Optics and photonics technology will play a key role in NASA's efforts to put more human footprints on the lunar surface—and to use it as a base for farther-flung expeditions.

C. David Chaffee

Back to the Moon —*and Beyond*

Concept illustration for a commercial lunar lander by Intuitive Machines.
Courtesy of Intuitive Machines

Anthony Colaprete (left), with LCROSS project scientist Kim Ennico, reviewing early results from the mission in 2009.

Dominic Hart / NASA Ames

In July of this year, the world celebrated the 50th anniversary of Neil Armstrong's first walk on the moon. And, looking ahead, the U.S. space agency, NASA, has once again trained its sights on the lunar surface. It already has begun implementing the Commercial Lunar Payload Services (CLPS), an aggressive program to improve scientific understanding of the moon via dozens of scientific payloads. The eventual goal: Land astronauts again on the moon and transform the moon into a permanent life-supporting facility—self-sufficient in areas such as water and rocket fuel—for use as a staging area to Mars and beyond.

Not surprisingly, photonics and optics are playing a crucial role in making this happen, particularly through a long-standing workhorse, the spectrometer. But the use of spectrometers is only one of many ways NASA is and has been using photonics and optics to revitalize its space effort. From the time of Galileo's telescope, photonics and optics have been foundational tools for better understanding the universe, and NASA and its scientists have consistently drawn on technologies ranging from spectroscopy to fiber optics to imaging to lidar.

"I have always been involved in various types of optical and photonics study," says Anthony Colaprete, a scientist at NASA's Ames Research Center, Calif., USA, and the principal investigator for the Near-Infrared Volatiles Spectrometer System (NIRVSS) program, one of the missions to be ferried to the moon in coming years under CLPS. "As a planetary scientist, I have to observe the planetary body remotely, and this kind of optics goes back hundreds of years."

"The ultimate goal is to understand the celestial system, its characteristics and then understand the universe," says Colaprete. "If we study the moon and Mars, we can find out more about the Earth. Photonics and optics are important enabling technologies to allow us to do that."

Searching for lunar water

CLPS is itself part of a larger NASA program known as Artemis, which has the lofty goals of landing astronauts on the moon by 2024, having a sustained human presence on the moon by 2028, and thereafter preparing the United States for sending astronauts to Mars. In the meantime, NASA continues to study Mars through other programs.

A big part of the Artemis effort involves searching for sources of water on the moon, crucial to supporting life there and on other planets. It costs thousands of U.S. dollars to transport one pound of material in space—and, with a gallon of water weighing in at more than eight pounds, continually transporting tens of thousands of gallons of water from the Earth to the moon to sustain a human presence there isn't feasible.

Photonics already has helped to reveal that the moon holds significant water deposits. Indeed, Colaprete credits much of the current optimism about going back to the moon and beyond to three recent NASA projects that, using photonic technologies extensively, initially revealed that potential starting more than a decade ago. The missions, planning for which began in 2006, focused in particular on confirming the presence or absence of water ice in a permanently shadowed crater near a lunar polar region.

One of the missions was the Lunar Crater Observing and Sensing Satellite (LCROSS), launched in June 2009. LCROSS was packed with photonic devices, including two near-infrared spectrometers, a visible-light spectrometer, two mid-infrared cameras, two near-infrared cameras, a visible-light camera and a visible-light radiometer. The mission involved crashing the spent Centaur upper stage of the spacecraft's launch vehicle into the crater Cabeus, near the moon's south pole. Then, the photonic instruments on the LCROSS Shepherding Spacecraft collected data from the resulting debris plume and transmitted it back to Earth before itself crashing into the moon six minutes later.

LCROSS did identify water ice, but also other volatiles, such as CO_2, SO_2 and NH_3, as well as metals and hydrocarbons. "LCROSS used a range of different wavelengths to study the characteristics of the moon," says Colaprete, who was project scientist and principal

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investigator on the mission. "We were able to develop an incredible spectral data set, ranging from short ultraviolet wavelengths to thermal wavelengths. That range of energy allows you to see each wavelength in a unique way. When you bring them all together, all eyes are open."

Also launching in June 2009 was the Lunar Reconnaissance Orbiter (LRO), a mapping mission geared to finding favorable terrain and the environment necessary for safe future robotic and human lunar missions. According to NASA, LRO achieved a number of photonic firsts, including the first deep-space precision orbit determined by laser ranging from Earth and the first multi-beam laser altimeter system in space. It has also collected more than five years of laser altimetric measurements yielding more than 8 billion topographic points.

