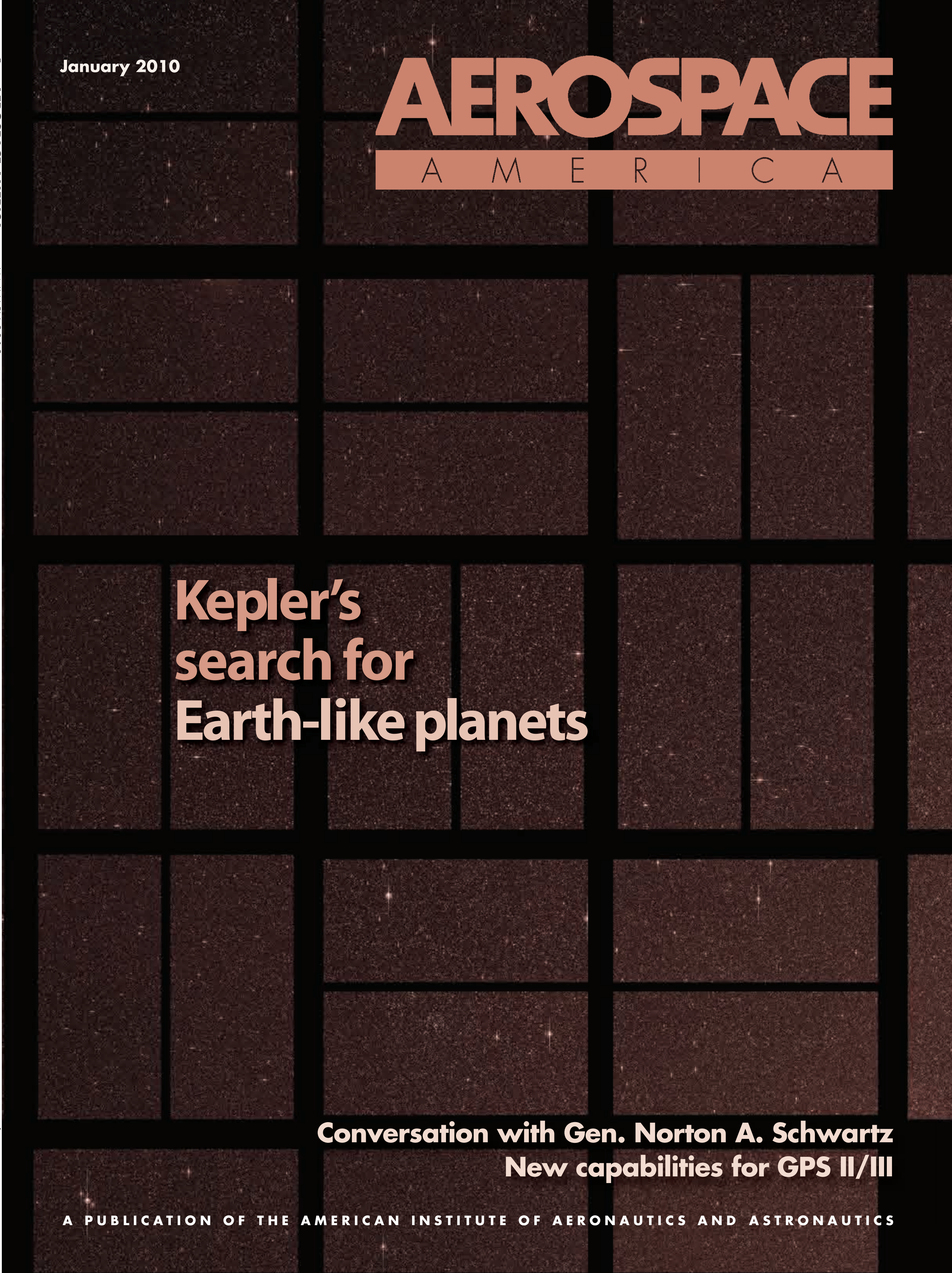

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Kepler's search for Earth-like planets

Conversation with Gen. Norton A. Schwartz

New capabilities for GPS II/III

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Kepler's search for Earth-like planets

NASA's Kepler spacecraft, which is seeking Earth-like planets orbiting stars in the Milky Way, began as an unlikely candidate for success. But unusual persistence by the project's principal investigator has paid off, and the spacecraft has already proven its capability with its first successful detection of such a planet.

by Leonard David
Contributing writer

Now far from Earth in a heliocentric orbit is NASA's Kepler spacecraft. This sharp-eyed probe is designed to spot Earth-size planets in or near the habitable zone of their parent stars. A planet residing in that not-too-cold, not-too-hot precinct is a world on which liquid water could exist. And where there is water, so too might there be life.

