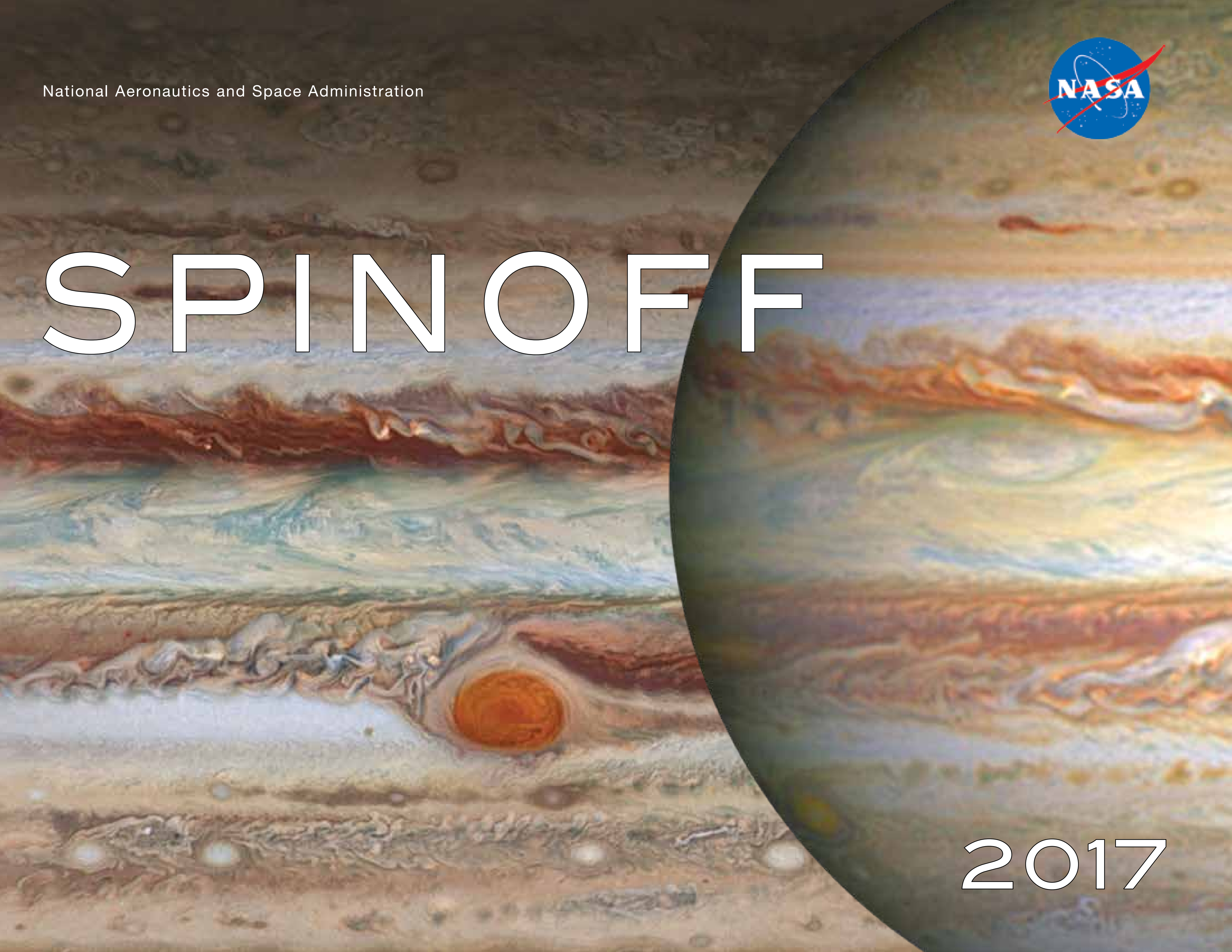
National Aeronautics and Space Administration

SPINOFF

2017



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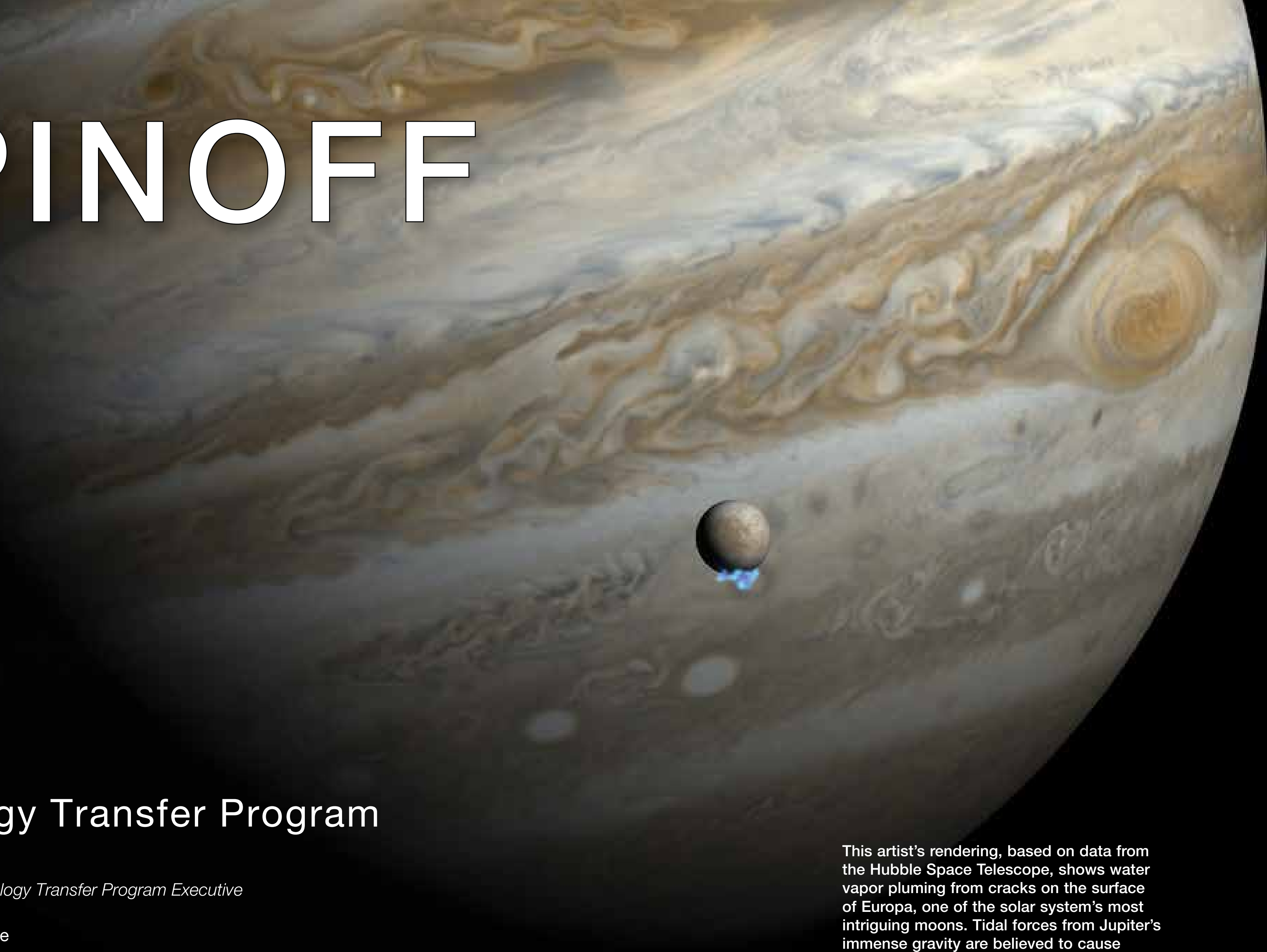

Technology Transfer Program

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This artist's rendering, based on data from the Hubble Space Telescope, shows water vapor pluming from cracks on the surface of Europa, one of the solar system's most intriguing moons. Tidal forces from Jupiter's immense gravity are believed to cause enough internal friction to heat a stable ocean of liquid water beneath the icy body's surface. The presence of this ocean has led scientists to speculate that Europa may even host life, and a future NASA mission is being planned that would conduct 45 flybys of the moon to gather detailed observations of its habitability.