A third mission, the Lunar Atmosphere and Dust Environment Explorer (LADEE), launched in September 2013 and orbited the moon for some six months, studying the delicate lunar atmosphere, which is only one-trillionth the density of Earth's. Among the instruments on the spacecraft was a UV-to-NIR spectrometer to measure exospheric atomic emissions, for example, from sodium and potassium. LADEE found that tiny meteoroids—some containing water—contribute to the moon's exosphere. The mission also demonstrated the first laser communication system in space.

CLPS spectrometers continue the quest

Together, these three missions confirmed the presence of water on the moon—possibly in abundance. The Artemis and CLPS programs aim to now follow those efforts up by landing a variety of scientific instruments on the moon to better understand its ability to support human occupation. As of the end of July, NASA had selected 24 science and technology demonstration payloads for that purpose—12 to be developed at NASA centers, and 12 by outside operations—including some payloads heavily populated with photonic and optical instruments.

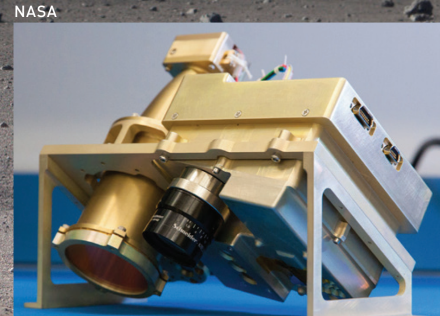
One such instrument is Colaprete's current focus, NIRVSS. This near-infrared spectrometer system is

What is CLPS?

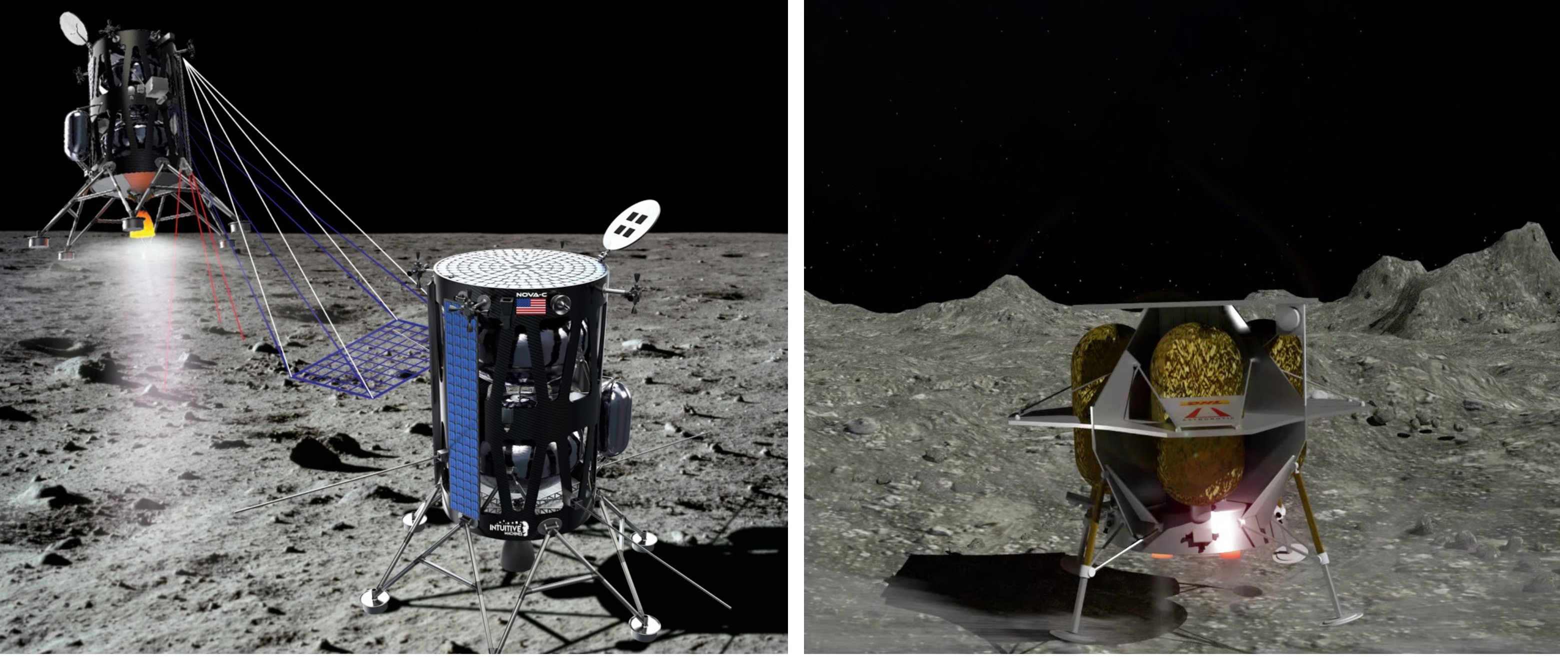
NASA bills its Commercial Lunar Payload Services (CLPS) program as "the first major step to return astronauts to the moon." In the program, NASA and a variety of industry partners are creating dozens of science and technology payloads to investigate the lunar surface and environment as a prelude to human exploration. The space agency is also contracting with several private companies to deliver those payloads to the moon, in an end-to-end approach in which these firms will take responsibility for payload integration, launch from Earth, and landing on the lunar surface.

