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Volume 21, Issue 8

The Challenges of Lunar Navigation

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The space race of the 1950s, 60s, and 70s was one of the most exciting and accelerated technological times. From sending the first satellite into space to putting the first people on the moon, there were giant leaps in a short time frame. It represented competition between superpowers and the soft and hard power that came from it.

Fast-forward to today, and humans are going back to the moon—but this time in an overarching spirit of cooperation and perhaps even necessity. We've become increasingly aware of the fragile nature of our existence on Earth, making the desire to explore space all the stronger. We've come up against limitations imposed by our atmosphere and physics, but the perennial need to explore more and to break new ground is not diminished.

So, the first stop is the moon. But despite its relative proximity to Earth, going to the moon, putting boots on the moon, and staying on the moon comes with a daunting set of challenges. One of the foremost is positioning, navigation, and timing (PNT for short). We've come to depend on PNT in almost every aspect of our lives. Our communications, banking networks, energy distribution, and critical infrastructure rely on precise timing. Our vehicles and operations depend on positioning and the derived navigation. From the military to the civilian smart phone user, PNT is a cornerstone of all our existences.

Navigating to the moon, then. Navigating on the moon. Even navigating beyond the moon is one of the first questions to answer. How do we do it, and what challenges must we overcome to achieve this great enabler?

Navigating to the moon

Navigating to the moon is probably the most approachable challenge here. We've done it before – without the use of advanced satellite navigation – and we've done it more recently (see recent experiments on using GPS receivers in lunar orbit). To navigate to and from the moon with regularity, precision, and consistency, though, it makes sense for us to take advantage of the modern PNT infrastructure that we all depend on: global navigation satellite systems – or GNSS for short (the most well-known of these is GPS, but there is also Europe's Galileo, China's BeiDou, and Russia's GLONASS).

The trouble with GNSS is that it was designed to aid navigation and timing on Earth. The satellites orbit

Earth; their transmitting antennas are trained on Earth; our calculations to use GNSS are based on their use on Earth. However, as recently shown by NASA, GNSS can be used to navigate as far as the moon. The challenge here is in power and calculation. GNSS signals are extremely low-powered. On Earth, they are heard by our devices as low as -165 dBm, far below the noise floor. For GNSS to be used as a navigation aid on lunar transfers, we need high-gain antennas and finely tuned signal processing. Picking out the signal and applying enough gain is no trivial matter. But it is not insurmountable, and using GNSS from the start of the journey from Earth means we need to worry less about the tricky acquisition sensitivity than we do about the simpler tracking sensitivity. As for signal processing, the calculations here are known or can be made. We would primarily be using satellites that are about to disappear behind the Earth as their transmit antennas swing around and point in our direction. Not only does this mean the satellites are further away – at any time, most GNSS are orbiting around 20,000 km above the surface of the Earth, meaning the difference in the distance if heading away from the Earth could be a mere 50-55,000 km. While this is important, it falls mainly into the power consideration. Signals travel further, get weaker, and are harder to pick out.

For signal processing, the challenge lies in how far those signals travel through the ionosphere. Our phones, cars, and communications networks all make calculations based on established models to account for ionospheric delay. This is calculated by knowing how far the signals will have traveled through the ionosphere and how much this slows them down to calculate what we call the pseudorange accurately. Accurate pseudorange gives us precise positioning and exact timing. Signals coming from the other side of the Earth are passing through more ionosphere, being slowed more, and even refracting around the Earth. New calculations must be applied! But it can be done. We can navigate to the moon consistently using our existing infrastructure – particularly as the precision requirements are generally much lower. There's less stuff to crash into in space than in, say, downtown New York or Tokyo.

Navigating on the moon

The biggest challenges come when we answer the most significant questions on current and forthcoming lunar missions: why? Why are we going back to the moon? There are many answers to this question…

- To create a permanent human presence on another celestial body
- To take advantage of the resources available
- As a stopping-off point in further exploration of the solar system and the galaxy

We can't rely on earth-centric infrastructure to achieve any or all of these goals. Even if we ignore the challenges of using GNSS from so far away, at any one time, half of the moon is completely obscuredfrom that infrastructure. So, the mission has become to create a dedicated lunar navigation system.

A lunar navigation system

A Lunar Navigation System (LNS) has been on the agenda for the world's leading space agencies for some time now. There is cooperation between NASA, ESA (Europe), JAXA (Japan), and many others to design and build that infrastructure. In the first instance, this will consist of a small regional system of satellites operating around the moon's south pole. This will serve as a proof of concept and enable early missions and activities on the moon's surface. It is slated to use the relatively free S-band frequency and will conform to the agreed-upon LunaNet specification. But there are still key questions to answer here:

Will the new LNS provide its own time source?

Time is different on the moon. For many years, our precise timing systems on Earth have been governed by the vibrations of atoms. Cesium atoms react to microwave radiation at a frequency of exactly 9,192,631,770 hertz – we call it a second, but that's how it is measured. There are no elephants or Mississippis here; we're talking gold standard. However, the different gravitational conditions on the moon mean that cesium atoms react more quickly. 9,192,631,770 cycles happen quicker than what we would call a second. Does the moon have to conform to our existing norms regarding time? The moon actually spins 27 times slower than Earth, so is a second, an hour, or a day even relevant there?

What reference system will the LNS use for positioning?

We have come to take a position for granted. X marks the spot, or the blue marker marks you. But position is relative. The position your phone or car outputs is calculated relative to a (nearly) unanimously agreed-upon reference point: the centre of the Earth (Russia defines a different centre of the Earth to everyone else). This makes absolute sense on Earth. But it doesn't make sense to use the centre of the Earth as your reference point on the moon – that will require agreement on a new, likely geocentric, reference point. Even when that problem is solved – in lunar transfer, at what point do you switch from earth-centric reference systems to lunar-centric? The same could be asked of time.

How do we build something that will work on or around the moon?

The answer here is pretty simple: testing. But testing comes with its own challenges! When you get a new radio-controlled car or a new golf club, you take it outside and drive it or whack balls with it to see if it works. When these things were being developed, they followed more scientific and representative test regimens. When we talk about millions – or billions – of dollars' worth of infrastructure that will operate in an environment nothing like "outside," this course of action isn't just unscientific. It's impossible.

Testing requires precise and highly realistic simulation. There's no room for error when sending the equipment 384,400 km into space, so the testing must be robust and representative. A simulation system has to be able to implement these new reference systems. It has to be able to control and generate GNSS signals at unfathomably low levels of power. It has to be able to implement the new LNS signals and apply them with the correct effects representing a different atmosphere, with different perturbations caused by various interactions with other celestial bodies.

JAXA recently announced its purchase of a Spirent simulation system to model and create this new navigation system and test the devices that will use it. The system combines power and flexibility with the expertise of Japan's (and collaborating ESA and NASA) engineers. This simulation capability means we can and will move from plan to action. We are going back to the moon, and we are taking PNT with us.