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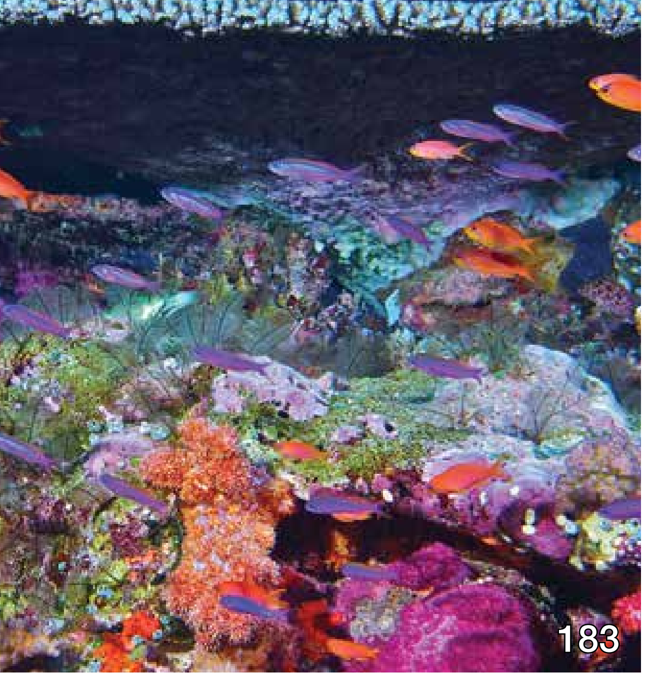

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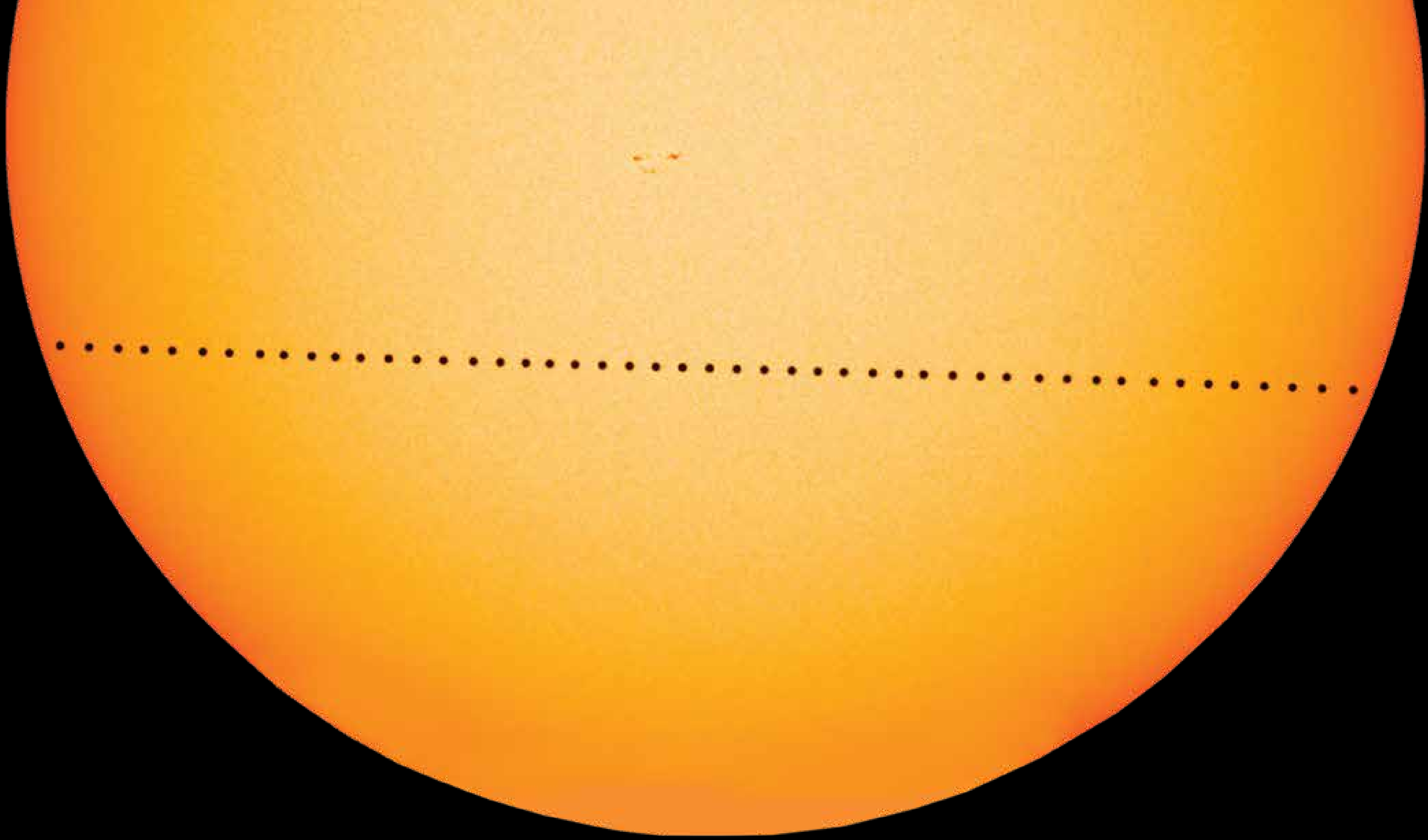


DISCLAIMER: While NASA does not manufacture, market, or sell commercial products, many commercial products are derived from NASA technology. Many NASA-originated technologies are adapted by private industry for use by consumers like you. Spinoff developments highlighted in this publication are based on information provided by individual and private industry users of NASA-originated aerospace technology who acknowledge that such technology contributed wholly or in part to development of the product or process described. NASA cannot accept responsibility or liability for the misinterpretation or misrepresentation of the enclosed information provided by these third-party users. Publication herein does not constitute NASA endorsement of the product or process, nor confirmation of manufacturers' performance claims related to any particular spinoff development.

On May 9, 2016, Mercury passed directly between the sun and Earth. NASA's Solar Dynamics Observatory studies the sun 24/7 and captured the entire seven-and-a-half-hour event, and its data was used to create this composite image. Amazingly, exoplanets near the size of Mercury have been discovered orbiting distant stars simply by measuring the amount of light the planets block as they pass between their star and our vantage point.

