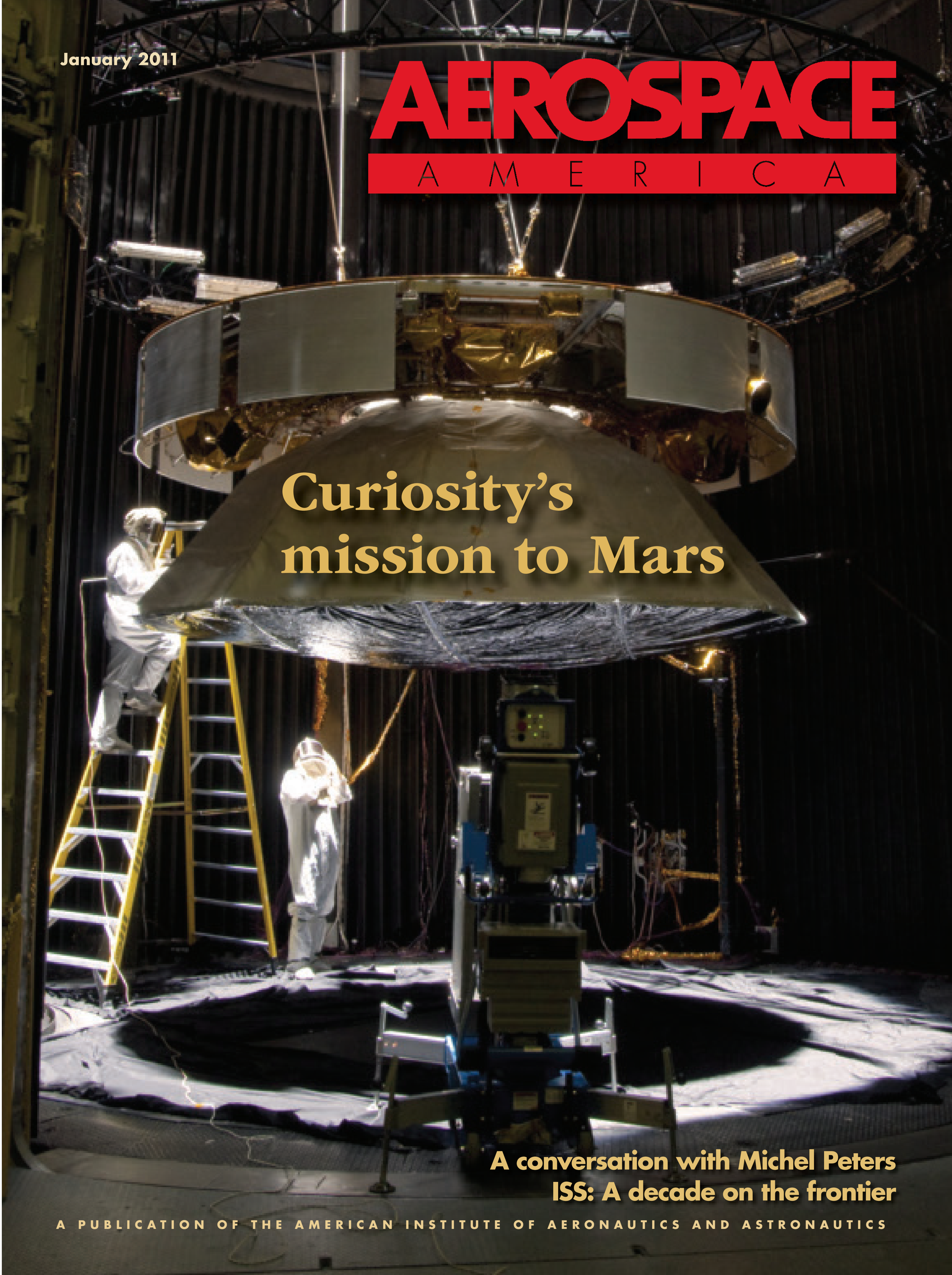

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Curiosity's mission to Mars

A conversation with Michel Peters

ISS: A decade on the frontier

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Curiosity's MISSION to MARS

by Craig Covault
Contributing writer

Curiosity, NASA's $2.3-billion Mars Science Laboratory (MSL) rover, is ready to push the bounds of science and technology in a search for clues to life on Mars. Although Curiosity cannot detect biological activity, it is designed to find specific geologic and