In addition to missions involving spectroscopy on the lunar surface, several of the two dozen payloads thus far announced for lunar delivery under the CLPS program include other optical technologies. One will even feature a next-generation set of lunar retroreflectors—supplementing and updating the ones left half a century ago by the astronauts of the Apollo mission to enable precise laser-ranging measurement of the Earth–moon distance.

NASA



When delivered to the moon via CLPS, the Near-Infrared Volatiles Spectrometer System (NIRVSS) will detect the different types of minerals and ices present in the soil, including water.



Landers by Intuitive Machines (left) and Astrobotic (right), two of the companies selected under the CLPS program to send the first robotic landers to the moon with their payloads. A third company, OrbitBeyond, has since withdrawn from the program; the two other missions are slated to start in 2021. NASA / Intuitive Machines / Astrobotic

designed to hunt for lunar water and volatiles, especially hydrated lunar minerals. The spectrometer includes an acousto-optic tunable-filter NIR (AOTF-NIR) spectrometer from Brimrose Corporation of America, Hunt Valley, Md., USA.

Initially developed as part of a Small Business Innovation Research grant, the AOTF-NIR spectrometer is a dual-channel unit with a spectral range from 1.3 to 4 microns—wide enough to measure for water and many other volatiles. "It uses acousto-optic tunable filters to do the wavelength selection, rather than gratings," says Colaprete. "There are no moving parts." He adds that the unit is "very controllable and programmable," with high throughput.

The system includes a shortwave indium gallium arsenide detector and a longwave mercury cadmium telluride detector. "Each channel is fed by an optical fiber bundle, which goes to a bracket assembly," Colaprete explains, "which represents the eyes of the system." The bracket assembly includes an infrared light source, a CMOS camera (Spectrometer Context Imager, SCI), a bank of LEDs, fiber optic cable mounts and a four-channel radiometer.

Using AOTF, an RF signal is applied to a TeO_2 crystal, producing acoustic waves within the crystal. Among the advantages to this technology, according to Brimrose, is that its passband wavelength can be tuned without the need for moving parts. TeO_2 also is considered a very efficient optical material, and AOTFs have an extremely high optical throughput compared with other dispersive optics. The instrument can use either sunlight or the included IR lamp as its light source. It is expected to be operational for 14 days only, or one lunar day.

The Chief Operating Officer at Brimrose, Vladimir Stanislavsky, says that the AOTF-NIR spectrometer is now undergoing final construction and should be completed by the end of the year. Final testing thereafter will include vacuum thermal testing, which includes the cycling of the instrument between thermal limits while in vacuum, simulating lunar-like environments. Also it will be tested in conditions similar to launch environments by shaking the instrument in all three axes (called random vibration testing) and shock testing. All is to be completed by next year, well in time for the planned 2021 launch.

Feng Jin, Brimrose lead scientist on the project, notes that the company has been working with NASA since 2001. This is a customized unit, based loosely on the Brimrose Luminar 4060. "This will help humans establish a base on the moon," says Jin. "The ideas we are using are not new, but providing an instrument for this kind of application is different."

Colaprete says that the NIRVSS program will work in coordination with another system, the Neutron Spectrometer System (NSS), provided by Lockheed-Martin, which will search for water and its elements a meter or more below the moon's surface. NSS works by measuring changes in the number and energy of neutrons that emanate from the moon; these subatomic particles lose significant energy when the collide with something roughly their own size—such as a hydrogen atom. NSS will thus allow scientists to infer the presence of hydrogen in the lunar soil—which is potentially

The moon's polar craters "are time capsules into the inner solar system," Colaprete notes. "If we can get at that ice, we can learn about the history of our solar system."

important for making rocket fuel to Mars, says Colaprete. In complementary fashion, NIRVSS "will determine whether there is water or not."