Foreword

When NASA sets out on a new mission to explore the cosmos, we know the results will often surprise and astonish us. Our most recent far-reaching achievement came with the arrival of the Juno spacecraft at Jupiter this past Fourth of July. The mission promises to give us unprecedented insights into the makeup of the colorful gas giant, as well as clues about how our solar system formed. And it will likely yield technology that improves life on Earth, too (see page 8).

Juno is the latest among a host of probes, landers, rovers, and telescopes that have played a key role in NASA's endeavors to extend humanity's reach into the universe. In just the past several years, using these instruments, we have excavated Martian soil, skimmed through water plumes over Enceladus' fractured surface, discovered more than a thousand planets orbiting other stars, mapped icy mountain ranges on Pluto, and so much more. Each new accomplishment answers fundamental questions of science, capturing the world's imagination and demonstrating the importance of expanding the horizons of our knowledge.

We go to space to explore, and the ultimate achievement in exploration is human missions to new frontiers. In particular, NASA is on a journey to Mars—a journey that will stretch the capabilities and resolve of our Nation. To prepare for the trip, much of the cutting-edge technology being developed by NASA right now is designed to help us put astronauts on the surface of the Red Planet in the 2030s. As we develop these technologies, NASA collaborates with American businesses to do its work. Every dollar spent on technology for space missions is a dollar spent on Earth, benefiting the economy.

But the Agency also makes sure these innovations go beyond their original uses to benefit the public as widely as possible. These secondary applications can be as surprising as the scientific discoveries made by our spacecraft: as you'll see in the following pages, NASA technologies can be found in your mobile devices, in self-driving tractors that work the fields, and in the latest 3D printers used by makers and hackers. They are making brain surgery safer and spotting rainforest fires before they spread. Spinoffs are even more diverse than the broad array of NASA missions they come from.

This issue of *Spinoff* celebrates our Nation's successes with robotics missions and looks to a future of human spaceflight and planetary exploration enabled by cutting-edge technology—with ever more down-to-Earth benefits sure to follow. I hope it opens your imagination to what's possible, both in space and on Earth, when we set our sights on venturing into the unknown.

Charles F. Bolden, Jr.
Administrator

National Aeronautics and Space Administration

Spinoff (spin´ôf) -noun.

1. A commercialized product incorporating NASA technology or expertise that benefits the public. These include products or processes that:
    - were designed for NASA use, to NASA specifications, and then commercialized;
    - are developed as a result of a NASA-funded agreement or know-how gained during collaboration with NASA;
    - are developed through Small Business Innovation Research or Small Business Technology Transfer contracts with NASA;
    - incorporate NASA technology in their manufacturing process;
    - receive significant contributions in design or testing from NASA laboratory personnel or facilities;
    - are successful entrepreneurial endeavors by ex-NASA employees whose technical expertise was developed while employed by the Agency;
    - are commercialized as a result of a NASA patent license or waiver;
    - are developed using data or software made available by NASA.
2. NASA’s premier annual publication, featuring successfully commercialized NASA technologies.

A prototype 13-kilowatt Hall thruster is tested at NASA's Glenn Research Center in Cleveland. This prototype demonstrated the technology readiness needed for industry to continue developing high-power solar electric propulsion into a flight-qualified system.

Introduction

For more than 40 years, NASA's *Spinoff* publication has demonstrated that there's more space in your life than you think, featuring more than 2,000 technologies with origins in space and aeronautics missions that have subsequently benefited our Nation and world.

The stories published in *Spinoff* represent the end of a technology transfer pipeline that begins when researchers and engineers at NASA develop innovations to meet mission needs. NASA employees report more than 1,600 new inventions annually, from hardware to cutting-edge software, and these technologies are captured and assessed by the Agency's Technology Transfer Program. Most are published to notify the public of NASA's work and to encourage public-private partnerships with industry where interests overlap. The Agency patents its inventions with the greatest commercial potential and offers these to American businesses for licensing. Meanwhile, NASA-created software is collected and annually published in a catalog, nearly all of it free to download and use.

In the following pages you can read about 50 NASA *spinoffs*, products and services at work in every sector of the economy. Notable examples include:

- The world's most widely used digital image sensor. The invention traces back to a scientist at NASA who wanted to miniaturize cameras for interplanetary missions. Today, whether you take pictures and videos with a DSLR camera or cell phone, or even capture action on the go with a device like a GoPro Hero, you're using NASA technology. (page 86)
- Self-driving tractors. Beginning in the 1990s, NASA researchers developed software capable of correcting for GPS signal errors, enabling accuracy to within inches. John Deere acquired the technology and used it to develop the world's first widely used self-driving farm equipment. Today, as much as 70 percent of North American farmland is cultivated by self-driving tractors, most of which still rely on technology originally developed at NASA. (page 110)
- Space-ready lidars used by archaeologists. An instrument that discovered snow on Mars has a direct connection to the commercial lidar that helped search for sites where prehistoric North Americans hunted bison herds en masse. (page 136)

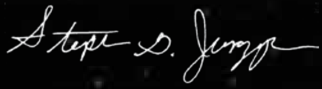
Alongside these mature, fully commercial products, you can also find 20 patented NASA inventions that the Technology Transfer Program has identified as being particularly ripe for use by industry, along with information on how you can acquire these technologies or partner with us to develop them further. (page 206)

Part of NASA's mission, written into the Agency's foundational legislation, is a requirement to "provide for the widest practicable and appropriate dissemination" of the fruits of its scientific and technological discoveries. *Spinoff* 2017 shows that this spirit is alive and well at NASA, and we hope that you enjoy reading about the many ways space exploration yields practical benefits for all of us on Earth.

Stephen Jurczyk

Associate Administrator

Space Technology
Mission Directorate



Executive Summary

Each year, *Spinoff* features dozens of commercial products derived from NASA technology that benefit everything from medical care and software to agricultural production and vehicle efficiency. The companies featured in this year's publication span a broad range of industries and geographic locations, showing the diverse benefits our Nation enjoys from its investment in aeronautics and space missions.

Active Pixel Sensors Lead Dental Imagery into the Digital Age

NASA Technology

They're in your cell phone camera and probably in your handheld digital camera, but they may have been in your dentist's X-ray machine first: image sensors based on CMOS technology. And they got their start at NASA.

NASA has an interest in capturing all sorts of images, in the visible spectrum and beyond. One of the pursuits the Agency is most famous for is transmitting spectacular vistas of other worlds, distant galaxies, and our home planet. Aside from providing windows into the cosmos, these images have significant scientific value, as they can be analyzed, for example, to determine the composition and temperatures of the objects they depict.

NASA spent much of the 1980s developing image sensors based on charge coupled device (CCD) technology, which had enabled the first digital cameras. But in the early 1990s, under a new administrator, NASA adopted a "faster, better, cheaper" approach, and engineer Eric Fossum, who had recently joined the Agency's Jet Propulsion Laboratory (JPL), had an idea that might achieve that goal for spaceborne imagers.

CCD-based pixel arrays operate like a bucket brigade, with the light-generated charge from each pixel passing along the entire array of pixels to the corner of the chip, where it is amplified and recorded. Fossum thought such imagers might be supplanted by CMOS—or complementary metal oxide semiconductor—technology, which consists of microelectronic transistors that have been integral to computer circuitry since the 1960s. Being amplifiers in and of themselves, photosensitive CMOS pixels in an array could each amplify their own signals. The concept had been explored before and discarded, but technology had advanced considerably in the ensuing decades.