As NASA's first mission capable of finding such planets, the census-taking Kepler rocketed into space atop a Delta 2 booster on March 6 from Cape Canaveral AFS, Fla.

But Kepler is not just a success story. It is also a tale of cost overruns, near-cancellation, squabbles over its technological readiness, and a heavy dose of sheer persistence. Call it the little spacecraft that could…and is.

Staring contest

It is no easy assignment taking on the centuries-old aspiration to discern other worlds similar to our own. Thanks to ground- and space-based observations, hundreds of planets orbiting other stars have already been discovered. At present there is clear evidence for three types of exoplanets: gas giants, hot super-Earths in short-period orbits, and ice giants. But Kepler's task is to detect terrestrial planets ranging from one-half to twice the size of Earth. The spacecraft will gaze at a patch of space for indications of Earth-size planets moving around stars similar to our Sun. The search space contains some 100,000 such stars. Kepler is specifically designed to survey our region of the Milky Way galaxy.

"If Kepler got into a staring contest, it would win," says James Fanson, Kepler project manager at NASA's JPL in Pasadena, Calif. "The spacecraft is ready to stare intently at the same stars for several years so that it can precisely measure the slightest changes in their brightness caused by planets."

Making use of a 0.95-m-diam. telescope and an array of 42 charge-coupled devices, Kepler serves as a very fancy light meter, or photometer. From its orbit, the craft can measure brightness changes in a parent star as a planet transits across its face. From that light fluctuation in starlight—and time between transits—scientists can deduce the size of the planet, even the size of its orbit, and make a ballpark estimate of the planet's temperature.

Kepler is in a sense a finder-scope, locating candidate planets that can then become the target for Earth-based observations to rule out false-positive detections.

Building Kepler has meant tackling a suite of key requirements: pointing accuracy, a very large field of view, and low-noise electronics to maximize the ability to read data from the sensitive detection system.

Ball Aerospace & Technologies developed the Kepler flight system and supports mission operations. And while Kepler almost did not have its day in the Sun, the spacecraft has already displayed its brilliance.

First find

In an August 6 NASA science briefing, Kepler officials joyously announced that the exoplanet-hunting spacecraft had detected the atmosphere of a known giant gas planet, demonstrating the telescope's skill in meeting its scientific objectives.

Kepler's observations were collected from a planet called HAT-P-7, known to transit a star located about 1,000 light-years from Earth. The planet orbits the star in just 2.2 days and is 26 times closer to it than Earth is to our Sun. Because of this proximity, and because its mass is slightly greater than the largest planet in Earth's solar system, HAT-P-7 is classified as a "hot Jupiter," with temperatures as high as the glowing red heating element on a stove.

"We are seeing a new discovery…the first time anyone has ever seen light from this planet. And we can use that light to understand the physics of its atmosphere," notes William Borucki, Kepler science principal investigator at NASA Ames. For 17 years he has worked to prove that Kepler is a workable proposition.

Borucki says Kepler's quest to determine the distribution of Earth-size planets is just a step, with more strides to follow, "in our exploration of the galaxy, to find out if there is other life out there."

Sara Seager, professor of planetary science and physics at MIT, was equally delighted. "This data today is just the tip of the iceberg…where discoveries will come much more rapidly than they have in the last 10 years," she said, also noting that exoplanet detection over that period has already been fast paced.