NASA manages the Brimrose NIRVSS spectrometer at the Ames Research Center and the Lockheed NSS spectrometer at the Goddard Space Flight Center in Maryland. Another instrument, the Linear Energy Transfer spectrometer, managed from NASA's Johnson Space Center, will measure the lunar surface radiation environment. Still another, the Ion-Trap Mass Spectrometer for Lunar Surface Volatiles, managed out of NASA Goddard, will measure for volatile contents in the surface and lunar exosphere. The spectrometers and other test instruments that will go to the moon as part of CLPS all must be fitted so they will comfortably integrate onto the commercially developed lunar landing vehicles that NASA selects.

The industry dimension

Beyond the mission's scientific and exploration objectives, CLPS serves to highlight the evolving relationship of NASA, a U.S. government agency, with private industry. NASA has, of course, always depended heavily on U.S. industry to deliver systems and equipment—indeed, NASA has historically tended to play down its administrative staff budget, arguing that most of its funds are transferred through to industry. These efforts have gained additional importance with the rise of the private space company SpaceX.

Meanwhile, for CLPS in particular, in May 2019 NASA named three private contractors that will be tasked with sending the first robotic landers for the program to the moon:

- *Astrobotic* (Pittsburgh, Pa.) has been awarded US$79.5 million and has proposed to fly as many as 14 payloads to Lacus Mortis, a large crater on the near side of the moon by July 2021.

- *Intuitive Machines* (Houston, Texas) has been awarded US$77 million and has proposed to fly as many as five payloads to Oceanus Procellarum, a scientifically intriguing dark spot on the moon, also by July 2021.

- *Orbit Beyond* (Edison, N.J.) was originally awarded US$97 million and proposed to fly as many as four payloads to Mare Imbrium, a lava plain in one of the moon's craters, starting as early as September 2020. However, in late July, the company notified NASA that it could not meet that deadline, and asked to be released from its contract.

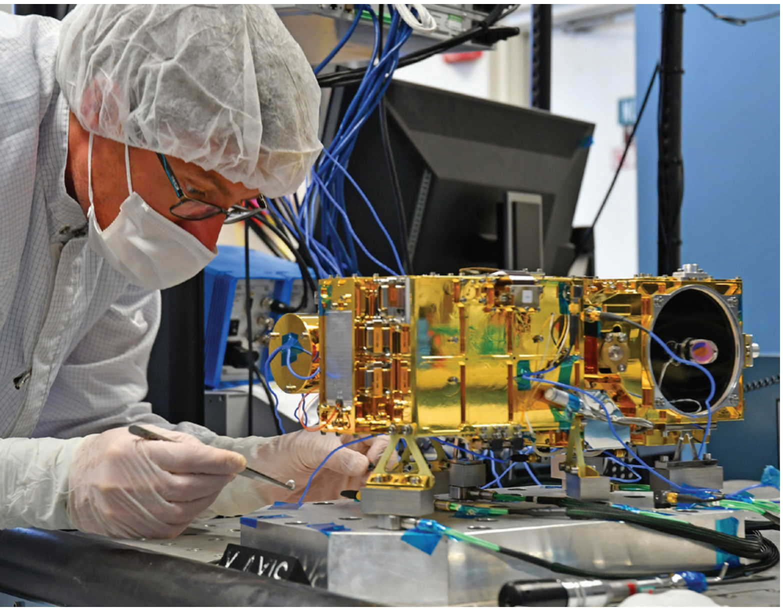
Also in late July, NASA issued a draft solicitation asking U.S. companies to submit ideas for the "human landing system that will land the first woman and the next man on the moon by 2024."

Contracting landers to private companies represents "a whole new commercial perspective" for NASA, according to Colaprete—one even more focused than in the past on the commercial sector to do critical NASA chores. And he believes that there will be further applications for the commercial sector, a priority for NASA. "This is one of the benefits that NASA provides to the taxpayer," Colaprete says, "a transfer of technology processes. Such research may be too risky for a commercial entity to undertake on its own." He cites the airline industry as one that has become safer and better performing as the result of this kind of tech transfer from NASA programs.

Whatever the mechanism for getting there, Colaprete stresses, the moon will always hold new secrets to explore. He is particularly fascinated by the craters in the lunar poles, which he says have not seen the sunlight for more than two billion years and are colder than Pluto or Mars. "These craters are time capsules into the inner solar system," he notes. "Whatever the moon sees, the Earth sees. They are similar to ice cores we have on Earth. If we can get at that ice, we can learn about the history of our solar system."