The use of CMOS imagers in dental X-ray devices reduces susceptibility to electrical noise and gives dentists images they can manipulate to make more accurate diagnoses.

In Fossum's innovation, pixels also contained a mini-CCD to transfer charges internally, as well as an amplifier that reduced readout noise compared to the earlier CMOS image sensors. By using well-established CMOS manufacturing processes to make an array of photodetectors, Fossum and his team were able to integrate almost all the other camera electronics, such as timing and control systems, an analog-to-digital converter, and signal processors, onto a single chip. The "camera on a chip" was born, and it would enable much smaller, more efficient imaging devices (*Spinoff* 1999, 2002, 2010; see also page 86).

The term active pixel sensor (APS) entered the popular lexicon. "Active pixel means the pixel's got an active transistor in it, an amplifier," says Fossum.

But the budding technology required a lot of development, and it was not immediately embraced. "Displacing an incumbent technology is always a big challenge," Fossum says. "The new technology must have compelling advantages."

Technology Transfer

In the interest of advancing and commercializing CMOS-APS, JPL entered into several Technology Cooperation Agreements (TCA) with industry partners during the early 1990s. No funds were exchanged under these agreements, but JPL and partners shared resources, expertise, and equipment, working together to advance and apply the new camera-on-a-chip technology.

Major players, including Kodak and AT&T Bell Labs, established such agreements with JPL and explored commercial uses for CMOS-APS, but many of these early efforts stalled for lack of corporate follow-through. In the end, perhaps the most significant TCA began when David Schick of Schick Technologies, then a three-person outfit in Long Island City, New York, contacted Fossum in 1994.

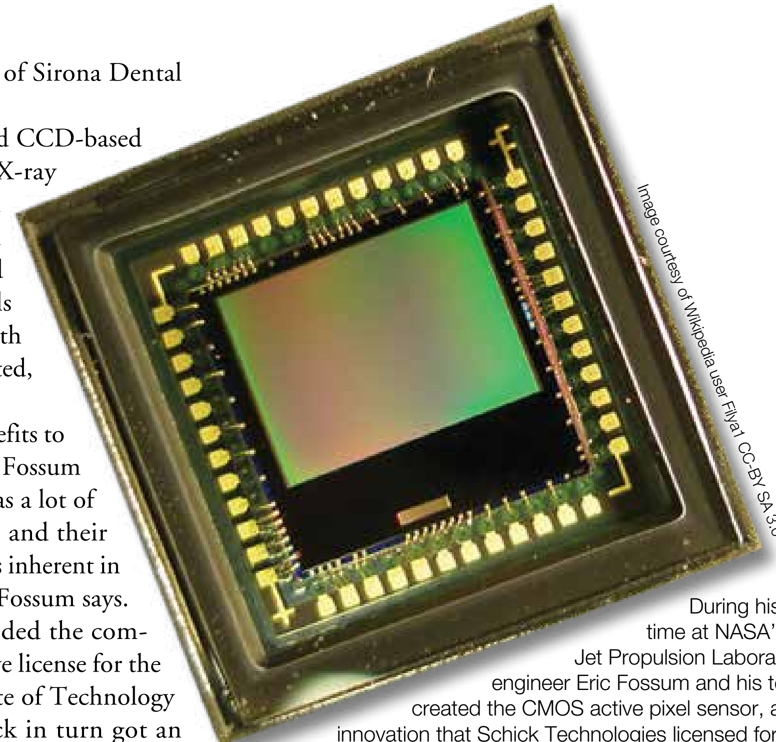
"I was trying to tell him it was still an early technology. I couldn't make small pixels," Fossum recalls. "He didn't care."

"As a dental device manufacturer, we were looking at next-generation technology specific to dental imagery, and specifically, radiology," says Stan Mandelkern, vice president of engineering at the original New York headquarters for Schick, which became a subsidiary of Sirona Dental Systems in 2006.

The company had already developed CCD-based digital imagers to replace traditional X-ray film. Their higher sensitivity allowed for a lower dose of radiation, and, with no need to develop film, turnaround was much quicker. The toxic chemicals and handling precautions associated with film development had also been eliminated, Mandelkern says.

But the company saw additional benefits to CMOS sensors and began working with Fossum and his team to realize them. "There was a lot of back-and-forth between our designers and their engineers" to work out the idiosyncrasies inherent in adapting the technology for X-ray use, Fossum says.

After he and a few colleagues founded the company Photobit in 1995, with an exclusive license for the technology from the California Institute of Technology (Caltech), which manages JPL, Schick in turn got an exclusive sublicense from Photobit and began producing CMOS-based dental imagers. Later, when Fossum sold his company, Schick obtained an exclusive license from Caltech for the use of CMOS-APS technology for dental imagery. It's a license the company holds to this day and one that has paid off handsomely, for both Caltech and Sirona.



During his time at NASA's Jet Propulsion Laboratory, engineer Eric Fossum and his team created the CMOS active pixel sensor, an innovation that Schick Technologies licensed for dental imagery when it was young. CMOS imagers have since taken over the digital imaging industry.

Benefits

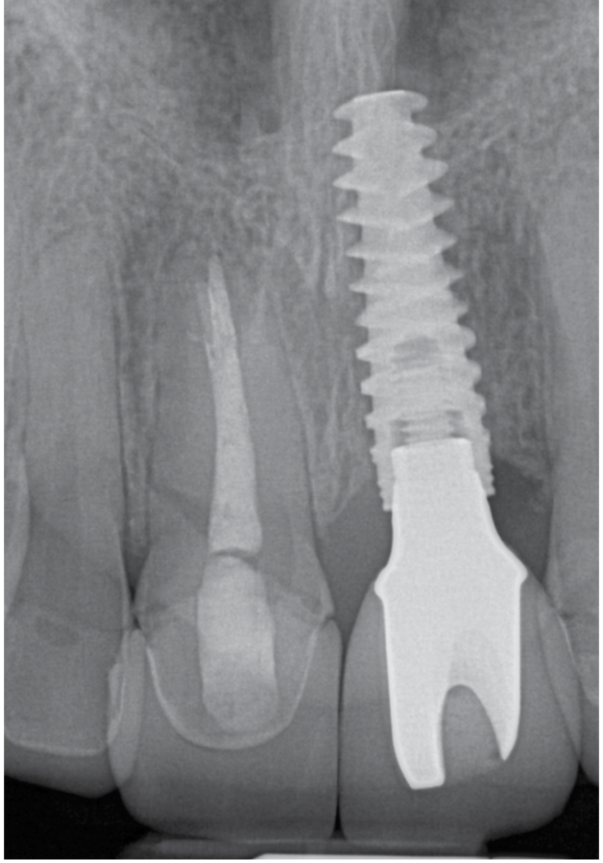
X-rays can't be focused with lenses, so the array of pixels in a digital X-ray imager has to be the size of the object being observed, says Mandelkern. That means a lot of pixels. A CCD-based array has to transfer each pixel's charge from pixel to pixel through the array with virtually no losses and requires a relatively high voltage. The more pixels, the greater the overall potential for loss. "If you lose even a small fraction of the charge as it's moving through the array, you really have almost no charge output at the end," he says. "Our array was really pushing that parameter with CCDs."

CMOS pixel arrays, able to convert each pixel's charge to a digital output, proved more efficient, which was important for devices the company wanted to power with batteries, says Mandelkern.