carbon-based evidence relevant to past life. The 2,000-lb vehicle features a maze of sample flow paths, mini-laboratories, and instruments developed by the U.S., Europe, Russia, and Canada.

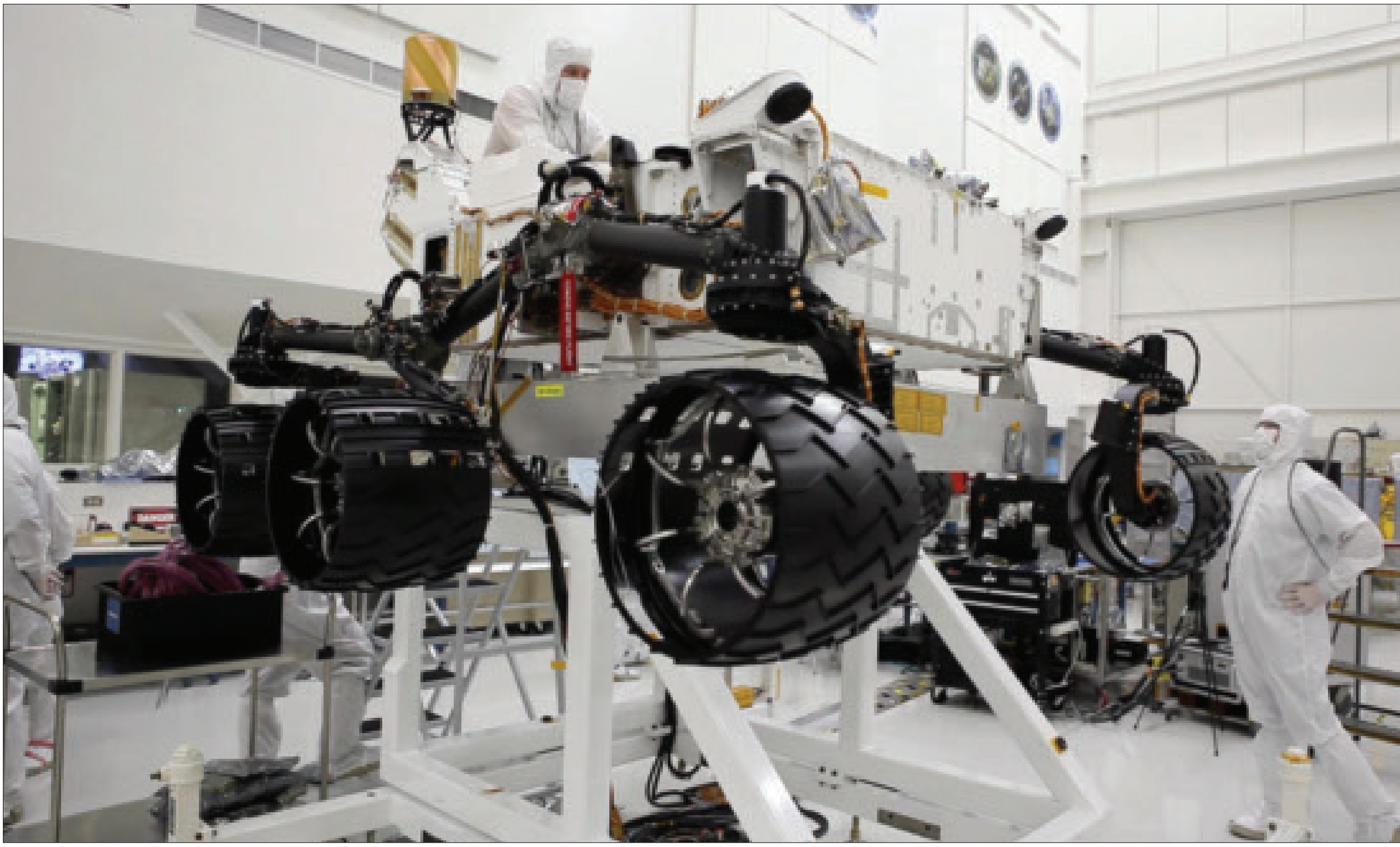
By June, the MSL spacecraft is to be shipped from Pasadena, California, to Cape Canaveral, Florida, on board an Air Force C-17. Scheduled for launch on an Atlas V rocket this November, Curiosity will lead NASA toward the future after the final shuttle mission recalls U.S. space glories of the past. MSL is targeted to land on Mars in August 2012.