SuperCam on Mars

Even though an important goal of Artemis, of which CLPS is a part, is to use the moon as a staging area, NASA also will continue to send rockets directly from Earth to Mars. The next big unmanned adventure on that front is the Mars 2020 rover project, slated to launch in July of next year and to land at Mars' Jezero Crater in February 2021. And that next-gen rover will



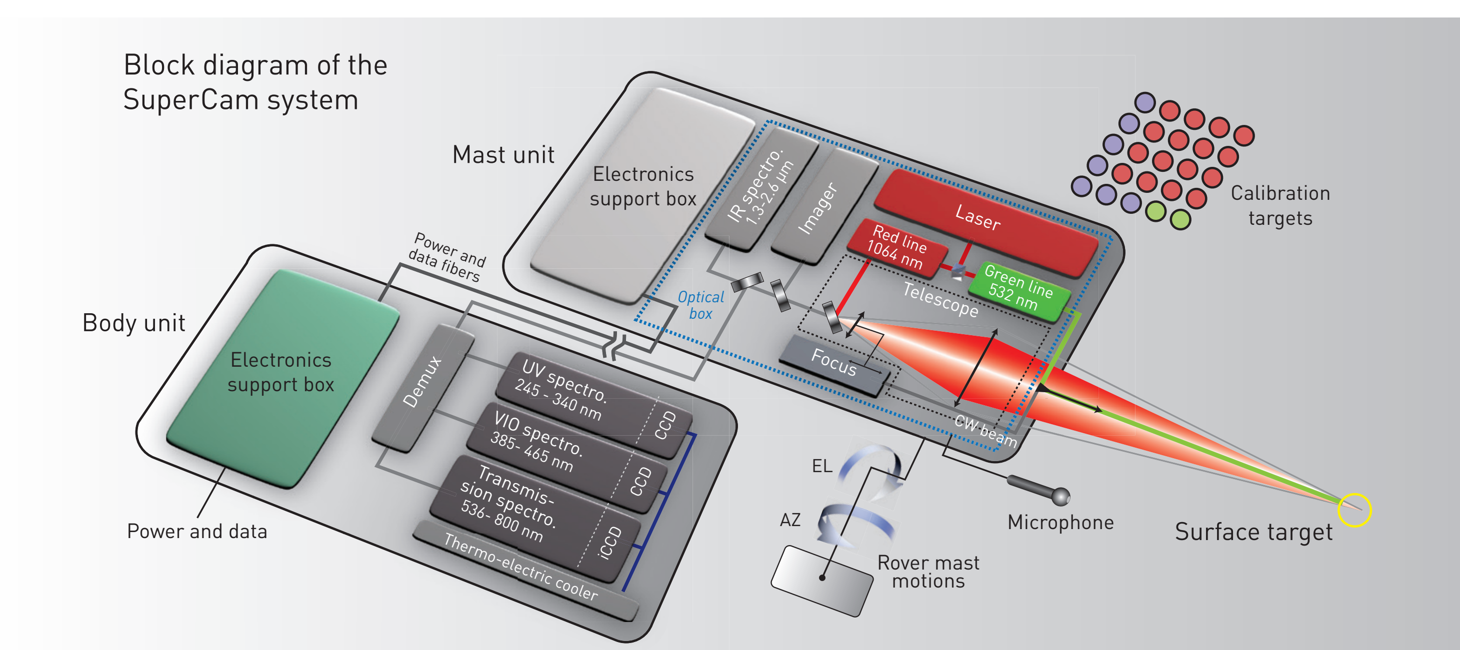
Bruno Dubois, Los Alamos National Laboratory (LANL), working on the SuperCam assembly. The camera is an upgrade of the ChemCam unit, still delivering images from Mars on the Curiosity rover.
LANL

be empowered by a suitably next-gen photonically enabled instrument, SuperCam.

The SuperCam instrument is a successor to the ChemCam instrument that was so successful on the Curiosity mission earlier in this decade. SuperCam is designed to identify the chemical and mineral makeup of very small targets from a standoff distance up to seven or more meters from the Mars 2020 rover, examining Martian rocks and soil to find organic compounds that could be related to past life on the Red Planet. It will perform this work through a combination of laser-induced breakdown spectroscopy (LIBS); Raman, time-resolved luminescence, and reflectance spectroscopy; and high-resolution imaging.