Since most of the camera electronics could be integrated onto the CMOS sensor chip, devices could be smaller, which, in the case of intraoral X-ray sensors that go inside the mouth, translated directly to patient comfort, he adds. And, he says, a CCD system was more susceptible to electrical noise than a CMOS imager, where the signal is processed directly on the chip. "If you can keep everything on one piece of silicon, you get higher signal integrity at lower power and lower cost."

CMOS imagers also give the radiologist the ability to get a low-resolution preview or check for exposure using a quick readout from a few pixels using minimal energy, whereas a CCD-based imager would have to read out the entire array, he says.

For a long time, CCD technology retained an advantage in panoramic imaging—say, of a full jaw—by using



An X-ray by one of Sirona's CMOS-based digital X-ray devices shows a tooth implant. Through Schick Technologies, which it acquired in 2006, the company holds an exclusive license for use of the NASA-invented technology for dental imagery.

a technique called time delay integration to create a single image from multiple frames, Mandelkern says. With the advent of fast frame-readout CMOS imagers, though, that integration can now be carried out by software in post-processing, he says.

In recent years, as CMOS sensors have been adopted across the imaging industry, intense research and development have led to rapid improvements in their size, speed, memory, and quality. Cell phone cameras in particular have driven the advancement and cheap mass-production of CMOS-APS sensors.

"We were able to take advantage of that and leverage that for our product line as well," Mandelkern says. "We're benefiting from the same processes and improvements the rest of the electronics world has benefited from."

> "If you look at what we're able to do today, there's a level of sophistication made possible that translates directly to better diagnosis and treatment for the patient."
>
> — Stan Mandelkern, Schick

For the patient, advanced digital dental imaging means lower exposure to potentially harmful X-rays, and it gives dentists images they can manipulate to make more accurate diagnoses, as well as communicate problems to the patient visually, Mandelkern says. "If you look at what we're able to do today, there's a level of sophistication made possible that translates directly to better diagnosis and treatment for the patient."

The company's latest development in CMOS is three-dimensional imaging that's being pioneered at Sirona's German location, he says. "We continue to use CMOS as the starting point for our imaging products."

Although Sirona still holds an exclusive license to use CMOS-APS technology for dental imaging, "other companies can sublicense to be able to use the technology," Mandelkern says. "Today, a lot of companies that compete with us sublicense the technology from us."

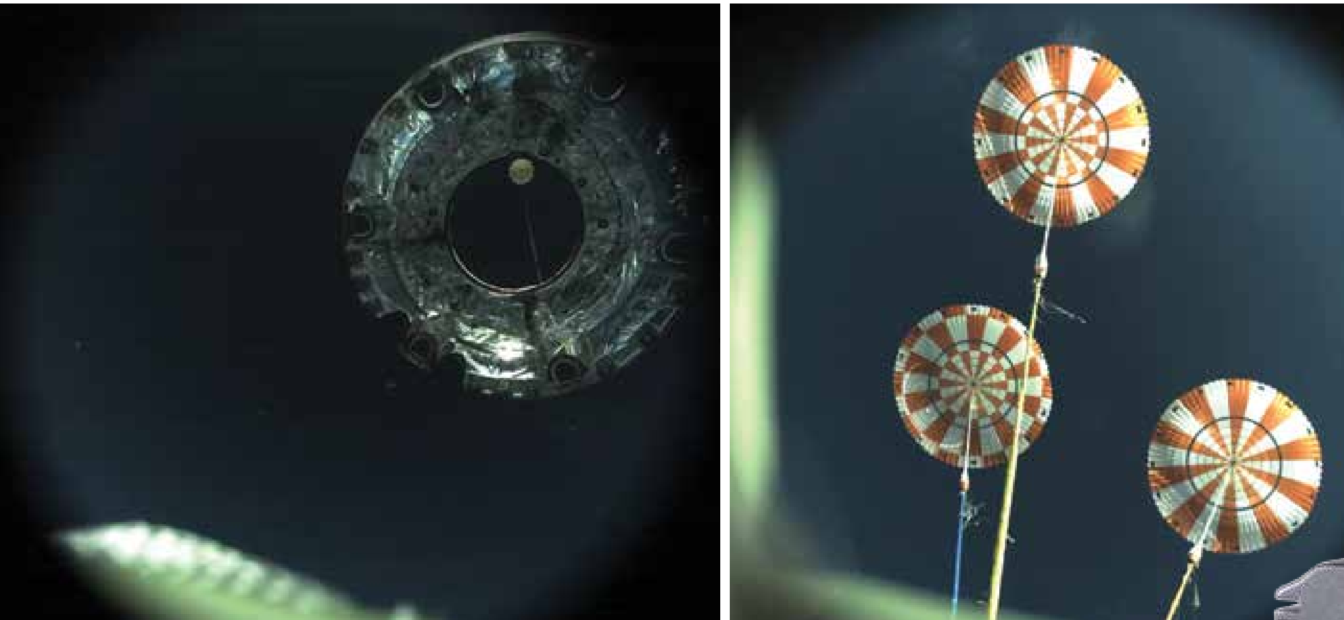
Mandelkern says this success was anything but predictable in the early days of the fledgling company's NASA partnership. "In 1997, looking at this technology at all was very risky and required a higher level of technical awareness than other companies in our industry were able to compete with us on," he says. "That's what our company has always stressed—innovation and keeping an eye on what's happening in technology and how we can leverage that in our product line."

Fossum credits JPL's cooperative agreements with companies like Schick for turning his experimental technology into successful products. "That program was critical for getting Schick going and for getting us going." ❖

Basing its dental X-ray devices on CMOS image sensors has allowed Schick and parent company Sirona to make the devices smaller and more energy-efficient, which is important for battery-operated technology.

Schick's dental imagers have benefited not only from the initial enhanced capabilities of NASA-invented CMOS image sensors but also from the rapid improvements and lower costs that have come with the technology's explosion across the digital imaging industry.

Orion Video Requirement Advances High-Speed, Compact Cameras



Integrated Design Tools (IDT) built a compact, rugged camera with an unprecedented rate of memory storage to record parachute deployment during the Orion spacecraft's flight test in high-speed, high-resolution video. To capture the left image, showing the capsule's forward bay cover immediately after it was ejected, the camera had to adjust from total darkness to broad daylight within a few milliseconds. By the end of the deployment, the capsule's three main parachutes had released perfectly to deliver the craft safely to splashdown, with the process captured on film at rates up to 1,000 frames per second.

NASA Technology

Parachute deployment is usually a fairly simple—if crucial—operation. A small pilot parachute tossed into the wind might pull free a pin securing the main parachute container and then drag the larger chute out and into the airstream, where its lines release and it fills with air.

Little in spaceflight, though, is simple.

As the Orion spacecraft careened sidelong back to Earth during its first test flight in December 2014, a precisely coordinated series of events had to go off just as planned to slow the 21,000-pound vehicle from speeds around 350 mph at an altitude of 23,000 feet to just 20 mph by the time it plunked down into the Pacific Ocean four and a half minutes later.

After a set of parachutes and pyrotechnic piston thrusters removed the cover of the capsule's forward bay, mortars inside the bay fired a pair of drogue parachutes to slow and stabilize the craft's fall before they were cut loose to make way for the three 116-foot-wide main parachutes to be pulled free by pilot parachutes. The main chutes even filled in synchronized stages, as circles of line, called reefs, that held them partially closed were cut.

