salvage a spacecraft more than 1 million km from Earth.

That night, SOHO had put itself into Emergency Sun Reacquisition mode. It was the fifth such event since SOHO's December 1995 launch, so operators sitting at Goddard viewed it at first as nothing too worrisome. But over the next 5 hours, a series of ground operational errors would doom the spacecraft, first causing loss of attitude control, then a break in telemetry, loss of power, and loss of thermal control. It was the bleakest of outcomes, with SOHO's scientific days in the Sun apparently about to set.

Although the prognosis for spacecraft recovery appeared dire, a blend of human perseverance, clever shot-in-the-dark troubleshooting, and good luck gave the observatory a second life.

by **Leonard David,**
contributing writer

Solar watchdog

The SOHO project, a joint international mission carried out by the European Space Agency (ESA) and NASA, is part of the larger International Solar-Terrestrial Physics program. Of SOHO's nearly $1-billion cost, NASA picked up $477 million and ESA paid the rest. Weighing in at 1,875 kg, the satellite stretches about 8 m across with its solar panels extended. An industry team led by Matra Marconi Space built SOHO in Europe. Its instruments were provided by nine European and three U.S. principal investigators. ESA was responsible for SOHO's procurement, final integration, and testing. And mission operations are provided by NASA through a Goddard contract with AlliedSignal Technology.

Launched from Cape Canaveral, Fla., atop an Atlas IIAS rocket on December 2, 1995, SOHO was placed into a special halo orbit around Lagrangian Point L1, a distant 1.5 million km away on the sunward side of the Earth. At this locale, SOHO would enjoy an uninterrupted view of the Sun, positioned where the gravity pulls of the Earth and Sun are in balance. After reaching its orbit and being checked out, the spacecraft was declared fully operational in April 1996.

SOHO's major observational task is to enable an international cadre of more than 200 scientists to delve into some of the Sun's most baffling features, including its internal structure, the heating of its extensive outer atmosphere, and the origin of the solar wind. The spacecraft simultaneously views the Sun's interior and atmosphere, including particles in both the outer atmosphere and the solar wind. By closely observing the Sun and the energy and material it spews at Earth, SOHO sheds light on how and why Earth's environment and long-term climate are being affected.

Instruments carried by SOHO include spectrometers and a telescope operating in the extreme ultraviolet, energetic particle analyzers, a chronograph, a Michelson Doppler Imager, and other devices that sense reverberations across the Sun's face and chart oscillations in its brightness.

Startling findings

Without question, the dozen SOHO instruments have helped revolutionize solar science. About 2 million images of the stormy Sun—representing over a terabyte of data—have been relayed from the spacecraft. Spectacular images and movies of coronal mass ejections have been made possible by SOHO. These pictures, showing megablasts comprising a billion tons of highly charged particles shooting outwards at hundreds of miles per second, have proven valuable for improving forecasts of space weather.

SOHO's discoveries include:

•"Jet streams" or "rivers" of hot, electrically charged plasma flowing beneath the surface of the Sun. These streams, which are similar to Earth's trade winds, transport gas beneath the Sun's fiery surface.

•Vast clouds of material "puffing" through streamers, like smoke through a chimney. This puffing action is possibly caused by powerful magnetic field line loops inside solar streamers that break and then reconnect.

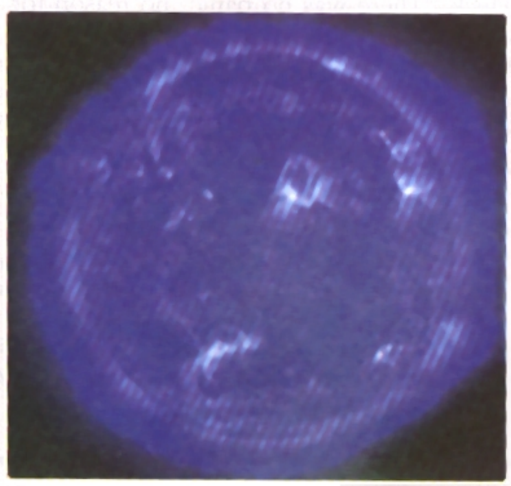
Although human error led to the failure of this solar observatory, it was human ingenuity and perseverance that brought it back to life

•Tall, gyrating storms far larger and faster than Earth's tornadoes. Steady wind speeds of 15 km/sec and gusts measuring 500,000 km/hr occur in the solar tornadoes.

