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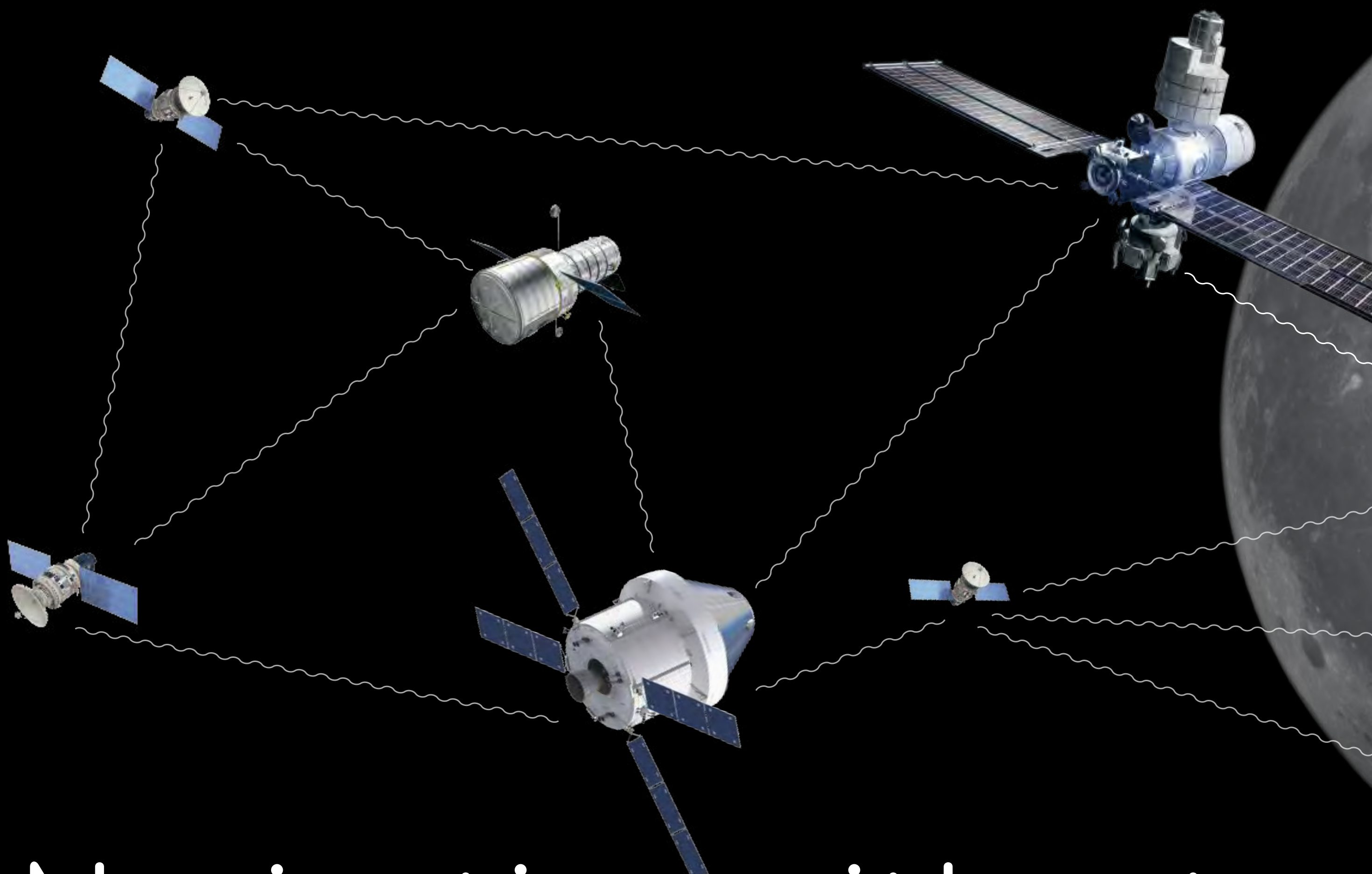
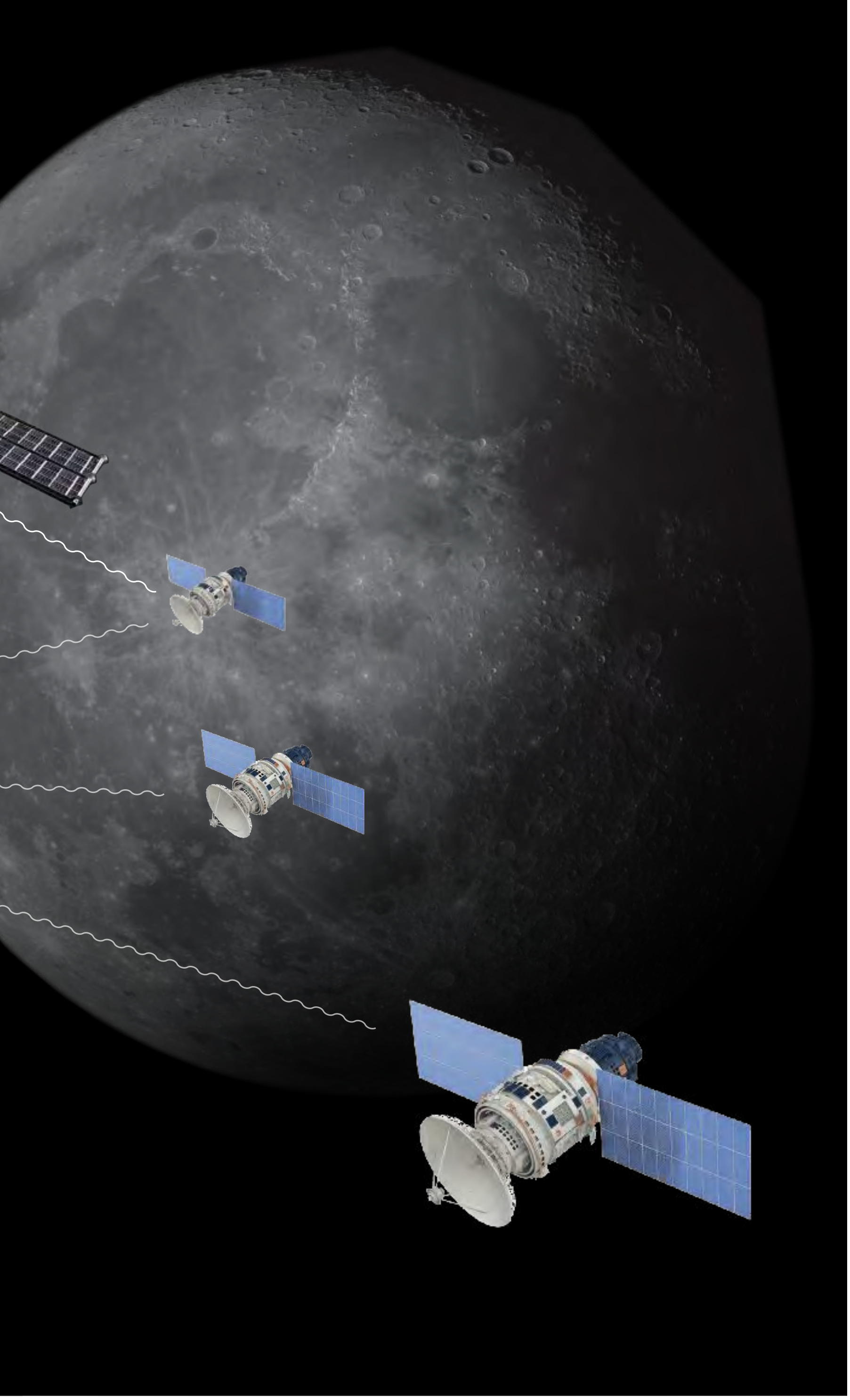