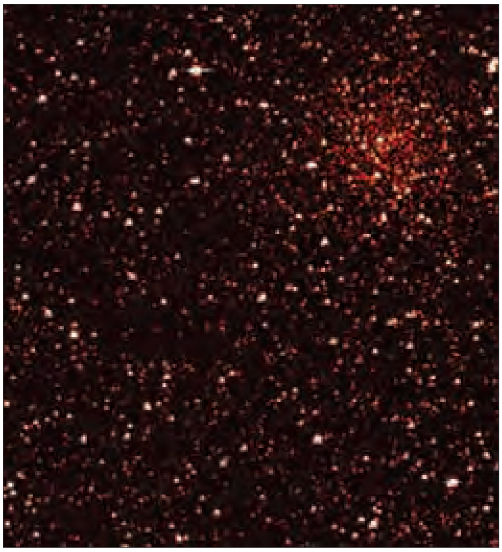
Taking part in the NASA science press conference, Alan Boss, an astrophysicist in the Dept. of Terrestrial Magnetism at the Carnegie Institution in Washington, D.C., gave kudos to Kepler. "We know now that Kepler can do it," Boss reported. "The question that remains is how many Earths are actually out there for Kepler to find? But the bottom line, the real headline for this whole press conference, is that Kepler works," he stated.

"The discovery of the optical light from HAT-P-7 proves that Kepler can find the transit of Earth-like planets. Now we have to wait for Kepler to do its job," Boss said.

Light curves over time

Kepler is a NASA Discovery mission costing $590 million. Overall, the spacecraft and its built-in photometer are about 2.7 m in diameter, and the craft measures some 4.5 m high—about as big as some shuttle buses. Its primary

The center of Kepler's photometer features a focal plane array of 42 CCDs. See a NASA animation of the optical path for the photometer at http://www.aerospaceamerica.org



This image zooms into a small portion of Kepler's full field of view—an expansive patch of sky in our Milky Way galaxy. An eight-billion-year-old cluster of stars 13,000 light-years from Earth can be seen in the image.

mirror is 1.4 m in diameter, and the spacecraft tips the scale at roughly 2,320 lb.

Kepler's Scientific Operations Center and project management (operations) are located at NASA Ames. Project management (development) is handled at JPL. The spacecraft's Mission Operations Center is in Boulder, in the Laboratory for Atmospheric and Space Physics (LASP) at the University of Colorado.

A Data Management Center for Kepler is situated at the Space Telescope Science Institute in Baltimore, with NASA's Deep Space Network maintaining spacecraft telemetry. Flight segment design and fabrication were carried out at Ball Aerospace & Technologies.

"Kepler is being nice and boring right now," according to John Troeltzsch, Kepler mission program manager at Ball Aerospace. "We're up there taking the data, storing it…doing our mission. The whole vehicle is very healthy. We have good signal margin," he told *Aerospace America* in an August interview.

Over its 3.5-year mission, Kepler will seek planets 30-600 times less massive than Jupiter. Given that Earth-size worlds do indeed exist around stars like our Sun, Kepler is expected to be the first to find them, and the first to quantify their distribution. Mission lifetime can be extended to at least six years.

While there are no Hubble Space Telescope-like images flooding out of Kepler, its very large field of view—105 deg^2—allows it to be perfectly optimized for gleaning light curves over time, Troeltzsch says.

The spacecraft rolls every 30 days to align a fixed high-gain antenna to download that month's gathering of readings to the Deep Space Network. Kepler also carries out a 90-deg roll every 90 days to keep its solar panels always pointed at the Sun. It is the first operational Ka-band mission to pipe its science data down to Earth once a month. X-band is used for uplink and downlink communications. X-band contact is twice a week, for commanding and also for checking out the health and status of the probe.

"Talking to and from the vehicle is working very well right now," Troeltzsch notes. "Our solid-state recorder is healthy. All the capacity is there, and our compression ratio, which is something that we couldn't fully test before launch, looks good. As for our solar panels…again, our margins are excellent."

The spacecraft provides the power, pointing, and telemetry for the photometer. Pointing at a single group of stars for the entire mission greatly increases the photometric stability and simplifies the spacecraft design. Other than Kepler's small reaction wheels, used to maintain the pointing, and a now-ejected dust cover on the telescope's front end, along with three focus mechanisms for the primary mirror, there are no other moving or deployable parts. The only liquid is a small amount for the thrusters, kept from sloshing by a pressurized membrane. This design enhances the pointing stability and the overall reliability of the spacecraft.

