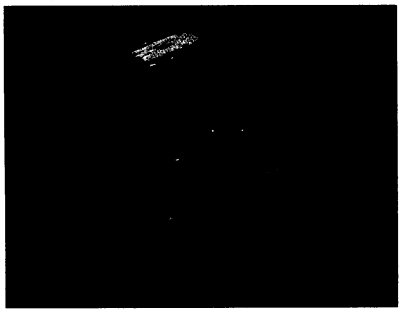
SPACE SCIENCE

Chain of Errors Hurled Probe Into Spin

The loss of the $1 billion Solar and Heliospheric Observatory (SOHO) has exposed a long chain of software and control errors, a NASA review panel has found. The report says a pair of software bugs laid the groundwork for a disastrous command from controllers at NASA's Goddard Space Flight Center in Greenbelt, Maryland, which caused SOHO to spin out of control early on 25 June. *Science* has learned that the debacle also revealed other foul-ups, which played smaller roles in the loss: a third software bug, which may have distracted the flight operations team during the crisis, and the failure of three of SOHO's four emergency batteries.

SOHO



Twisting in the solar wind. The SOHO solar probe, now feared lost.

The panel, which issued its preliminary report last week, is not writing an epitaph for SOHO, which had been watching the sun for two-and-a-half years and was expected to keep gathering data into the next millennium. The spacecraft, a joint project of NASA and the European Space Agency, is now mute and is thought to be tumbling in an orientation that prevents its solar panels from collecting sunlight and generating power. As it moves around the sun over the next few weeks, however, the panels may rotate sunward again and enable the craft to answer NASA's calls. But Joseph Gurman of NASA Goddard, the U.S. project scientist for SOHO, says the debacle holds important lessons. "We ended up with a system that was more complex than was consonant with the very highest degree of safety," he says.

The incident centered on two gyroscopes, called A and B, which sense the spacecraft's roll—its rotation around its longest axis, which is normally aimed at the sun. Because of slight imbalances and electronic inaccuracies in the gyros, they must be calibrated occasionally to determine their "drift," or the amount of actual roll SOHO has when the gyros read zero. To help with the fine-tuning, gyro B's output is set to 20 times its normal sensitivity during calibration. The first software error—introduced during a recent effort to streamline the SOHO software—left gyro B in its hypersensitive mode after calibration rather than resetting it. "It was left indicating roll rates 20 times greater than actual," says Gurman.

This error caused trouble when controllers at Goddard began a second routine procedure, in which SOHO's thrusters are fired to hold the spacecraft steady while a set of wheels, accelerated to twist the spacecraft during maneuvers, are slowed from the high rates of spin they acquire over time. As soon as the procedure was finished, gyro B began telling SOHO, incorrectly, that the spacecraft was spinning 20 times too fast. On the evening of 24 June, the spacecraft went into a mode called Emergency Sun Reacquisition (ESR). Triggered automatically if SOHO detects anomalies in its orientation, ESR fires thrusters to reorient the craft toward the sun.

At that point, a second critical software bug did its damage. To save wear and tear, gyro A shuts off while the wheels are braked. But because a necessary command sequence had been omitted from onboard software during a rewrite about a year ago, gyro A, unknown to controllers, had failed to come back on. Gyro B's erroneous output had, by then, been reset, but it conflicted with gyro A's false zero. And while this problem was developing, other errors cropped up in software written for a recent move to a new control room. Controllers hustled down a hall to the original room, where they hoped the instrument readings would be more reliable.

Here, they took the fateful step described succinctly in the report: "A rapid decision was made that gyro B was faulty and should be commanded off." When gyro A reads zero, SOHO's thrusters fire briefly to compensate for its drift and stabilize the spacecraft. But because gyro A continued to give its false zero, the thrusters had been firing continuously, spinning SOHO faster and faster. Its befuddled sensors triggered two more ESRs, eventually sending it flailing out of control, like a ballerina tripped in midpirouette. Communications faded rapidly as the solar panels lost sunlight—far too rapidly, one panel member says. Surprised controllers now found that undetected failures sometime earlier this year had taken out three of the four batteries.