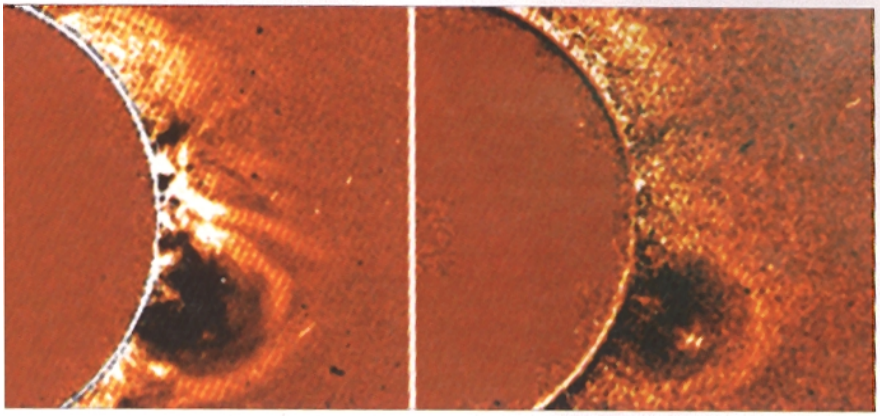
•A magnetic "carpet" on the surface that seems to account for much of the energy needed to cause the very high temperatures of the Sun's outermost layer, the corona.

•More than 50 Sun-grazing comets, several of which SOHO observed as they fell into the Sun's atmosphere in close succession.

In April 1998, SOHO scientists marked two years of successful operations. Further cause for celebration came when ESA and NASA decided to extend the spacecraft's mission to 2003. This would allow it to observe the intense solar activity predicted for 2000-2001, when the count of sunspots rises



SOHO-EIT image in resonance lines of eight and nine times ionized iron at 171 Å in the extreme ultraviolet shows the solar corona at a temperature of about 1 million K. It was recorded on September 11, 1997, and is dominated by two large active region systems, composed of numerous magnetic loops. All photos and captions courtesy of the SOHO consortium.



The onset of a coronal mass ejection was observed by the LASCO C1 coronagraph on December 23, 1996, in the forbidden line Fe XIV 5303 Å at 21:04 UT (left), and the K corona at 21:07 UT.

to a maximum. SOHO was now set to remain the flagship of a multinational fleet of Sun-watching spacecraft.

Falling through the net

Shortly after 7:15 p.m. U.S. eastern time on June 24, ground monitoring equipment at NASA-Goddard indicated that SOHO had slipped into Emergency Sun Reacquisition (ESR) mode. In this procedure, enacted in the event of spacecraft anomalies, SOHO autonomously enters a safe hold mode. Once this occurs, a recovery sequence must be commanded and executed under ground operator control. This necessary step leads to placement of the spacecraft back into Mission Mode, the mode from which science observations are made. SOHO's Sun-observing attitude results from careful orchestration of the momentum management of three roll gyroscopes and an on-board attitude control unit. This computer unit fires SOHO's thrusters to keep the spacecraft pointed toward the Sun under the guidance of an on-board Sun-sensor.

At first, ground operators were comfortable with the misbehaving spacecraft, believing the situation was under control, recalls ESA's SOHO project scientist, Bernhard Fleck. "There was no panic...no reason for concern," he says. With actions under way to recover from the initial problems, a second ESR was triggered a few hours later. Once again, this event was seen as resolvable. Indeed, that second emergency call of the night mimicked a situation that had occurred a few months earlier. Back in March, with an ESR recovery in progress, SOHO had gone into another ESR.

"My perception at the time was that nobody felt we were very close to a disaster," Fleck says.

Ground operators again commanded SOHO into an initial Sun acquisition mode. As roll thrusters resumed firing, however, a third ESR was encountered. Tension in the control room mounted. The time was 12:38 a.m. on June 25. In less than six minutes, SOHO would be lost.

Far out in space, SOHO was spinning faster and faster. The excessive pitch and yaw Sun-pointing errors that resulted caused the spacecraft's ESR controller to become unstable, and SOHO's attitude was diverted. Telemetry from SOHO went silent, a consequence of either insufficient power or loss of a communication link caused by spacecraft attitude.