Everything went off without a hitch. We know this because the deployment also awakened a high-speed, high-resolution video camera within the forward bay that was custom-made to capture the entire sequence at speeds up to 1,000 frames per second. After all, if there was a snag, engineers needed to know precisely what went wrong and when.

In spaceflight, cameras aren't simple either. Not only did the engineers at Johnson Space Center and Lockheed Martin, who were designing and building the capsule, want a camera with higher-speed memory storage than any in existence at the time, but the device would also have to meet a host of other requirements.

"A camera with additional memory, controls, and environmental ruggedness, built in a sealed container that would

The Os V3 video camera takes advantage of some of the advances in high-speed, solid-state memory storage, as well as compactness and sturdiness, that the company had to make to meet the requirements for filming parachute deployment during the Orion spacecraft's first test flight.

“It's like having highways of **data with** very **wide lanes.”**

— Luiz Lourenco, Integrated Design Tools

One application for IDT’s highest-speed cameras is in automobile crash testing, where every millisecond must be immediately and permanently stored. The company’s cameras can be seen here mounted on both the car and the crash-test device.

withstand both the space vacuum and water immersion after landing, was required," says Vic Studer, video systems lead at Johnson. "The device also needed to be very small and lightweight and run on low power. No camera existed that could meet all these requirements."

Some came close, though. A company called Integrated Design Tools (IDT), located in Pasadena, California, specializes in cameras mainly aimed at the industrial and scientific markets, for uses like crash testing, which also requires rugged, high-speed cameras.

Technology Transfer

NASA and Lockheed Martin approached IDT with a request for a camera that would meet their stringent set of requirements.

"We had to come up with an elegant solution that was also cost-effective enough for the Government to accept it," says Luiz Lourenco, CEO of IDT, which ended up providing several cameras for the project through a subcontract with Lockheed Martin. "Our pride is that we were able to do it with very limited resources."

Most high-speed cameras are "what we call bricks," Lourenco says, meaning they're large and heavy, which runs counter to any space mission. Every pound it launches into space costs NASA about $10,000, and room aboard a capsule is extremely tight. So the company created an ultra-compact camera that fits in the palm of a hand.

The device had to survive not only the violence of liftoff and the saltwater of splashdown but also the radiation beyond Earth's protective atmosphere. There, radiation threatens what Lourenco calls "the soul of the electronics"—the memory chips and software, the computation model that will execute a series of commands, adjusting them according to feedback loops.

Such a sequence of commands might mean waking up and beginning to record at 1,000 frames per second, then slowing to 60 and speeding back up to 500 as events unfold, Lourenco explains. To preprogram this sequence of recordings, the company created what it calls "mission mode." The parameters—such as frame rates, durations, and shutter speeds—for up to 64 recording events are entered into an Excel spreadsheet, which is loaded into the camera to program a series of separate video shoots or a continuous recording at different speeds.

> "Some of this know-how already existed, but then you have to adapt it to these very stringent requirements. It's not a moneymaker, but it's a very good test bed for technology we want to incorporate into our products."
>
> — Luiz Lourenco, Integrated Design Tools

The camera also must automatically adjust for light exposure with each image it captures, even at hundreds of images per second.

The biggest challenge, though, was enabling the camera's computer to back up the data nearly as fast as it acquired it, storing each frame as it was recorded. Most high-speed imaging technology saves video to what's known as volatile memory, which loses all stored data when the power is cut. This would mean that if the camera aboard Orion experienced a broken cable or other glitch, all the parachute data from a very costly test run would be lost. The camera also needed all the video backed up before switching off for splashdown.

To permanently store hundreds of frames per second, the camera had to be able to transfer 10 to 12 gigabits per second to a hard drive, Lourenco says. "It's like having highways of data with very wide lanes."

Ken Barkman, the Lockheed Martin Communications and Tracking camera lead for Orion at NASA's Michoud Assembly Facility, says the camera lived up to expectations. One of the biggest challenges, he says, was capturing the forward bay cover as it was ejected from the capsule, letting light into the bay. "At 500 frames per second, the exposure algorithm adjusted the camera to the abrupt change in lighting from complete darkness to daylight within a few milliseconds," he says, adding that the high-speed "mortar events" that launched the drogue and pilot parachutes were also captured with high fidelity, as was the main parachute deployment at 400 frames per second.

"All of this video provided excellent support for the imagery analysis demonstrating that the features of the Orion vehicle performed as designed," says Ben Sellari, of Johnson's Vehicle Integration Office, who determined the initial requirements for image capture.

Benefits

"Some of this know-how already existed, but then you have to adapt it to these very stringent requirements," Lourenco says. "It's not a moneymaker, but it's a very good test bed for technology we want to incorporate into our products."

Some of these improvements have already been incorporated into IDT's product line. All of the Os series of cameras, in which the O stands for Orion, include the high-speed, solid-state memory the company developed for Orion.

In automobile testing—one of IDT's specialties—a car is typically outfitted with 8 to 16 cameras, and after a test, data is downloaded from each camera, one by one, explains Rick Sutherland, sales manager for IDT. "During that download, if anything happens to the camera or power source, you've lost all your data." In crash tests using members of the Os family, though, all the data from every camera is backed up within two seconds after impact.

In its testing, the Air Force films the deployment of weapons at high frame rates, and IDT's high-speed memory means planes in flight can fire test shots every two seconds or so, rather than circling and burning fuel while waiting for data to be backed up, Sutherland says, adding that the

Air Force has added a specification that these test cameras all include solid-state memory capability like IDT's.

Likewise, when broadcasters record at high frame rates for slow-motion sequences, the entire crew is left standing around while the video is stored before the next shot. "Our technology minimizes the cost of production, and they can shoot continuously," Sutherland says. He notes that the cameras also eliminate the need for a separate recorder for slow motion.

The cameras' light weight and small size are also advantages across industries. In crash testing, the vehicle has to weigh what it would on the road, so 16 heavy cameras would require other components to be removed from a vehicle. Even on a boom at a recording set, a lighter camera is easier to manage.

During recent military helicopter testing by IDT customer Boeing, Sutherland says, it was considered too dangerous for most personnel to approach the helicopter. Instead, test engineers were able to program three days' worth of recording using an Excel spreadsheet. "Even just that mission mode developed for Orion has paid off hugely," he says.

The cameras' ruggedness is another advantage that plays out across a range of applications. While it's an obvious necessity in crash testing, Sutherland says, "Even the movie guys, they're very hard on equipment. The ability to withstand a lot of G-force is an advantage to anybody."

Because the Orion camera had to survive not only splashdown but also a wide range of temperatures that can cause condensation and other problems, it also had to be completely sealed. The results are IDT cameras that can be submerged with no need for a waterproof housing, which Sutherland says has already piqued the interest of the Canadian Navy and is likely to get a lot more notice.

As more people and companies learn about the new capabilities stemming from IDT's Orion work, sales have continued to rise, he says. "The number we're selling is increasing, because we're getting them out and in front of people."

In fall of 2015, those technological advances culminated with the release of a camera that incorporates nearly all of them, the Os10 4K. ❖

The military uses IDT's high-speed cameras to film test-firing of weapons. The company's video cameras can store the massive data files immediately, eliminating down time between test shots.