The most complex spacecraft ever developed by JPL, MSL is so vital to the search for Martian life—and to NASA's faltering exploration strategy—that Congress voted to continue the program even with a 60% cost increase and a two-year launch delay to 2011. Part of the delay resulted from disappointing motor and actuator tests conducted at temperatures from -70 F to -90 F, similar to the levels Curiosity will experience on the coldest winter nights.

Pete Theisinger, MSL project manager, says that some of MSL's difficulties have also revealed strategically important problems with U.S. aerospace components. Although declining to be specific, he notes, "There are weaknesses in the U.S. space technology parts and supply community that have surprised us at JPL."

Curiosity is over five times heavier than either Spirit or Opportunity, the Mars exploration rovers (MERs) that made airbag landings in 2004. MSL's sky crane sys-

In searching for clues to life in Martian rocks and clay, NASA's Curiosity rover will also give the space program new life.



Engineers installed six new wheels on the Curiosity rover and rotated all six at once on July 9, 2010. This milestone marked the first in a series of "tuneups" to get the rover ready for a drive in the clean room at JPL, where it is being assembled.

tem will enable Curiosity to carry at least 165 lb of science instruments, compared with less than 20 lb of science hardware on Spirit and Opportunity.

Shortly after Curiosity begins to rove, a Russian robotic spacecraft will attempt to land on the Martian moon Phobos. Part of the lander is to return to Earth in 2014 with a sample of Phobos material that could be rich in Mars dust. This would be a huge achievement that might accelerate plans for manned Phobos missions.

During this first-ever round trip between Earth and Mars, the Russian spacecraft will also deploy a 250-lb Chinese Mars orbiter. China says that in about 2013 it will conduct its own launch of a heavier Mars orbiter that it is now developing.

Technology

Two major technological firsts will enable MSL to do more than previous rovers and aid the design of future Mars landers too heavy for airbags. One is sky crane, a landing system that will function like an Army helicopter lowering a vehicle to the surface of, in this case, another planet.

The other first is called active guidance with aerodynamic lift, a combination that will allow MSL to fly—rather than just fall—through the Martian atmosphere. No previous Mars mission has used a maneuvering, fully guided lifting aeroshell for precise landing capability.

"It is difficult to overstate what a major step forward this is beyond the earlier MERs," says Theisinger, who also led JPL development of Spirit and Opportunity. "MSL is not your father's Mars rover," he says. "We clearly underestimated the size and scope of MSL."

But a potential problem lies within the plutonium-fueled radioisotope thermoelectric generator (RTG) that will power Curi-

MSL mockup sits with the Mars exploration rover and Sojourner rover at the Jet Propulsion Laboratory.

osity. There is concern that the critical thermocouple device in the RTG that converts heat to electricity may be degrading ahead of its specification life, says John Grotzinger, MSL program scientist.

