

Remote makeovers maximize return on spacecraft science

Altered trajectories, spare or repurposed instruments, new software, and other clever tactics can give spacecraft a new lease on life.

Since starting up last year, the K2 space mission has discovered several exoplanets, including one that could potentially harbor life. K2 is the continuation of *Kepler*, which NASA launched in 2009 to eye a patch of sky for exoplanets. In 2013, the second of four reaction wheels, or gyroscopes, failed, and the spacecraft could no longer be precisely pointed.

K2 is the ingenious response to that failure. Engineers on the ground figured out how to stabilize the craft, with the two remaining reaction wheels balancing the radiation pressure on the solar panels. The spacecraft remains in the same Earth-trailing orbit, but the new mode of operation restricts it to pointing only in the ecliptic. “It took months to figure out how to point with solar pressure as the third wheel,” says *Kepler* and K2 project scientist Steve Howell of NASA’s Ames Research Center. “It turns out that the ecliptic plane is a beautiful spot that can look at all kinds of new science—not just exoplanets, but young stars, old stars, star clusters, variable galaxies, and bright exoplanet-host stars.”

A comeback like *Kepler*’s is “not unique, but it’s unusual,” says Derek Buzasi of Florida Gulf Coast University, who reinvented the *Wide-Field Infrared Explorer* (WIRE) after it failed following its 1999 launch. “Spacecraft are built for a specialized purpose, so they are hard to repurpose. You have to come up with something they are capable of at the same time they are incapable of their original mission.”

Payload versus payback

At one extreme on the repurposing spectrum are the rare instances when astronauts make repairs in space, as with the *Hubble Space Telescope*. The launching of a spare satellite, or relaunching of a grounded mission, is also hands-on. An example is a navigational satellite built in the 1960s that did not end up flying. It hung in the Smithsonian’s National Air and Space Museum for more than eight years until 1984, when it was reworked and

then in 1986 was deployed as *Polar Bear* to study communications interference from solar flares and auroral activity.

More common are the instances of extending a spacecraft’s lifetime or troubleshooting from afar to recover from failures. “You might even argue that this is pretty routine stuff,” says

Fabio Favata, head of the science planning and community coordination office at the European Space Agency (ESA). In some cases, the same sorts of data continue to be collected in the same ways. In others, different targets are observed, orbits are changed, or new modes of observation are employed.

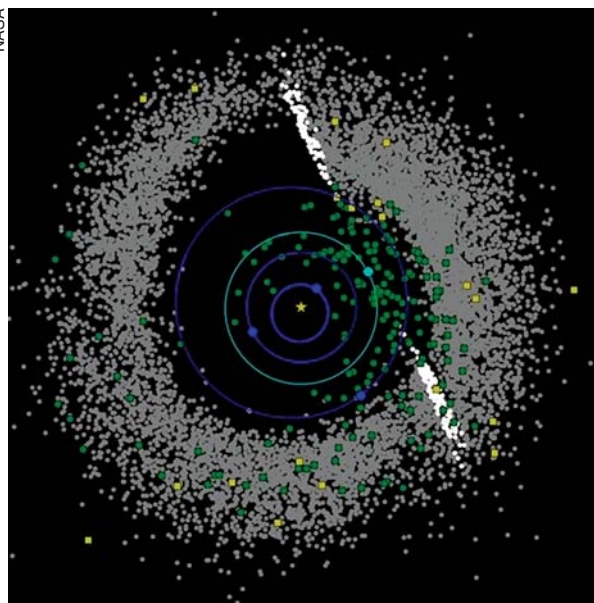
“Assuming nothing changes, everyone wants to continue to use [their spacecraft],” says Michael Werner of the Jet Propulsion Laboratory (JPL), who is project scientist for the *Spitzer*



BALL AEROSPACE

The *Kepler* spacecraft, shown here in preparation for its 2009 launch, is now in its repurposed incarnation as K2. Roughly every 85 days the telescope is adjusted to point to another field in the ecliptic plane.

NASA



Comets and asteroids observed by NASA's *NEOWISE* spacecraft after its restart in December 2013. In this snapshot, green circles represent near-Earth objects—comets and asteroids that come within 1.3 astronomical units of Earth—and yellow squares and gray dots represent more distant comets and asteroids, respectively. The white is the leading edge of time, and the circles represent planet orbits. A time-progression video can be viewed at <http://www.jpl.nasa.gov/video/details.php?id=1353>.