Looking back on the trio of ESR events that preceded SOHO's silence, Fleck points to a false sense of security. "We had flown the spacecraft for more than two and a half years successfully, through difficult situations. It's a bit like a pilot and crew, flying for so many landings and takeoffs, through sunny days and thunderstorms...and everything is under control. Nobody realized at that time that our plane was nose diving. It was a slow realization. One security net after another was lost," he says.

Human error

After the loss of the spacecraft, a SOHO Mission Interruption Joint NASA/ESA Investigation Board was formed. The board focused on the most likely reasons for the mishap and set out to recommend necessary changes and corrective actions to prevent similar events. The board consisted of NASA and ESA managers and engineers with broad experience in both the development and operation of flight projects. Representatives from each of the two agencies cochaired the panel.

In its final report, completed last August, the group concluded that there were no anomalies on board SOHO. Rather, it said, a number of ground errors led to the spacecraft's major loss of attitude.

"The board finds that the loss of the SOHO spacecraft was a direct result of operational errors, a failure to adequately monitor spacecraft status, and an erroneous decision which disabled part of the on-board autonomous failure detection," the final report stated. Furthermore, the 10-person board concluded that "inappropriate" decisions were hastily made by ground operators in response to the ESR events. Loss of SOHO was due to improper commands sent from the ground, including a wrong decision to disable part of an autonomous safety net built into the spacecraft.

The fact-finding team underscored several issues that added up to the spacecraft's loss. In the end, removing the functionality of SOHO's normal safe mode, along with not noting the incorrect setting and wrongly diagnosing the status of two of the spacecraft's three gyros, resulted in attitude control problems that ultimately put the spacecraft out of commission. Boldly spelled out by the board was one finding: At any time during the more than 5-hr period of ESR situations, verification of the nonspinning status of one of the three SOHO gyros—Gyro A—would have precluded the mishap.

SOHO's autonomous safe mode requires the use of Gyro A for roll control. Accordingly, any procedure that spins down Gyro A must also enable a warning flag in the onboard computer's software to respin the gyro whenever the safe mode is triggered. Unfortunately, this software enable command had not been included as part of a modification to operational procedure. The reason was a lack of system knowledge by the person who modified the procedure.

Furthermore, the change review process itself was faulty. It was found that procedure modifications did not appear to have been controlled adequately by AlliedSignal Technology's configuration board. In addition, the change was not properly documented or reviewed and approved by either ESA or NASA.

Other factors that indirectly contributed to SOHO's problems were identified by the board. These included:

• Failure to perform risk analysis of a modified procedure set.

• Shortcomings in the implementation of ESA/NASA agreements; these inadequacies caused a lack of clear leadership in the handling of contingency situations.

• Too much emphasis on science return at the expense of spacecraft safety.

• An operations team overload that did not permit the use of data crucial to the recovery of SOHO.

The board strongly recommended that NASA and ESA scrutinize SOHO operations. Issues of ground procedures, procedure implementation, management structure and process, and ground systems must be quickly reviewed, said the board.

"The real moral to be drawn from this," says Joseph Gurman, U.S. project scientist for SOHO, "is that when you have a really complex system made by human beings and human beings are operating it, sooner or later we're going to do something wrong."

Salvaging hope

Shortly after SOHO was lost, attempts to regain the spacecraft using NASA Deep Space Network (DSN) capabilities failed. Commands were uplinked to the spacecraft about once per minute, instructing it to activate its transmitters. There was no response.

Based on the last telemetry data received from SOHO, the spacecraft clearly was spinning. The central question was, how long would it take for SOHO to go into a flat spin around the axis of maximum momentum of inertia? It was determined that this dampening process would likely take a long time to play itself out. If the spin rate was excessive, could the satellite also have suffered structural damage? Those first four weeks were devastating to recovery teams.

ESA and NASA engineers believed the spacecraft was spinning with its solar panels nearly edge-on toward the Sun, and thus was not generating any power. Predictions of SOHO's orbit showed that in late September 1998, illumination of the solar arrays and, consequently, battery recharging, should approach a maximum. This window of maximum illumination would gradually diminish as the spacecraft-Sun alignment continued to change. By mid-July, NASA's DSN transmitted commands approximately 12 hr a day in the hope of salvaging SOHO.