The newly designed Boeing/Dept. of Energy multimission RTG has proven design and hardening features to prevent dispersal of any plutonium dust in the event of an Atlas V launch accident. Just in case, however, the DOE will position more than a dozen mobile emergency field teams around Cape Canaveral for the launch. If an accident occurs, the teams will immediately check for any release of plutonium 238 or radiation.

What's new and different

There are several key differences between Curiosity and its MER predecessors:

•**Ballast to leverage angle of attack.** The MSL aeroshell will eject eight blocks of ballast, together weighing 660 lb, to maintain a proper angle of attack during different phases of the landing. The ballast alone weighs 250 lb, more than the Spirit and Opportunity rovers.

•**Wheels and speed.** Curiosity will use six 50-cm-diam. wheels, compared with the 20-cm-diam. wheels on the MERs. The larger wheels will provide a 20% increase in maximum speed to 6 cm/sec.

•**Mission duration.** The formal MSL mission specification is for two Earth years of lifetime while driving 10 mi. or more. The MER specification called for 90 days and about 900 ft of driving, which both rovers blew away following their January 2004 landings. Spirit remains silent after having become stuck in mid-2009 following 5 mi. of mountain exploration, while Opportunity is ready to begin its eighth year and has passed 15 mi. on its odometer.

•**Size.** Curiosity is 9 ft long, 8.8 ft wide, and 7.2 ft tall; the MERs are 5.2 ft long, 7.5 ft wide, and 4.9 ft tall.

•**Computer power.** Curiosity's computer is substantially more powerful, says Mark W. Maimone, a lead computer and robotics engineer for the MSL and MER. He says MSL's computer is a BAE Systems Rad 750 whose overall integration was done at JPL. Its central processing unit is five times faster than either of the MER CPUs.

Curiosity can perform runs at 100 MHz/sec, compared with 20 MHz/sec for the MERs. By contrast, a low-end home computer will have 2 GHz of power but is not radiation hardened, an upgrade that can take years of testing and certification.

More computer power will enable robotic roving to proceed faster with fewer mistakes. MSL will have the same basic capabilities as the MERs, such as hazard avoidance, the ability to circle a rock, terrain assessment, visual odometry, and autonomous arm functioning.

•**Arm operations.** The extra computer power will enable far more robotic arm operations, which will be substantially more demanding on MSL. Another difference is that for MSL, unlike for the MERs, the team will not have to write a sequence of hundreds and hundreds of lines of software for these daily operations.

"With MSL we will have those kinds of sequences, developed here at JPL, already on board the rover," says Chris Leger, robotic arm flight software developer and the surface software development lead for the MSL flight.

"In terms of mass and strength, the 7.5-ft MSL arm is much beefier and much stronger than the 3-ft MER arm," says Matt Robinson, lead engineer for robotic arm systems. "Just the turret on the MSL arm weighs more than the whole arm electronics and science on the smaller MER rovers," he notes.

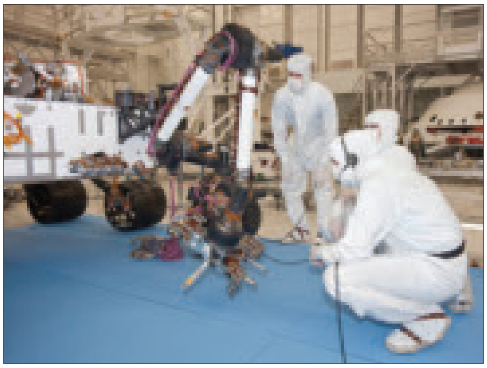
"We have a whole different style of motions with the MSL arm, because we use a lot more 'gravity-relevant' motions to move samples where we want them to fall inside the mechanisms," adds Leger. "When we do sample processing you will see the turret spin around to do different sample orientations, while other actuators are creating vibrations to move the sample along."