Space Telescope. “That leads adiabatically to some repurposing—the science changes or some instruments may get flaky.” Werner says “a sizeable fraction” of astrophysical and planetary spacecraft launched in the past 10 years have had their missions extended. “It’s a testimony to three things,” he says, “the ingenuity of people, the reliability of instrumentation, and the openness of NASA to new ideas.”

As a rule of thumb, developing and launching a spacecraft costs four to five times as much as the operations phase, and continuing operations usually costs even less, says Alan Stern, associate vice president for R&D at the Southwest Research Institute and a former NASA associate administrator. In fuzzy numbers, launching and running a mission typically costs in the hundreds of millions of dollars, while the cost of extending a mission can be less than \$10 million a year.

Still, money is often tight. “You have to accommodate operating existing missions and building new spacecraft,” says Rune Floberghagen, mission manager of the *Gravity Field and Steady-State Ocean Circulation Explorer* (GOCE). In ESA’s Earth Observation directorate, he says, “we don’t have examples of flight missions closing because of fantastic new ideas emerging, but clearly it’s a factor in discussions about how money is apportioned.” At NASA, extending missions is subject to review every two years, and other space agencies have their own protocols.

Grandfathers of repurposing

The *Voyager* spacecraft are the grandfathers of extended missions. Launched

in 1977, the two probes continue to send home data. Their initial goal was to observe Jupiter and Saturn. For *Voyager 2*, that was expanded to Uranus and Neptune. More extensions followed, and in 2012 *Voyager 1* became the first probe to enter interstellar space, says project scientist Edward Stone of Caltech. “We had to make major changes when we embarked on the Uranus flyby and going to interstellar space.” Software has had to be modified to deal with reduced power, and for the Uranus flyby an on-board decoder was turned on so the craft could send back more information, he says. Different ensembles of ground antennas, sometimes fitted with receivers, have been used to retrieve *Voyager* data. (See the article by Joseph Lazio and Les Deutsch in *PHYSICS TODAY*, December 2014, page 31.)

Along the way, says Stone, “things have failed, but fortunately nothing catastrophic.” For example, he says, the radio transmitters use vacuum tubes, and the backup on *Voyager 2* was turned on after 21 years. If nothing else fails, he says, the *Voyager* program could run for another 10 years. The probes are powered by heat created by radioactive decay of plutonium-238. “Each year we have about 4 W less electrical power than the year before. By 2025 we won’t have enough power to keep any instruments on.” Ongoing ground operations for the two *Voyagers* cost about \$5 million a year, he says.

Changing orbits

The *International Sun–Earth Explorer-3* (*ISEE-3*) was repurposed repeatedly. Launched in 1978 as part of a three-craft NASA–ESA collaboration to study the interactions of the solar wind and Earth’s magnetosphere, *ISEE-3* spent three years around the Lagrange point, where the pulls of the Sun and Earth balance. Says Robert Farquhar, who is retired from the Johns Hopkins University’s Applied Physics Laboratory, “I

knew I would do different things with it even before it launched.”

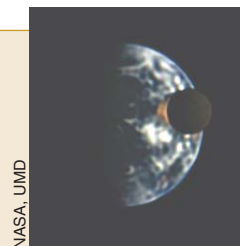
Farquhar, who is sometimes called the “guru of repurposing,” arranged for the craft to be hurled via a complicated pattern of lunar flybys into a trajectory through a comet’s tail and deep into Earth’s magnetotail. Following that 1985 impromptu encounter came more comet flybys and a heliospheric stint investigating coronal mass ejections. The craft was turned off in 1997.

Then last year, a group of amateur space enthusiasts raised money through crowdfunding (see *PHYSICS TODAY*, April 2013, page 23) to wake up the spacecraft to make space physics measurements. With NASA’s blessing and advice—and Farquhar’s participation—the group made contact with the craft but then lost it a few months later.

Other spacecraft that have been repurposed through rerouting include NASA’s *Deep Impact* and ESA’s *GOCE*. *Deep Impact*’s original mission was to hurl a copper ball at a comet and watch the impact. In its continued form as *EPOXI*, the spacecraft went on to visit another comet and, on the way, served as an observatory for user-proposed targets.

“*Deep Impact* had a flaw, and we turned it into an asset,” says Drake Deming of the University of Maryland in College Park, who led the mission’s observatory phase. “The high-resolution imager was defocused. For *Deep Impact*, this was not tragic; they compensated. But for looking at bright sources, it was an advantage because you spread the light over more pixels of the detector and don’t saturate.” The team used existing

This image of Earth and the Moon was captured by a repurposed telescope. The original *Deep Impact* mission was designed to visit comets. In its incarnation as *EPOXI* it also became an observatory, exploiting a defocused telescope to observe bright objects.