Optimism that SOHO might be recovered and brought back to life was strengthened by ESA's experience in regaining the Olympus telecommunications satellite in 1991. A similar attitude loss suffered by Olympus led to intermittent power availability, causing the batteries and fuel to freeze.

This sequence of images of the Sun in the UV light of an He II emission line at 304 Å was taken by the Extreme-ultraviolet Imaging Telescope on Feb. 11, 1996, from the L1 gravity neutral point 1 million m sunward from Earth. An "eruptive prominence" or blob of 60,000 deg gas, over 80,000 mi. long (at left in each image), was ejected at a speed of at least 15,000 mph.

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Telecommand access to the satellite was regained in four weeks' time. Although on-board equipment sustained damage from the low temperatures, Olympus was successfully recovered and its mission resumed.

A glimmer of hope emerged on July 23. The 305-m-wide Arecibo radio telescope in Puerto Rico radar locked onto the silent SOHO. NASA's DSN tracking dish in Goldstone, Calif., picked up the radar reflection. By sifting through over an hour's worth of radar measurements, the agency determined that SOHO was spinning at a rate of one rotation every 53 sec. "This was our first boost in spirits," ESA's Fleck says. "Those measurements were very important. It was a boost in morale—there was still one piece up there where it was supposed to be. This confirmation was tremendously helpful. We knew it wasn't spinning excessively fast. This gave us hope for the recovery."

Trying to communicate with SOHO, given its cold state, proved to be a laborious effort. With a freezing spacecraft comes a change in up- and down-link frequencies. By installing a spectrum analyzer, loading specially written computer software, and establishing an Internet connection to display live video and audio, the team was able to formulate and try various up- and down-link frequency sweep strategies and sequences.

On August 3, after six weeks of silence, signals broadcast via the NASA DSN station at Canberra, Australia, were answered by SOHO. The heartbeat of the spacecraft came in the form of bursts of signals lasting 2-10 sec. The signals were intermittent, containing no data, but did show that the spacecraft was capable of picking up and reacting to ground commands. Immediately, the slow process of regaining control of SOHO and restoring it to an operational attitude was begun. The team also tried to initiate data transmissions in order to perform an initial assessment of SOHO's on-board condition.

Good news

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Responding to the good news was John Credland, ESA's head of science projects: "Recovery will be a slow and careful operation. The main thing is that the spacecraft is now responding to us, and we will take one step at a time to bring it into a more favorable attitude before assessing any damage which may have been caused by its six-week unforeseen hibernation."

During that period, SOHO's bursts of carrier signals were too short to allow the sensitive ground station receivers to lock on to them. The 10-sec-duration signals were caused by the cyclic variation of the on-board power supply as the solar arrays were shadowed, prompted by the spacecraft's unintentional spin motion.

Within days after SOHO first responded, controllers at Goddard were able to cajole information from the spacecraft to begin a health check of its systems. Rounds of telemetry from SOHO were received after 10 hr of spacecraft battery recharging. "This is the best news I've heard since we lost contact with SOHO," proclaimed Roger Bonnet, ESA's director of science: "I never gave up hope of some recovery of this fantastic mission. We should just hope that the damage sustained during SOHO's enforced period of deep freeze does not affect the scientific payload too much."

The SOHO recovery team asked for and received from NASA's DSN full 24-hr coverage of the spacecraft to attempt more complete battery charging. Efforts were then focused on thawing the on-board hydrazine fuel, which had plunged to 0 C. In some cases, instruments aboard SOHO had been through an ordeal of heat or cold, with temperatures skyrocketing or falling to ±100 C.

SOHO's ever-improving solar power condition was tapped over roughly three weeks to gradually thaw out the hydrazine. Fuel lines were warmed, as were spacecraft thrusters and SOHO's fuel tank. Here again, the going was not easy. Not enough power was available to defrost every hydrazine line. This meant that SOHO's recovery could not utilize all available thrusters. The solution involved a combination of control software changes, judicious cycling of battery power, gyro control plus star tracker and momentum wheel control, and bursts from available thrusters. On September 16, with nine days of delicate finessing behind them, engineers successfully nulled out SOHO's spin, placing it in the correct orientation toward the Sun.