Safing events and science creep

Kepler's photometer, its sole instrument, has a field of view 33,000 times greater than that

Noise in the system

Kepler engineers have encountered one glitch that has slowed the process of spotting Earth-size worlds.

Data from three of Kepler's array of 42 light-sensing detectors is subject to systematic noise. That noise is large enough to swamp out the ability of those detectors to identify tiny changes in light—central to spotting the minute Earth-size planet signal that they are looking for, says John Troeltzsch, Kepler mission program manager at Ball Aerospace.

The problem is not unique to Kepler. Every instrument that NASA has ever flown has its own unique characteristics. However, be it image artifacts or noise, calibration software on the ground can be rejiggered and refined to special process those effects.

Troeltzsch emphasizes that "Kepler is producing great data. It has demonstrated its capability to find Earth-size planets." Scientists at NASA Ames are developing new algorithms or adjusting existing algorithms to exploit Kepler's stream of planet-searching data, he says.

"The final release of software for the science pipeline is going to be in 2011," Troeltzsch tells Aerospace America. *"It's a little later based on what we've learned on-orbit …than what we predicted prelaunch."*

Those ground fixes will be in place in plenty of time to process Kepler data to confirm detection, if they are there to be spotted, of Earth-size worlds. Meanwhile, the spacecraft continues to churn out a mother-lode of exoplanet information, Troeltzsch suggests.

A wealth of information regarding larger-than Earth-size planets that Kepler has found is to be released this month at the annual meeting of the American Astronomical Society in Washington, D.C.

Troeltzsch reemphasizes that "Kepler is doing fine. We have software that we have to update for the ground to handle things that we have learned on orbit." The bottom line, he concludes: "Kepler is an amazing facility for finding exoplanets."

of the Hubble telescope. At its center the photometer features a focal plane array of 42 CCDs with more than 95 million pixels, the largest camera NASA has ever flown in space.

To detect an Earth-size planet, the photometer must be able to sense a drop in brightness of only 1/100 of a percent—analogous to sensing the drop in intensity of an automobile headlight when a fruit fly flutters in front of it.

"The one area where we had the most risk was in the camera, and it's working well. The CCDs are stable, the electronic temperatures are stable," says Troeltzsch. "Our overall noise number, which is really our sensitivity to finding planets, is coming in really nicely. We had our requirements. We had our goals. And we're inside of those. Not every CCD behaves exactly the same. There are a couple of them that are outside the specification, but that was to be expected. The distribution is nice."

But Kepler's commissioning has not all been smooth sailing. There have been hiccups. Spacecraft operators are looking into two safing events, apparently prompted by resets of the RAD750 main processor. The team is working to isolate the root cause of the events, "looking at observables, looking at the facts, and looking at our assumptions," says Troeltzsch. This process has led them to use a cause-and-effect tool, a fishbone analysis.

All flight programs have issues that operators have to live with, Troeltzsch stresses. "If you can deal with something that's a problem by just living with it, that's a perfectly acceptable way to run the mission."

Overall, Kepler's commissioning process took 67 days, a week longer than anticipated. That extra time adds up to a bit of "science creep"—with scientists asking for an even tighter pointing of the spacecraft, beyond specifications. "What they are doing is exploiting the capabilities of the machine," Troeltzsch adds, "so we're helping them achieve better than what was required performance. We did and it worked out well."

Call it the greedy scientist philosophy, something Troeltzsch realizes up front. "This is what they do for a living. They are going to come up with all kinds of powerful ways to get better science out of the machine. The goal is to build a machine that meets requirements, has some flexibility and margin so that when you get it on orbit you can exploit it, resulting in even better data."

Lesson learned: Persistence

Kepler has taken a long and winding road to its destination in space. At one point, it was facing the ax at NASA.