Searching and sampling

The arm uses a percussion device to break rock into powder that can be moved to the rovers' mini-labs. "There are at least 50-100 different arm motions to get the samples out of the drill and over to the instruments," says Leger.

The rover will explore a once water-rich region in search of the carbon-based building-blocks of life. It will also sample Martian geology up to 10-20 mi. from the landing site and generate broader data to determine if habitable conditions ever existed during the Martian eons.

The rover's labs should be able to assess rock and soil to obtain key data, such as how much life-giving oxygen has come and gone in the Martian atmosphere over the past 4 billon years.



Curiosity's 7.5-ft robotic arm, which will use a percussion device to break rock into powder, is much stronger than the 3-ft MER arms.

More than any other planetary mission in history, MSL will benefit from extremely detailed collaboration with other NASA and ESA missions orbiting Mars.

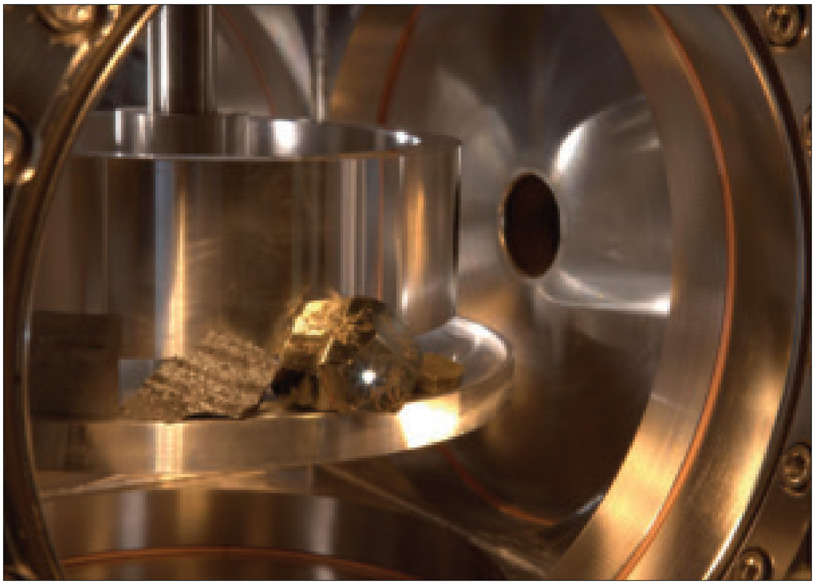
MSL's operations on the Martian surface will be more like a military campaign on Earth where reconnaissance satellites provide all manner of data before ground forces—in this case Curiosity—move in.

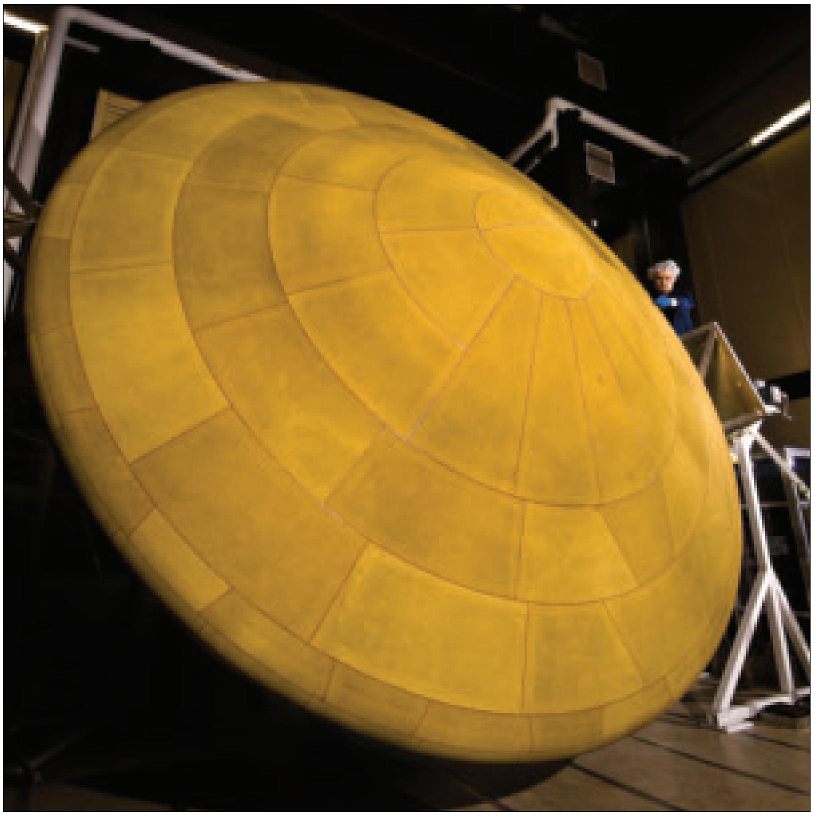
ESA's Mars Express and NASA's Mars Reconnaissance Orbiter have taken very high-resolution imagery, while the Mars Odyssey has helped trace the presence of water. They will also relay data to Earth from Curiosity, just as they continue to do for Opportunity and will do for Spirit, if it awakens from a power-starved winter.