"It really was a remarkable achievement," says NASA-Goddard's Joseph Gurman, also an investigator on SOHO's Extreme Ultraviolet Imaging Telescope. "This was an international team of people working single-mindedly together to recover contact with SOHO...to recover control of the spacecraft and its telemetry...and eventually to work out solutions to bring SOHO back in line," says Gurman, calling the effort "space business at its best."

Sharing that thought is ESA's Fleck. The long hours, the dedication and cooperation between multinational teams of contractors, government agencies, universities, scientists, and engineers made possible SOHO's recovery, he says.

"Everyone worked together in a spirit of helping us out. I won't forget the feeling that we were all in one boat, pulling in one direction. That spirit, that atmosphere is very difficult to express. But it is an experience that I will long remember," Fleck says.

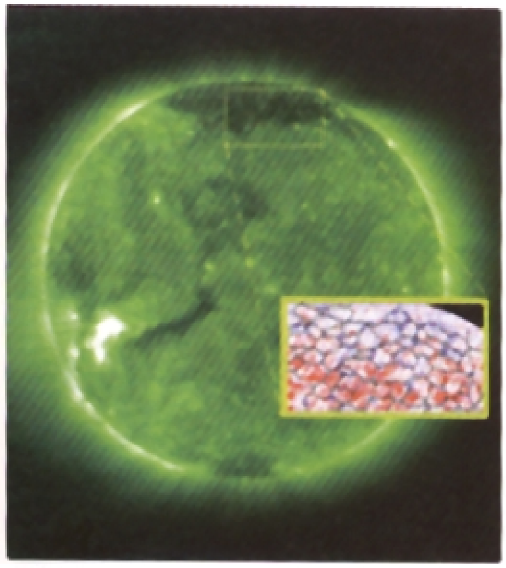
A Sun-watching encore?

The lengthy and dramatic space rescue of SOHO offered up an extra surprise. By late October, most of SOHO's science instruments had been turned on. Scientists and engineers were astounded to learn that the sensitive equipment remained in working order. After several days of detailed instrument checking, the first images from SOHO were relayed back to Earth. By the end of 1998, all but two of the spacecraft's dozen instruments appeared none the worse for wear after months of exposure to thermal stress. In fact, one instrument detector performed better than it had prior to SOHO's shutdown—solar baking of the detector had removed impurities far better than the instrument's own heaters.

"This was an exciting fact. Even though temperatures were well beyond any that the items had been tested to, things did work...they did not fail," says H. Richard Freeman, chief engineer in Goddard's Applied Engineering and Technology Directorate. He was also a member of the SOHO Mission Interruption Joint NASA/ESA Investigation Board.

"I think the robustness of all the hardware, especially the instruments, really was a surprise," Freeman says. "I think it was a very good save...a very lucky, very carefully orchestrated save," he notes.

However, the success was marred by the loss of two gyros. Then, on December



After going back into service, SOHO discovered the source of fountains of electrified gas that flow from the Sun. Called the high-speed solar wind, this gas flows out at 2 million mph from the edges of honeycomb-shaped patterns of magnetic fields at the Sun's surface.

21, the remaining gyro failed, putting the spacecraft into a slow roll and ESR mode. Although the gyros were not required for carrying out science duties, SOHO had ceased transmitting scientific data. Because roll gyro redundancy had been lost, the risk associated with recovery from future spacecraft anomalies also increased.

Keeping the spacecraft pointing at the Sun and within its halo orbit began using precious fuel reserves. The more fuel SOHO consumed, the more its life was shortened. Plans were put into place to transfer SOHO's attitude control functions to the spacecraft's reaction control wheels. That step bought ground controllers time and decreased hydrazine use. European teams busily began working on computer algorithms and SOHO attitude control unit software patches.

This January, hopes ran high that SOHO could resume a back-in-business, but modest, science-gathering agenda. And by early February ESA and Matra Marconi Space engineers had successfully installed the new software, reprogramming SOHO to resume science operations without its gyroscopes. ESA and NASA now believe the spacecraft will continue its mission until 2003.

"The issue right now is just to go very slowly so they don't lose anything. They have come so far that it would be a shame to lose something now, especially [with the Sun] going into solar maximum in just a couple of years," Freeman concludes.

Given its new lease on life, albeit life on the edge, time will tell if SOHO, Earth's solar watchdog, can maintain its vigilant sleuthing of the Sun's inner and outermost mysteries. ▲