Navigating without the "surly bonds"

Spacecraft in deep space must exchange signals with ground stations so that their owners know where they are. That approach is not going to work if humanity sends swarms of spacecraft to the moon. The Deep Space Network receiving stations and those of other nations would be overwhelmed. Amanda Miller tells the story of a software that could solve the problem, if its developers can convince spacecraft operators to try it.



▲ **Spacecraft orbiting the moon** would navigate mostly by exchanging radio signals among themselves instead of frequently with Earth. NASA is partially funding the software development.

BY AMANDA MILLER
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Aerospace engineer Bradley Cheetham likes to keep a cubesat frame on a table in his lab at Advanced Space, the mission planning company he co-founded in 2011 in Colorado. The palm-sized frame is a reminder to himself and the company's 14 employees that someday, maybe soon, the moon will be swarming with spacecraft — mostly cubesats, he expects — all of which will need to be tracked as they perform a variety of roles, such as looking for water ice.

Cubesats would be just one class of spacecraft destined for the vicinity of the moon and its surface as space agencies and entrepreneurs seek to pick up where the Apollo astronauts left off in 1972. Lunar advocates want to continue exploring and ultimately commercialize the moon as a tourism destination and source of natural resources, while NASA and some in the private sector want to hone skills needed for a mission to Mars. The enthusiasm is multinational, with German company PTScientists planning to land two rovers on the moon next year, for instance.

If waves of spacecraft indeed are launched toward the moon, Cheetham predicts there is no way that NASA's Deep Space Network and the similar transmitting-and-receiving antennas operated by other nations could, or should, handle so many tracking pings.

"The more we have to use these ground assets in tracking, the less we can use them to relay information," Cheetham says. He's referring to the commands, software patches and upgrades that NASA, private companies and other space agencies must be ready to send to spacecraft operating in deep space. For NASA, the list of spacecraft includes the Curiosity rover on Mars, the planned Mars 2020 rover, and the InSight lander scheduled to touch down on Mars this month. Images and scientific data must be free to flow back to Earth via the DSN antennas in Australia, California and Spain.

Cheetham thinks his company has the solution to the risk of overwhelming DSN or other sites with tracking signals. He wants to simulate and eventually prove in space an entirely new navigation strategy in which moon-orbiting spacecraft would exchange radio signals among each other to estimate their orbits, thus reducing the burden on the ground network.

The foundation for the concept is software called CAPS, short for Cislunar Autonomous Positioning System, which Advanced Space is developing under a series of NASA-funded small business contracts, the most recent being one for $750,000 announced in June, plus a $250,000 grant from the state of Colorado. He's pushing to ready some subset of the software, even just a data-gathering element, for a test in space as soon as mid-2020.

To achieve that schedule, software development must proceed on pace, and Cheetham must find a moon spacecraft that's willing to give CAPS a ride.

Among the software's advocates is NASA's Jenifer Donaldson, a space navigator and mission designer who has been scouting for spacecraft to try CAPS. When she learned about the software, "it just popped straight out to me — this is what we need," she says. She works in the Space and Communications Navigation group at Goddard Space Flight Center in Maryland. "One of our higher-level goals for future technology is to make communication

“The more we have to use these ground assets in tracking, the less we can use them to relay information.”

— Bradley Cheetham, Advanced Space, referring to the commands, software patches and upgrades that operators on Earth must send to spacecraft in space

and navigation services more seamless,” she says.

Today, a spacecraft orbiting the moon requires two-way contact with the DSN, for example. A station sends a succession of radio signals to the spacecraft, which sends the signals back. The ground station times the signals’ round trip, and those times factor into the formulas for estimating the spacecraft’s orbit. This process factors in distance, velocity, estimation theory and statistics. Commands to correct the course go back via the same antennas. Demand for antenna time is already competitive and about to start adding up.

CAPS would be loaded onto a spacecraft’s flight computer during construction. When the spacecraft gets to lunar orbit, the software would tell it when to bounce radio signals off various other spacecraft running the system, producing frequent estimates of a spacecraft’s orbit based on Advanced Space’s proprietary algorithm, or “secret sauce,” as Cheetham calls it.

Navigating on the fly

One challenge for liberating spacecraft from Earth is that today navigation requires atomic clocks at ground stations on Earth. Spacecraft trajectories and orbits are estimated by determining the distance from the station’s antenna, and the change in that distance (aka velocity). This requires sending batches of round-trip radio signals and determining the transit times with atomic clocks.

The problem is that, although NASA plans to launch a prototype Deep Space Atomic Clock this month, today’s spacecraft don’t have such clocks. They would not fit on cubesats anyway.