The Wright approach

MSL's descent to the Martian surface will come 109 years after the Wright brothers made fundamental discoveries about aerodynamic lift, angle of attack, and active control. Those principles will now be demonstrated for the first time in the Martian atmosphere. MSL will use Apollo command module reentry algorithms and also roll re-

The ChemCam instrument uses a pulsed laser beam to vaporize a pinhead-size target, producing a flash of light from the ionized material (plasma) that can be analyzed to identify chemical elements in the target. Here a ball of luminous plasma erupts from the surface of an iron pyrite crystal in the sample chamber approximately 3 m from the instrument. The laser beam itself is invisible. Credit: NASA/JPL-Caltech/LANL.





The finished heat shield for the MSL, with a diameter of 4.5 m, is the largest ever built for descending through the atmosphere of any planet. Lockheed Martin Space Systems Denver built and tested the heat shield. Credit: Patrick H. Corkery. Courtesy Lockheed Martin.

versals, just like the space shuttle, to alter its lift vector during reentry.

Active guidance of a lift-generating vehicle and the sky crane will deliver the MSL rover to within a circular target area just 7.7 mi. in diameter. This compares with Pathfinder and MER unguided entries that targeted a 50 x 6-mi. ellipse. The 1976 Viking landers used a "full lift up" but unguided aeroshell that required a much larger landing footprint measuring 175 x 62 mi.

The MSL's entry into the Martian atmosphere at nearly 13,000 mph will use the largest aeroshell and heat shield ever flown in space. Curiosity and the Mars sky crane will be encased in an aeroshell shaped like an enlarged Apollo command module. It measures nearly 15 ft across its heat shield—2 ft larger than an Apollo command module and 6 ft larger in diameter than the MER and Pathfinder rover aeroshells.

Because the unique entry trajectory profile will create external temperatures of up to 3,800 F, the heat shield uses phenolic impregnated carbon ablator (PICA) thermal protection tiles. This is in place of the older Mars heritage SLA (super lightweight ablator) 561V used in past Mars landings.

On its nine-month flight, the aeroshell with the sky crane rover inside will fly attached to a large solar-array-equipped circular cruise stage. During cruise the aeroshell will have a symmetrical mass and will rotate at 2 rpm. But all that will change starting 10 min before reentry when the two 165-lb cruise balance mass weights are ejected. "During entry into the Martian atmosphere, we will fly a symmetrical aeroshell body but with asymmetric mass," says JPL's Adam D. Steltzner, manager of MSL entry, descent, and landing.