NASA, UMD

onboard software instead of uploading improved flight software, says Deming. "This was done on low funding, and flight software is sacred. It's regarded as a high-risk item."

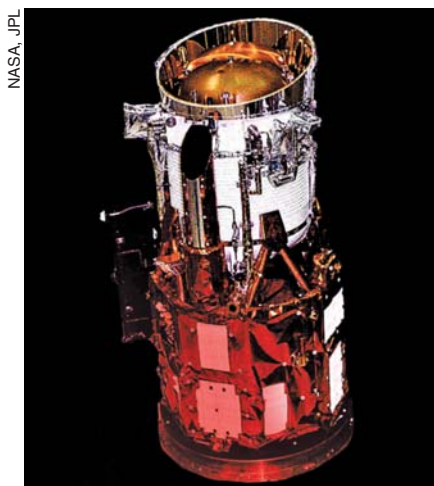
The repurposing of *GOCE* involved taking a risk to get better measurements. Starting in March 2009, the craft orbited Earth at the unprecedented proximity of 255 km and mapped gravity fields. Once the primary mission was completed, says *GOCE* project scientist Floberghagen, "we proposed to take a plunge deeper into the atmosphere." For every 20 km closer in, the drag is roughly doubled, he notes. If the drag compensation provided by the onboard instruments was lost, says Floberghagen, "you would soon be on a kamikaze trajectory." The plunge to 224 km occurred in 2012, and the mission collected data for 15 months until the craft ran out of fuel.

Warming up

Both *Spitzer* and *NEOWISE* (the asteroid-hunting phase of the *Wide-Field Infrared Survey Explorer*) grew out of IR observatories that had used up their cryogen. But at warmer temperatures—75 K instead of 7 K for *NEOWISE*—the crafts' detectors still work at shorter wavelengths. "The day after we lost the last bit of hydrogen we discovered Earth's first Trojan asteroid," says *NEOWISE* principal investigator Amy Mainzer of JPL. "Trojans are gravitationally stuck. Jupiter has millions of Trojan asteroids, but this was the first time an asteroid had been spotted being dragged along by Earth." *NEOWISE* collected data for a few months before being put into hibernation in early 2011. The extension was funded by NASA's planetary division; the original *WISE* mission's deep-sky survey was under the agency's astrophysics division.

Two and a half years later, says Mainzer, "NASA came to our team at JPL and said, 'We'd like to see about turning [*NEOWISE*] back on to look for asteroids.'" Since the reactivation in late 2013, she says, "we have been surveying the entire sky and mopping up asteroids and comets." Eventually, atmospheric drag will shift the plane of the orbit so that sunlight and earthshine can no longer be kept out of the telescope, which will put an end to the mission. "We suspect that will happen in 2017," Mainzer says.

On *Spitzer*, née the *Space Infrared Telescope Facility*, the detectors for longer wavelengths and a spectrographic imager designed for the original operating temperature of 5 K no longer work at



After its frozen hydrogen vaporized when a dewar door opened, the *Wide-Field Infrared Survey Explorer* seemed doomed. But scientists turned the failure into a new mission for asteroseismology by exploiting a small guide telescope (black cylinder, front left) designed to track stars.

30 K. "We had three instruments; now we only have half of one," says Werner. But the two bands that still work, he says, "turn out to be sweet spots that have allowed the spacecraft to maintain scientific vitality, most important in the search for exoplanets and studies of the distant universe."

In the case of *WIRE*, a cryostat with frozen hydrogen that was supposed to cool the mission's IR instruments opened prematurely shortly after launch. As it boiled away, the hydrogen thrust the craft into a tumble, and by the time NASA recovered it, the coolant was gone. Buzasi had the idea to use the craft's star-tracking guide telescope for asteroseismology. "The key for me was that it had a large, high-quality CCD." He got the nod from NASA. The repurposing required software changes—in particular, data that were intended only for orientation purposes had to be downloaded.

"Asteroseismology had not been done from space before," says Buzasi. "Overall, we characterized about 200 bright stars. Seismology essentially lets you look inside directly. If you do a nice job, you can get down to 1% precision on parameters like mass, age, and composition, which are hard to get accurately in any other way." The mission ran for seven years. "That star tracker was not intended for science," says Werner. "There is no substitute for human ingenuity."

Toni Feder

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