Image courtesy of the U.S. Navy

Consumer Goods

You might be surprised by the number of space technologies in your home and among the products you use every day. This year's *Spinoff* shows how NASA technology can be found in your cell phone camera, golf clubs, ski goggles, and bottle of wine. Spinoffs are also improving large-scale 3D printers, enabling rechargeable hearing aid batteries, and strengthening sporting goods with nanomaterials.

CMOS Sensors Enable Phone Cameras, HD Video

NASA Technology

"People told me, 'You're an idiot to work on this,'" Eric Fossum recalls of his early experiments with what was at the time an alternate form of digital image sensor at NASA's Jet Propulsion Laboratory (JPL).

His invention of the complementary metal oxide semiconductor (CMOS) image sensor would go on to become the Space Agency's single most ubiquitous spinoff technology, dominating the digital imaging industries and enabling cell phone cameras, high-definition video, and social media as we know it.

Imaging devices based on metal oxide semiconductor devices had been attempted since the 1960s, but no one had ever succeeded in making the technology marketable. The little signal amplifiers had long been used in computer circuitry, but imagers using CMOS as sensors suffered from signal noise, among other problems.

Instead, a different imaging technology, using sensors based on the charge coupled device (CCD), allowed high-quality digital photography to come of age by the late 1980s. These image sensors comprise an array of photodetecting pixels that collect charges when exposed to light and transfer those charges, pixel to pixel, to the corner of the array, where they are amplified and measured.

While CCD sensors are capable of producing scientific-grade images, though, they require a lot of power and extremely high charge-transfer efficiency. These difficulties are compounded when the number of pixels is increased for higher resolution or when video frame rates are sped up.

Fossum was an expert in CCD technology—it was why JPL hired him in 1990—but he believed he could make digital images with smaller and lighter machinery using CMOS technology to create what he called active pixel sensors (APS) (*Spinoff* 1999, 2002, 2010).

CMOS technology in general had improved since earlier attempts at using it for image-sensing, and Fossum hit on an approach to reduce the signal noise that had plagued earlier imagers, applying a technique called intra-pixel charge transfer with correlated double sampling—something already used in CCDs. Using this technique, he measured a pixel's voltage both before and after an exposure. "It's like when you go to the deli counter, and they weigh the container, then weigh it again with the food," he explains. The sampling corrected for the slight thermal charges and transistor fluctuations that are latent in photodetector readout, and it resulted in a clearer image.

Because CMOS pixels are signal amplifiers themselves, they can each read out their own signals, rather than transferring all the charges to a single amplifier. This lowered voltage requirements and eliminated charge transfer-efficiency issues. And it had the added benefit of allowing almost all the other camera electronics to be integrated onto the computer chip with the pixel array using conventional CMOS production processes, a development that would make CMOS-APS imagers more compact, reliable, and inexpensive.

The very idea of digital photography was dreamed up at JPL by engineer Eugene Lally in the 1960s. Now the concept of a digital camera on a chip shared the same birthplace.

Cell phone cameras, which require tiny, highly efficient image sensors, ended up being the main driver for the mass production of CMOS active pixel sensors. Whenever you take a picture with your phone—or, nowadays, virtually any other digital imager—you're using NASA technology.

“Cell phones became the ‘killer application.’ Battery life and camera size are very important on a cell phone.”

— Eric Fossum, inventor

Technology Transfer

By 1993 Fossum and his team knew they were onto something that could be huge for NASA missions and consumer electronics alike, but as they took their findings on the road, giving talks and publishing papers, they met with resistance from the digital imaging industry and even colleagues at JPL. Fossum attributes this skepticism both to earlier failures in CMOS imaging and to people’s instinct to protect their own livelihoods.

“Even a lot of my friends were negative,” he says. “The technology was basically trying to eat their lunch.”

Despite early doubts about CMOS’s potential, several companies signed Technology Cooperation Agreements with JPL and partnered with Fossum and his colleagues to develop the technology.

In 1995, Fossum became the first JPL scientist to license his own invention from the California Institute of Technology (Caltech), which manages the lab, as he, his then-wife and JPL colleague Sabrina Kemeny, and two other JPL coworkers founded a company, Photobit, to develop custom sensors. Caltech’s Technology Transfer Office was created that year, and the office granted Photobit an exclusive license.

“It was sort of the breakthrough spinoff that showed we could do tech transfer out of JPL, too, not just Caltech,” says Fred Farina, the university’s chief innovation and corporate partnerships officer. “So it was the pioneer, in terms of spinoffs out of JPL.”

The following year, Fossum left JPL to become the company’s full-time technological lead. In addition to designing custom sensors, Photobit licensed technology to companies like Kodak and Intel, although most of those early licenses didn’t lead to product lines. By 1997, however, CMOS was being taken seriously, and several companies invested in Photobit, including Schick Technologies, which also obtained—and still holds—an exclusive license for CMOS for dental imaging (see page 34).

The action camera company GoPro takes maximum advantage of the small size and high efficiency of CMOS digital image sensors, using the technology to build tiny, high-definition video cameras that users can affix to themselves, selfie sticks, or surfboards to capture their adventures in high fidelity.

That same year, Sandor Barna, now vice president of core technologies at GoPro, finished his graduate degree and took a job as an engineer at Photobit.

"It was a great example of a truly disruptive technology," he says, noting that CMOS did not yet perform as well as CCD imagers, but the potential to improve was clear. In addition, it promised to be easier to use with far lower power and could be more cheaply manufactured, he says.

While Photobit held an exclusive license to the technology developed at JPL and filed more than 100 of its own patents, company leadership was concerned that defending its intellectual property would prove difficult as several electronics giants began developing their own CMOS imagers.

Anticipating heavy competition, in 2001 the founders sold Photobit to Micron Technology, which could bring more resources and manufacturing capability to bear. By then, the company—and subsidiary Photobit Technology Corporation, created to handle custom-design contracts—had built a healthy business for itself, and CMOS's takeover of the imaging industry had begun.

Benefits

Before Photobit was sold, its sensors had made their way into webcams made by Logitech and Intel, as well as ingestible "pill cameras" that are still offered by Given Imaging as a noninvasive endoscopy technique. "I feel very good about that one," Fossum says of the so-called PillCam. "It's still used. It's become a huge industry."

Digital single-lens reflex cameras, better known as DSLRs, were also early adopters of CMOS technology, which allowed bursts of rapid shots at high resolution.

But by far the widest use of the small, low-power cameras enabled by CMOS technology has been in cell phones. "Cell phones became the 'killer application,'" Fossum says. "Battery life and camera size are very important on a cell phone."

As that industry drove Micron and others to turn out more and more CMOS imagers every year, resulting improvements to the technology and its manufacture drove costs down and quality up until CCD-based devices couldn't compete, even where size and power weren't priorities.

Now, outside of a few niche markets, virtually all digital still and video cameras use Fossum's invention.

When Photobit was sold, the original

"It was a **great example** of a truly **disruptive technology."**

— Sandor Barna, GoPro

GoPro cameras, which leverage the small size and high efficiency of NASA-invented CMOS active pixel sensors, were originally conceived as surfboard-mounted video cameras, an application that remains popular today.