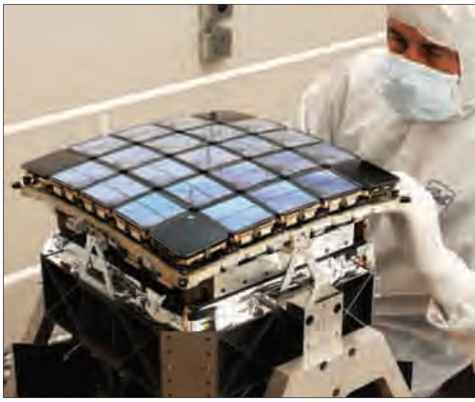
It was Borucki, Kepler's science principal investigator, who first suggested the transit technique for detecting Earth-size planets, in 1984. The lesson learned, he says after all those years, is "Be persistent. Get the data and show the data to make your case."

Kepler gained flight approval as a NASA Discovery mission in late 2001. But the price tag rose several times following its selection, with the total cost rising above $550 million. In the spring of 2007 the team asked for an extra $42 million, a request not well received by then-NASA science chief Alan Stern, who bluntly told the Kepler team to look within to keep costs down—or face termination.

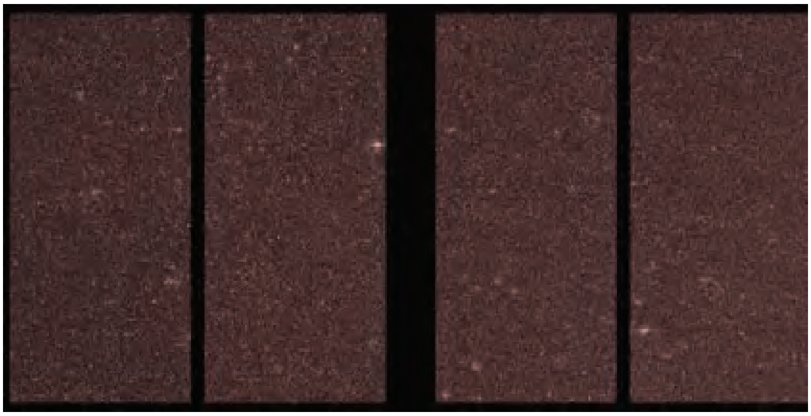
At Ball Aerospace, there was a lot of pressure, Troeltzsch remembers vividly. That Stern warning and call for replanning had a catalyzing effect, he says, and sparked a flurry of activity, including elucidation of management, accountability, roles, and lines of authority inside the company as well as with NASA's partners on the project. "Trust and accountability are two things that are just critical to success," he says, and the Kepler team had challenges in both those areas.

In the end, the team demonstrated that it could deliver, and it did.

"Kepler went from the poster child for what could go wrong in a development program to the poster child for how to turn a project around and deliver a fully working scientific mission, on cost and schedule," says Stern, now associate vice president of the Southwest Research Institute's Space Science and Engineering Division in Boulder. "From what's been released so far in flight, Kepler has all the makings of a smashing success. The mission team deserves congratulations."

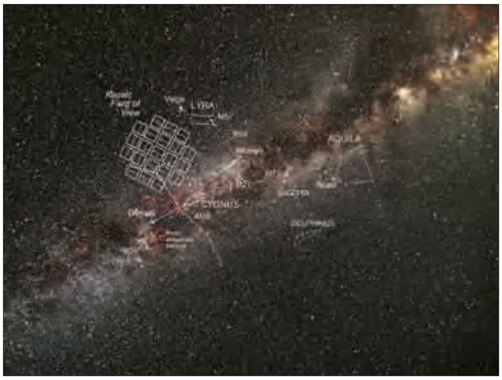


Focal plane assembly was conducted at Ball Aerospace.



Images were gathered from two CCD module pairs—Kepler first light.

Each rectangle indicates the specific region of the sky covered by each CCD element of the Kepler photometer. There are a total of 42 CCD elements in pairs, each pair comprising a square. Image by Carter Roberts.



Planetary payoff

Indeed, Kepler and tenacity go together, according to astronomer Jill Tarter, director of the SETI Institute's Center for SETI Research, in Mountain View, Calif. "If it were easy, somebody else would have done it by now," she points out.

Years ago, in workshops on detecting planets, precision requirements such as microarcseconds and millimagnitudes seemed unbelievably unattainable. However, "there were dreamers in the crowd who grew older but never stopped working on their dreams," recalls Tarter.

Early critics were justified in being skeptical about the feasibility of detecting transits of Earth-size planets—it's an extremely challenging measurement. "But perseverance, guided by a vision, can pay off," says Fanson.