Cheetham had to make sure spacecraft loaded with his software would not need such clocks. He’ll do that by exchanging tracking signals more frequently and by taking advantage of the spacecraft’s position in the unique three-body system in which the spacecraft’s orbit is significantly influenced by gravity from both the Earth and moon.

Specifically, to figure out how far apart spacecraft are from each other, they would send signals between each other more often than the busy ground stations could permit. This means the software would have more frequent range data, adding up to better accuracy. Only occasionally would the spacecraft need to exchange signals with Earth to determine range.

The technique would not work for satellites in Earth’s orbit, because of our planet’s symmetrical gravity field, which is not heavily influenced by the moon. Attempting to estimate a satellite’s path would produce two possible orbits. That’s not so in lunar orbit, where the gravity fields of Earth and the moon factor into the software’s proprietary math.

Self-monitoring

On the ground, it’s easy to know whether tracking software is working properly. Navigators with particular expertise routinely analyze incoming data to figure out if something is amiss with a spacecraft’s software or computer.

In Cheetham’s scheme, the owner of a satellite wouldn’t have that luxury because the software would be thousands of kilometers away in space. “Nobody’s there to say, ‘Hey, that doesn’t look right,’” he says. “The system has to know, itself, if it’s working or not.”

So the combined team of software engineers and aerospace engineers have been developing tests to automatically check aspects of the software as they are developed. Code would, for example, regularly analyze the location estimates to look for inconsistencies that might suggest that the software needs to be rebooted.

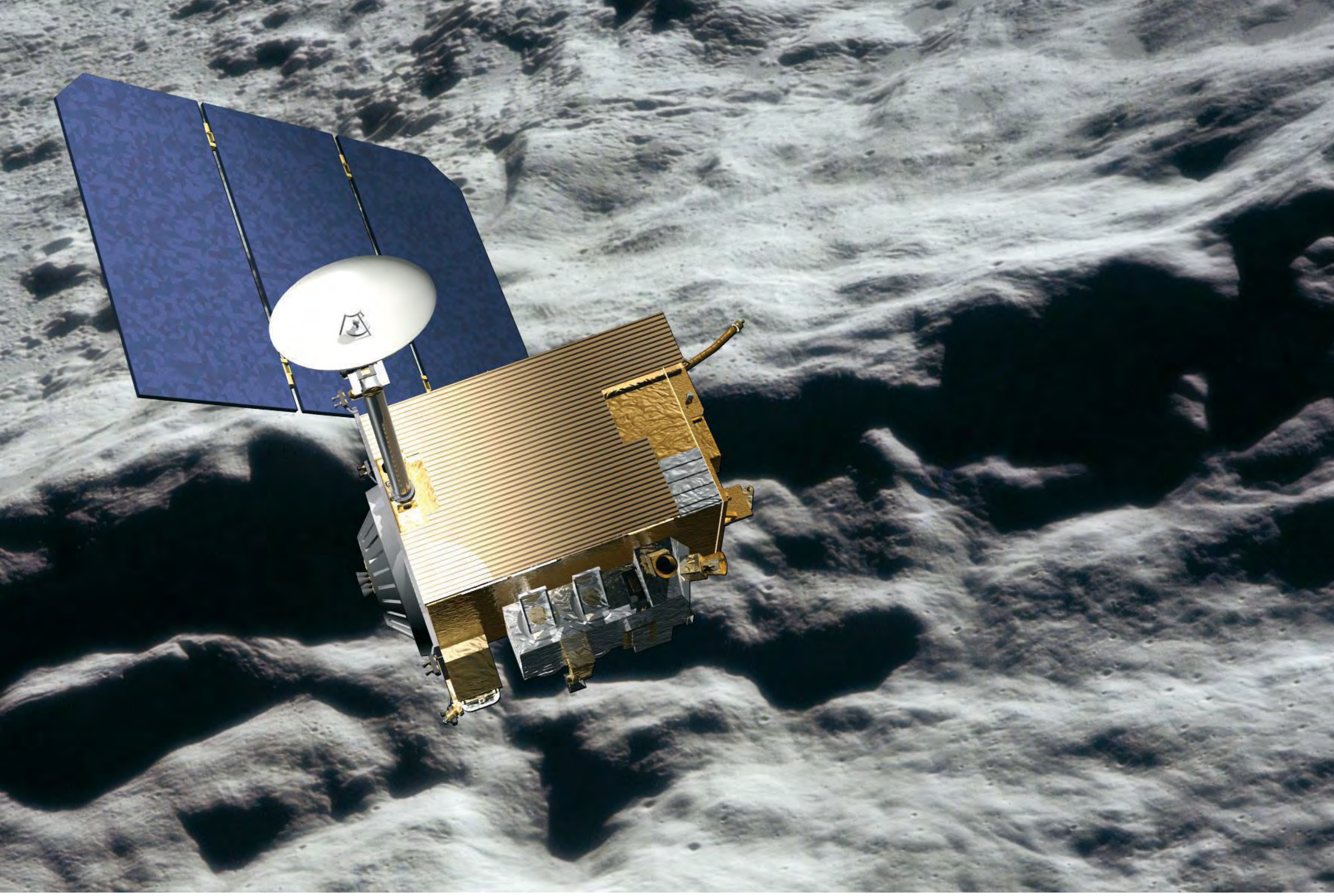
Early versions might not have that full functionality. For the prototype due at the end of this two-year NASA development phase, CAPS could just record the fact that an error occurred. In the future, Cheetham hopes the software will be able to command itself to reboot or revert to a trusted version.