"That will make us fly at a canted angle that will enable the heat shield to develop lift," Steltzner says. To enable steering and lift control, the rover computer will calculate when to fire eight 57-lb-thrust attitude control jets to roll or bank the vehicle with the optimal angle of attack for a lift-over-drag ratio of 0.24 at Mach 24. For the first time in any Mars landing, the altitude, attitude, and velocity of the vehicle will be updated continuously in a closed-loop data stream for real-time maneuvering commands.

Innovative radar

Another key to accuracy and a safe landing will be a new radar configuration never before flown to Mars. "It has taken substantially more time to develop, but it is a superb radar," says Theisinger.

"We needed good velocity and altimetry data relative to the surface of Mars. When slowing from nearly 13,000 mph it is tough to get the velocity data correct down to under feet per sec—and that is what we need for landing this thing," says Steltzner.

"It would be difficult to near-impossible to land a vehicle like this using just an inertial measurement unit, so we chose to develop our own Ka-band six-beam radar. Recent helicopter tests of this system turned in excellent results and aided the MSL team in determining how best to cycle the antenna selection during the descent.

"We feel great about the radar," Steltzner continues. "One reason we decided to build our own is that we struggled in the past with Phoenix, MER, and Pathfinder radars when we tried to modify existing weapons system radars."

Enter sky crane

With a PICA heat shield, a flying aeroshell using Apollo-proven math, a tested parachute design, and spiffy new radar, the untested Mars sky crane must work perfectly. Here is how that will happen:

•**Additional ballast ejection.** The first 67 mi. of the entry will be with the vehicle's mass offset to enable it to generate lift, to fly, and to maneuver to a point almost directly above the landing site. Now six more pieces of ballast, each weighing 55 lb, are ejected at 2-sec intervals to reestablish a neutral center of gravity. The ballast separation phase is designated the "surfer" maneuver (for "straighten up and fly right"), followed immediately by MSL's "victory roll" to establish proper attitude. MSL is ready for its next big event.

•**Parachute deployment.** The aeroshell hypersonic entry phase will take out 99% of the kinetic energy imparted by launch and now by Mars gravity. At 6-mi. altitude and 1,000 mph, Curiosity will deploy its Pioneer Aerospace 52.5-ft-diam parachute. On MSL the chute will be lowering a mass of 3,400 lb, including the aeroshell, sky crane, and 1-ton rover. The MSL chute will remove 99% of the remaining 1% of kinetic energy.

•**Heat shield separation.** The chute will slow Curiosity's descent velocity after 2.5 min to 358 mph at 4-mi. altitude. At this point the PICA heat shield, just 1 in. thick, will be severed, opening the bottom of the aeroshell to reveal the six-wheeled rover grasped by the sky crane with an extended platform holding all six radar antennas. All computations and commands are being done by the rover's computer.

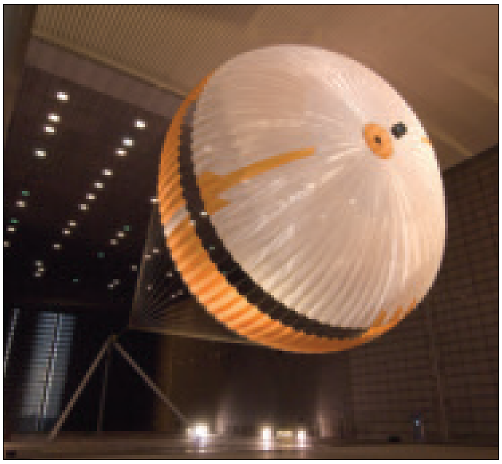
•**Radar activation.** With the heat shield gone, the sky crane's radar will be activated to measure altitude and velocity.

•**Real-time imaging.** The down-facing Mars descent imager, developed by Malin Space Science Systems, will begin taking a continuous stream of high-resolution images (up to four per second) to show the landing from the rover's perspective.

•**Backshell and parachute separation.** Descending through 6,000 ft, the vehicle will separate its backshell and parachute, revealing the sky crane and sports-car-sized rover.