Michael Greenfield, an official in NASA's Office of Safety and Mission Assurance who co-chaired the panel, puts the blame squarely on the controllers' decision to turn off gyro B. "The team had sufficient time—over 24 hours the spacecraft would have been stable—to reevaluate what to do," he says. "You generally stop, call in experts, senior management. That was not done."

Others, however, point out that many individual failures contributed to the loss. "We've got to avoid any finger-pointing," says Goddard's Art Poland, the previous SOHO project scientist, who emphasizes the scientific successes the mission has already scored. "Each of us can share part of the blame," agrees Gurman, who was on vacation at the time. "If I had been driving the *Titanic*, would it have hit the iceberg?"

—**JAMES GLANZ**

GLACIOLOGY

West Antarctica's Weak Underbelly Giving Way?

The news out of West Antarctica remains unsettling. Early this month, researchers sifting through mud drilled from beneath the West Antarctic Ice Sheet reported that the massive pile of ice had disintegrated to next to nothing at least once in the past 1.3 million years (*Science*, 3 July, p. 17), presumably during a warm interlude between ice ages. Now, space radar images hint that the ice sheet may be weakening again in today's warming world. One of the glaciers flowing from the ice sheet into the sea—a glacier that has long been seen as the ice sheet's weak point—is eating into stabler ice at a startling rate.

The observations, reported on page 549 of this issue of *Science* by radar scientist Eric Rignot of the Jet Propulsion Laboratory in Pasadena, California, show that the "grounding line" of the Pine Island Glacier—where ice resting on its bed gives way to floating ice—has been retreating inland at a rate of more than a kilometer per year, presumably because the glacier is losing mass by melting at its base. "That's not catastrophic yet," says glaciologist Richard Alley of Pennsylvania State University in State College, "but most models indicate [that the retreat] would speed up if it kept going."

T. J. HUGHES/UNIV. OF MAINE

End of the line. The Pine Island Glacier could soon be dumping more of the West Antarctic Ice Sheet into the sea.

And that, say some glaciologists, might be a first step toward the collapse of the entire West Antarctic Ice Sheet, which covers one-quarter of Antarctica. In 1981, University of Maine glaciologist Terence Hughes dubbed Pine Island Glacier and the adjacent Thwaites Glacier the "soft underbelly" of the ice sheet because they seemed particularly vulnerable in warm climates like today's. They lack the extensive floating ice shelves thought to buttress other glaciers that are draining the ice sheet, he noted. They are also exposed to the relatively warm South Pacific Ocean.

Once these vulnerable ice streams began to give way, Hughes speculated, the generally downward slope of the seabed that the ice sheet rests on would accelerate the grounding line's retreat and the accompanying thinning of the ice, ultimately leading to the complete collapse of the ice sheet within a couple of centuries. The result would be a sea level rise of more than 5 meters—enough "to back up every sewer in New York City," as one researcher puts it, not to mention flood any low-lying coast, from all of South Florida to the city of Bangkok.

Rignot looked for early signs of collapse in observations of the 33-kilometer-wide Pine Island Glacier made between 1992 and 1996 by the radars aboard the European Earth Remote Sensing satellites ERS-1 and ERS-2. In his computer analysis, he allowed radar signals reflected from the glacier during satellite passes a few days apart to interfere with each other. The resulting interference pattern, sensitive to small vertical motions, revealed the subtle flapping of the floating ice as ocean tides raised and lowered it. The grounding line at the hinge of the flapping ice shelf retreated into the ice sheet at a rate of 1.2 ± 0.3 kilometers per year during the 4-year period, Rignot concluded. "That's a significant retreat," he says.

"I would say it's surprisingly large," agrees radar glaciologist Mark Fahnestock of the University of Maryland, College Park. "It could potentially lead to a collapse" of the ice sheet. But researchers aren't panicking yet. Their primary reservation, which Rignot shares, is that 4 years "is a very short interval," says Alley. "Glaciers do weird things." For example, one of the ice streams draining into the Ross Sea stopped flowing about 100 years ago, and another slowed by 50% during the past 35 years.

More radar surveillance should tell whether the glacier's retreat is continuing, and measurements of exactly how the seabed slopes beneath the glacier should indicate whether the retreat really will accelerate. "That guarantees a very high priority will be to map the sea floor in that whole area," says Hughes.