Together but separate

Cheetham’s software would be a new way of doing business for the industry. He needs to convince the people building spacecraft to choose off-the-shelf computers and radios that would be compatible with CAPS.

Just a handful of radios, for example, might perform with a sufficiently consistent signal-turnaround time for the software to calculate a signal’s round trip accurately enough. Plus, radios will need to operate on the same frequencies.

Making sure spacecraft designers have a heads-up about the system’s likely hardware requirements, which are being defined now, is one of Cheetham’s core strategies on the business side. As he finds out from a company or institution which computer it’s using on a particular mission, his developers build a new



▲ **NASA's Lunar** Reconnaissance Orbiter could help Advanced Space prove its software's efficacy.

NASA

simulation to figure how well CAPS would run on it.

Another issue is that companies and space agencies might view themselves as competitors in exploitation of the moon. They might hesitate to join the CAPS network, if they perceive a cybersecurity risk from intersatellite links. To solve that, CAPS will be designed so that when one spacecraft receives a signal from another, the signal arrives in the form of a ranging tone that the radio on the receiving spacecraft simply sends back, with no data left behind.

New software — dated computers

Another challenge is that Cheetham's sophisticated software must run on spaceflight computers whose designs were tested and sealed so long ago that they are 15 years behind consumer laptops in terms of performance. Flight computers lag behind because of the extensive testing they must undergo to assure they can handle the rigors of launch and years in space.

So his team must be careful not to design "in a vacuum from reality," as he puts it.

In the testing lab at Advanced Space, simulations are run on modern processors while several circuit boards — some configured to fit in a cubesat, all judged to perform like proven spaceflight computers — wait at the ready to try out CAPS. This results in a scenario that's closer to real life.

How to beat the rush

To help market the software, NASA could pitch in a third phase of funding at the end of this two-year phase, but that won't be soon enough.

With missions such as the German rovers launching as soon as 2019, "We can't be starting that process of, 'Hey, let's go fly,' in July of 2020," Cheetham says.

So Advanced Space is spending its grant from the state of Colorado to start networking with the organizations that have lunar aspirations. Part of that involves pitching to potential early customers the idea of signing on with the company for conventional tracking at the outset while positioning themselves to upgrade once CAPS is online.

Part of the strategy for having CAPS ready soon comes from sticking with tried-and-true, two-way radio tracking, just doing it between two points in space.

The company has another idea that could help. Rather than having to line up a minimum of two spacecraft to launch with CAPS aboard, Advanced Space thinks it might only need one. The hope would be to get permission to trick a satellite already in lunar orbit — for example, NASA's Lunar Reconnaissance Orbiter — into thinking the new satellite is a DSN site.

"One of our big fears, one of the things we're trying to prevent," he says, is someone with a good idea being stymied by the ground station logjam. ★