Powered descent

Things begin to happen fast at backshell and parachute separation, but the first thing the sky crane and Curiosity do is nothing. The contraption is programmed to free-fall for 1 sec to be well clear of the 100-ft-long parachute canopy, risers, and backshell.



An MSL parachute test is conducted at the Ames/NFAC 80x120 wind tunnel. Credit: T. Wynne.

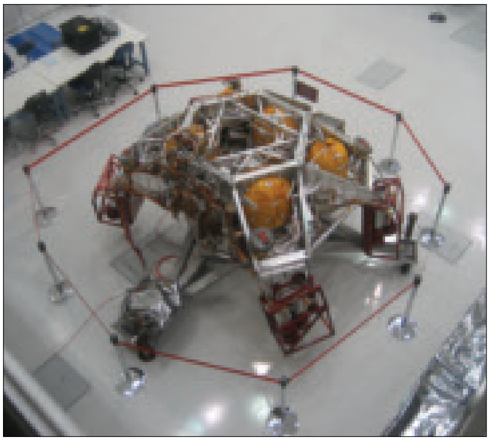
The sky crane has eight Aerojet 675-lb-thrust hydrazine-fueled Mars landing engines (MLEs). Paired on each corner, all eight MLEs are ignited as the whole shebang streaks below 5,000 ft. Engine ignition will dramatically slow the descent and gain attitude control for the fast-approaching Martian touchdown.

Next the vehicle maneuvers laterally to prevent having the backshell and parachute collide in midair or land on top of each other—the worst of luck 150 million mi. from Earth. After the lateral maneuver, the sky crane's engines will null out motions in all axes.

The rover computer will then command the sky crane to fly the vehicle to a point 656 ft above the spacecraft's estimate of where the Martian surface is.

Maximum velocity cancellation occurs at a point that the spacecraft's computer is programmed to perceive as a horizontal plane in the air—200 ft above the surface. But the computer is being tricked. The rover team calls the area "the terrain accordion," which in fact is at least 100 ft farther above the surface. This is ample space for

The aeroshell is a blunt-nosed cone that will encapsulate and protect Curiosity during its deep space cruise to Mars, and from the intense heat and friction that will be generated as the system descends through the Martian atmosphere. Credit: Adam Mattivi, courtesy Lockheed Martin.



The rocket platform (MSL descent stage) will act as a sky crane and lower the MSL rover onto Mar's surface from a hover, then fly away to crash at a safe distance.

the sky crane to exercise its descent capabilities, but with a plentiful safety margin.

Rockets blazing, the sky crane descends, but slowly—like a Marine Corps Harrier landing, though with less noise because of the super thin Mars atmosphere. Still holding Curiosity tightly, sky crane will begin to descend at a sedate 7 mph, now on the thrust of just four engines at about 50% throttle. This setting gives maximum control.

The scene all around will be of endless red terrain. When the two vehicles descend to about 70 ft, the sky crane will release the rover on a 25-ft set of lines called the bridal umbilical device (BUD). It has three load-bearing lines of woven nylon wrapped with slackened electrical umbilical.

Both the rover and sky crane will continue to drop at 2.5 ft/sec. Halfway down, Curiosity unfolds its wheels, which had been tucked in to fit inside the aeroshell.

The rover will drop more rapidly on the bridal than the sky crane is descending. Suddenly the rover computer will sense the sky crane has no load—Curiosity has been safely deposited on Mars. This will cue Curiosity to fire a cable cutter to sever the BUD. It will also cue the sky crane to begin its flyaway maneuver. Notes Steltzner, "We love to smartly say that we do not look for the touchdown event, but rather perceive the postlanding state of the vehicle."

As MSL's Curiosity rover searches for evidence of life on Mars, it will do more than seek answers to an endlessly intriguing question. It will also serve to rejuvenate NASA's space program as other nations inevitably begin to challenge U.S. leadership in planetary exploration.