Kepler was the dark horse in the race, with NASA's Space Interferometry Mission (SIM) and then the Terrestrial Planet Finder (TPF) being the odds-on favorites to be launched first, notes astrophysicist Boss.

"In the end, Kepler won the race by so many lengths that SIM and the TPFs still haven't even made it to the starting gate, much less to the finish line. The lesson is that it is not a bad idea to bet on missions with long odds. They just might win in spite of the poor odds," Boss says.

In his recent book, *The Crowded Universe: The Search for Living Planets*, Boss says that "a new space race" has begun—an international and lively competition to discover how numerous Earth-like planets are in our neighborhood of the Milky Way galaxy. That contest is being spurred by the blossoming quest to detect planets with life around other stars. The bottom line for the astrophysicist is that life is not only possible elsewhere out there…it is common.

Joining Boss in saluting Kepler and its early shakeout is James Kasting, a professor of geosciences at Pennsylvania State University: "I, like others in the exoplanet community, am absolutely thrilled by the data that we expect to get out of Kepler. So far, they've shown us enough to indicate that the telescope is working very well. The really interesting data on Earth-like planets will take awhile, perhaps two to three years, but I think it could have a big impact on getting momentum built up for more ambitious planet-finding missions like SIM and TPF."

Borucki's insistence that Kepler was doable met with repeated rejection for a decade, Kasting notes. "It is a tribute to his perseverance that he eventually pulled it off and now has the hottest thing going in all of exoplanet science," says Kasting.

Putting on his forecasting hat, Troeltzsch of Ball Aerospace looks to the year ahead:

"The only star that we've really studied intensely from this photometry point of view is our Sun—we have a sample of one. And now we've got 120,000 stars under the microscope out there. And I tell you…the Sun is not generic. I think there are going to be two really cool things that come out from Kepler. One is going to be an understanding of stars in our galaxy. The other, I think, is that we're going to find a bunch of planets."

Kepler-certified students

Kepler's on-orbit operation is conducted at the Laboratory for Atmospheric and Space Physics (LASP) at the University of Colorado in Boulder, under a $5-million contract to Ball Aerospace. The Kepler mission control activity melds the talents of professionals and students at the university and specialists from Ball Aerospace.

"Overall, it's actually working better than we expected. It has been really smooth," says Bill Possel, director of Mission Operations and Data Systems at LASP.

Working with the long-distance Kepler spacecraft, in concert with NASA Ames and the Deep Space Network, is a first for LASP. Along with Kepler, Possel explains, the LASP control center is presently flying four Earth-orbiting satellites: the Aeronomy of Ice in the Mesosphere, the Solar Radiation and Climate Experiment, ICEsat, as well as QuikSCAT. All of them need different degrees of care and maintenance, he says.

In terms of intensity, however, Kepler rates the highest. Still, spacecraft operations make use of LASP-developed software akin to that used for the other university-run satellites.

Some 27 student operators are trained on Kepler, each taking 4-hr shifts. Not only is engaging LASP a cost-reduction step in Kepler mission operations, but the hands-on learning is also a priceless, career-enhancing opportunity for students, Possel says.

"It's a win-win," says Troeltzsch of Ball Aerospace. "It gives the university a chance to participate in these big programs and a chance to have an educational experience with their students. On our side, it's a way to efficiently run a satellite for a good cost for the taxpayers."

There is an eventful future ahead for LASP. On the books is the NASA Mars Atmosphere and Volatile Evolution (MAVEN) mission, set to launch in 2013. LASP will provide science operations and data packaging. Lockheed Martin Space Systems, based in nearby Littleton, Colo., will provide the MAVEN spacecraft, as well as mission operations; JPL will navigate it. LASP is also on tap to carry out science operations duties in 2014 for a NASA Goddard project, the Magnetospheric MultiScale mission, consisting of four spacecraft flying in formation to gauge magnetospheric and solar wind interaction.

"That's 11 instruments each on four spacecraft—that's 44 instruments we'll be operating from here. So it's going to be pretty busy," Possel concludes. "LASP has been growing for the last few years, and I think we're still looking at growing more."