The SuperCam project is led by Los Alamos National Laboratory (LANL). According to LANL's Roger Wiens, the SuperCam principal investigator, the instrument itself consists of three parts: a mast unit inside the white box at the top of the rover's mast; a body unit inside the rover, and an extensive set of calibration targets at the back of the rover. The mast unit includes the laser, a telescope to project the laser beam and collect light for analysis, an infrared spectrometer, a microphone, and a camera called the remote micro-imager (RMI).

The body unit, sponsored by NASA and designed and built at LANL, receives light from the telescope via a 6-m-long optical fiber. The data pass to an optical demultiplexer and then to three spectrometers used for the LIBS, remote Raman, and visible-light reflectance spectroscopy. The mast unit is provided by the



Adapted from LANL / Illustration by Phil Saunders

The next-gen rover on the Mars 2020 mission, due to launch in July of the coming year, will be empowered by a suitably next-gen photonically enabled instrument, SuperCam.

French Space Agency (CNES), l'Institut de Recherche en Astrophysique et Planétologie (IRAP), and the Paris Observatory in Meudon. The calibration target assembly, meanwhile, uses targets from an international partnership including France, Denmark, Canada, the United States and Spain; the assembly was built, integrated, tested, and delivered by a Spanish consortium.

Building on ChemCam technology

The laser driving SuperCam is manufactured by Thales Optronique, which also produced the laser for Curiosity's ChemCam. SuperCam's laser is a Q-switched Nd:YAG device with a single amplifier stage; it is passively cooled and designed to operate between –30 °C and +10 °C. It fires 4-ns pulses between 3 Hz and 10 Hz, using the fundamental frequency (1064 nm) for LIBS and doubled (532 nm) for Raman spectroscopy.

In either LIBS or Raman mode, the laser will be able to deliver a maximum energy of 11 mJ to its standoff targets. For LIBS measurements, the beam is expanded through the telescope and then focused to a 250-to-400-micron spot to create brief plasmas on targets within 7 m of the rover. In Raman mode, a collimated beam around 8 mm in diameter illuminates the target, stimulating the vibrational modes of surface molecules, according to Wiens.

As with ChemCam, SuperCam uses three optical spectrometers in the body unit to collect the LIBS spectra, Wiens notes. Two of these spectrometers, covering the 245-to-465-nm range, are crossed Czerny-Turner reflective-grating designs that are essentially identical to those of ChemCam. The third spectrometer uses three transmission gratings and an optical intensifier from Harris, which permits it to also function as a remote Raman spectrometer—a new development for SuperCam.

In the LIBS mode, the intensifier's gain is low, with time gating set at 10 μs to collect the atomic emission spectrum. In the Raman mode, the intensifier gain is high, and the gate is set to 100 ns to remove essentially all background light and collect the weak Raman molecular signal. By changing the delay of the intensifier gate, SuperCam can also use time-resolved luminescence spectroscopy to study mineral luminescence properties and search for organic materials, Wiens says.

Typically, SuperCam will analyze in a raster pattern of observation points, taking enough RMI images to show the scene before and after analysis. "For targets within seven meters of the rover, we plan to do LIBS first because the shock wave from the plasma removes the dust from the targets, which benefits the other techniques as well," says Wiens. "At the end of the day, the rover sends the data to a satellite passing overhead, and from there it is transmitted to NASA's Deep Space Network on Earth."

Getting at a warmer, wetter past

What makes SuperCam super? Wiens notes that ChemCam, on the Curiosity mission, was the first instrument to use LIBS to collect elemental compositions remotely from a rover. Across seven years on Mars, it has collected about 700,000 spectra. SuperCam retains that elemental-composition capability—and adds two techniques to get at mineralogy: visible/infrared reflectance spectroscopy and remote Raman spectroscopy. In addition, the RMI camera provides color images and will take microphone recordings of the laser-produced shock waves during the LIBS sampling. These will provide a measure of the rock hardness, based on changes in the "zapping" sounds as the laser beam profiles into the rock.

All of this makes SuperCam effectively a geological observatory with many tools—one that NASA, on announcing the project five years ago, called a "Swiss Army knife" of instruments. But why study Mars, a cold and dry planet, in such detail?

Wiens responds that it has remained in pristine shape for billions of years—and says that early in Mars' history, it may have had a warmer, wetter climate with rivers and lakes. Given this Earth-like early environment, "we want to know if Mars harbored life," he says. "And if so, what happened to it." OPN

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