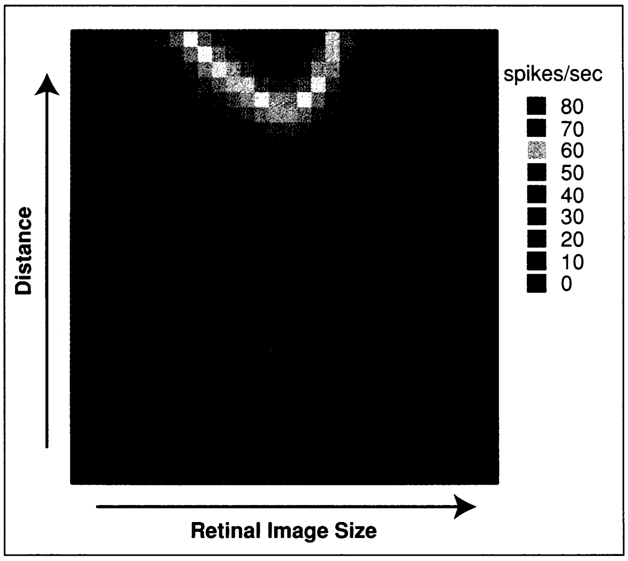
Getting to know Pine Island Glacier better will not be easy. It's "a hideous place to work," says Alley. It's so remote, "you can't get there from anywhere, and the weather stinks." But to see what the warming world might hold, glaciologists are already breaking out their cold-weather gear.

–RICHARD A. KERR

NEUROBIOLOGY

How the Brain Sees in Three Dimensions

When Renaissance painters solved the problem of depicting three-dimensional (3D) scenes on flat canvases, their paintings blossomed into realistic representations of the world. Our brain must solve this problem every day to reconstruct 3D views from images that fall on the 2D surface of our retinas. Researchers have long known that we use various cues to accomplish this, such as the stereoscopic effect of binocular vision and the relative sizes of objects. Now, a team at the California Institute of Technology in Pasadena has made a surprising discovery about the neurons that apparently translate distance cues for the brain.



Far-out. A "farness cell" responds best to a distant object that produces a midsize retinal image.

RICHARD JEO/CALTECH

Most neuroscientists thought that neurons sensitive to object distance would be located in the so-called "where" processing stream, a set of brain areas that receive information from the primary visual cortex and use it to compute spatial relationships that, among other things, guide movements, such as the reach of a hand toward an object. But on page 552, Caltech's John Allman and Allan Dobbins and their co-workers report finding brain neurons outside the "where" stream that register depth, as indicated by correlations between their firing rates and the absolute distances of objects.

"This paper is going to attract a lot of interest," predicts Robert Desimone, director of intramural programs at the National Institute of Mental Health. Terrence Sejnowski, a neuroscientist at the Salk Institute in La Jolla, California, agrees, noting that it suggests that depth-sensing neurons are found throughout the visual cortex, their information combining with the 2D map that already exists in each visual cortical area to provide the areas with full 3D maps of visual space.

The Caltech team identified the depth-perception neurons by recording the activity of neurons in monkeys' brains as the animals looked at bars of light displayed on a computer screen at various distances from the monkeys. The team looked in two brain areas, the primary visual cortex and a nearby area called V4, and found that some neurons in each area respond best to light bars that produce a particular size image on the retina. Because the size of the retinal image changes with the screen's distance, that means the brain's response to any bar would also change with distance—no surprise there.

But when the researchers kept the size of the retinal image constant by varying the size of the light bar as they changed the position of the screen, they still found, Allman says, that "distance was having a very powerful modulatory effect" on some neurons. There were "farness neurons" whose responses increased as the screen moved away, "nearness neurons" whose responses grew stronger when the screen moved near, and other neurons that peaked in between.

The researchers then monitored the firing rates of these neurons as they selectively removed visual cues for distance. Some neurons stopped registering distance when one eye was covered, suggesting that they depend on binocular cues. Others worked monocularly as long as the monkey had a broad view of the room and the monitor, but lost depth perception when the monkey viewed the image through a tiny hole. And some neurons continued to register distance when both context and binocularity were removed. Allman and Dobbins think those neurons may respond to cues such as the focus of the eye, which varies with distance, or the angle of gaze, which shifts inward toward the nose as an object gets nearer.

"It is interesting that different cells appear to be tuned to different kinds of depth