Image courtesy of Kat Patterson

patents returned to Caltech, which still holds the intellectual property rights that haven't yet expired, and the world's top image sensor suppliers, such as Sony and Samsung, license the technology. Meanwhile, Micron spun off its image-sensing business into a company called Aptina, which ON Semiconductor purchased in 2014 for about $400 million.

Fossum says he was pleased that CMOS allowed the United States to recapture a portion of the imaging market, however briefly, before much of it was lost again to Japan, South Korea, and China. "Micron, GoPro, Omnivision, and a host of others generated tens of thousands—if not hundreds of thousands—of jobs in the United States because of this technology," he says.

GoPro remains headquartered in San Mateo, California, and employs most of its 1,500 or so workers—now including Barna—in the United States.

Barna says the video industry switched to CMOS cameras with the advent of high-definition video. To shoot video with so many pixels on a CCD-based camera would require dramatically more power, draining batteries and quickly overheating the machine, he says. "You would only be able to take very short bursts, and it wouldn't be the same experience at all."

CMOS sensors also allow both the device and the battery to be smaller, and small size is one of GoPro cameras' strongest selling points. The company's devices are designed to be mounted, usually on the body, to capture action sequences in video or still images, some at up to 240 frames per second.

"It would be very unpleasant to put a two-pound or four-pound camera on your head," Barna points out.

By 2013, more than a billion CMOS image sensors were manufactured every year, and by 2015, the technology's market, which also includes applications in the automotive, surveillance, and medical industries, reached nearly $10 billion.

For Caltech, the financial returns from the licensing, which fund research and education, are only part of the benefit of the CMOS success story, Farina says. "This helps motivate other researchers at Caltech and JPL, and for the whole culture of entrepreneurship it's really powerful to have good stories."

Image courtesy of the White House

CMOS-enabled cell phone cameras gave rise to the "selfie" phenomenon, as well as a broader culture of online photo and video sharing. Here, President Barack Obama poses for a selfie with science popularizers Bill Nye, left, and Neil deGrasse Tyson, right.

He notes that cell phone cameras, which would likely not be possible without CMOS imaging, have also had an enormous cultural impact, bolstering the rise of social media, raising questions about police conduct, and bringing awareness to uprisings and crises around the world. "These things can be documented because people are all carrying around cameras," he says. "The impact went well beyond expectations."

"It's kind of amazing to me how much of a life of its own it's taken on," Fossum agrees.

Fossum, who was inducted into the National Inventors Hall of Fame in 2011, now teaches engineering and entrepreneurship at Dartmouth College's Thayer School of Engineering, where he is working on what he believes will be the next revolution in digital imaging. His Quanta Image Sensor would cram a billion pixels, each designed to sense a single photon, into an array no larger than those in current CMOS imagers, significantly enhancing low-light sensitivity.

Just as his first image sensor could be built using manufacturing processes that were well-established more than 20 years ago, Fossum is designing this next-generation imaging chip to be compatible with the enormous existing CMOS camera industry. "For factories building CMOS sensors, I think it will be pretty easy for them to switch to the Quanta Image Sensor if they want to do that," he says.

He's designing the sensor with the assistance of one of his PhD candidates, an experience that in some ways mirrors his early days at NASA. "I had some great organizational mentors at JPL," Fossum says. "Personally, I loved working for JPL—best job ever." ❖

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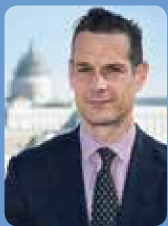

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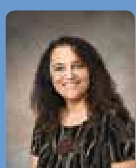

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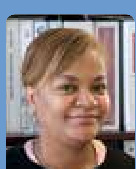

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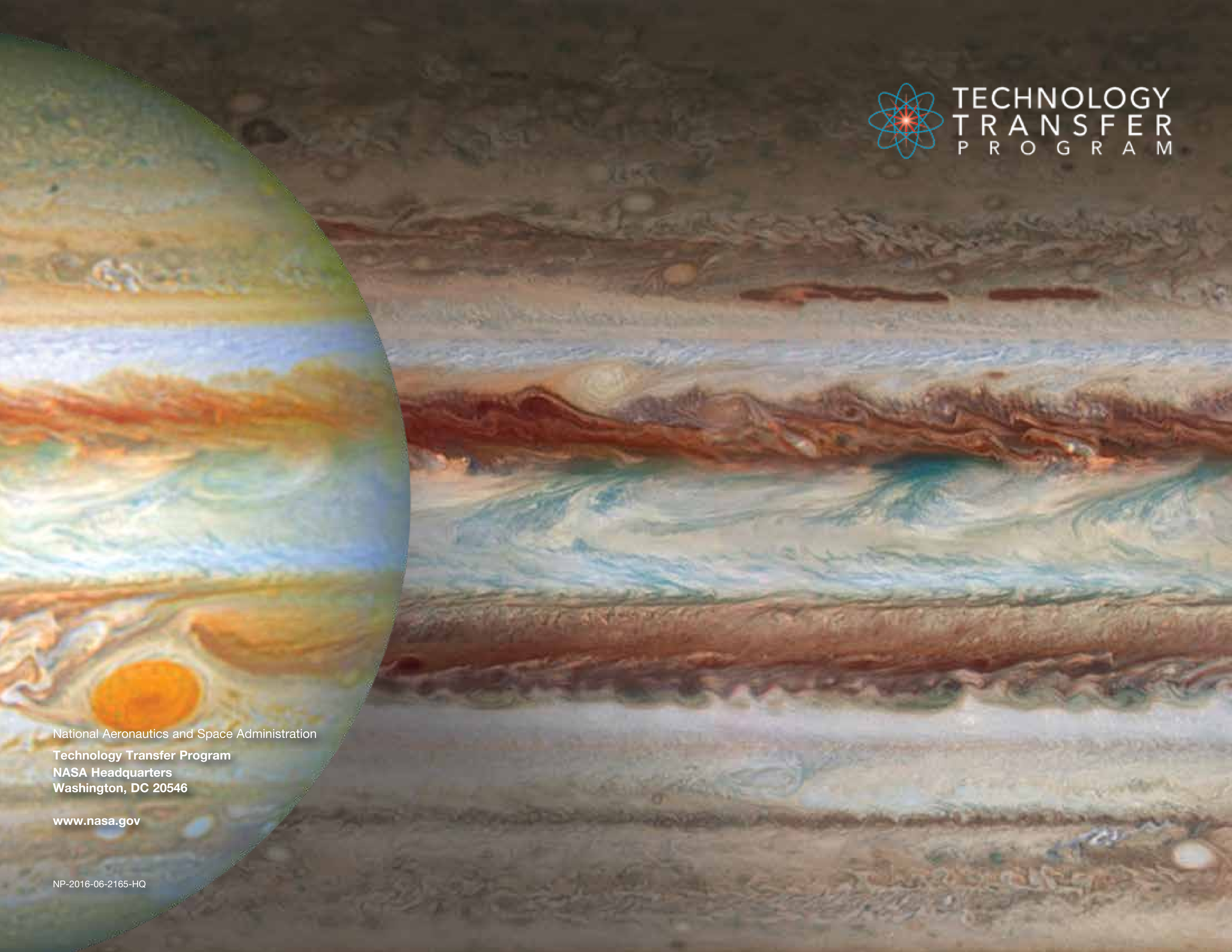

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NP-2016-06-2165-HQ