Water makes its mark on GPS signals

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In addition to being a navigation tool, GPS signals are helping scientists observe Earth's hydrologic cycle.

Gone are the days of asking for directions. Now anyone with a smartphone can quickly find the location of the nearest coffee shop, closest gas station, or the fastest way out of town. Runners can stay on pace, or not, and they can know how far, or how little, they have traveled, thanks to their GPS watches. The use of the global positioning system has become so ubiquitous that some researchers are worried that humans are losing their sense of direction because of it.

Despite GPS's popularity, few are aware of an unintended use of its signals. Aside from providing location information, GPS signals can be used to glean information about Earth's hydrologic cycle. They can distinguish whether the surface is wet or dry, how much water is contained in the soil and vegetation, and how much snow is on the ground.

Although GPS satellites were first launched in the late 1970s, their use as a remote-sensing tool was not explored until the mid 1990s. Since then, multiple ground and airplane experiments have shown transmitted GPS signals to be sensitive to a host of geophysical variables, such as near-surface soil moisture, snow depth, flood-inundation extent, sea-ice concentration, and ocean-surface winds. Now researchers are expanding their efforts to investigate how GPS signals recorded by satellites could revolutionize remote sensing.

Trash or treasure?

Earth is constantly bathed in GPS signals. Some of them are directly intercepted by the receivers located in cell phones and watches. Others first bounce off the ground, buildings, or anything nearby before being picked up by a GPS receiver. Those ground-reflected, or multipath, signals are normally a nuisance; they introduce errors and noise into the positioning estimate and are partly responsible for GPS being less reliable in cities with a lot of large buildings. Many GPS receivers have special algorithms that suppress those multipath signals. And the GPS antenna itself can be designed to block them.

Yet multipath signals can still creep in. In 2008, researchers at the University of Colorado were studying how to suppress multipath signals in GPS antennas and receivers. Those installations, like the one shown in figure 1, were designed to monitor the movement of tectonic plates, with antennas that are surrounded with metal rings that physically block multipath signals. But some multipath signals were still present in the data. Moreover, the signals appeared to change in intensity on a somewhat regular basis, especially for receivers located in fields and rangelands far from buildings and structures known for causing significant reflections.

When the researchers approached a hydrologist at the university, he recognized that the changes in the multipath signals looked eerily like a time series of soil moisture—regular and predictable signal increases during and shortly after rainstorms, with a subsequent slow decrease, indicative of the soil drying out.

The Colorado research group began investigating whether the ground-reflected signals could be

FIGURE 1. THE GPS ANTENNA under this hemispherical dome was designed to monitor the movement of tectonic plates. Ground-reflected GPS signals can be used to infer the soil moisture content near the antenna.

used to infer the moisture content of the soil. Their goal was to effectively repurpose the GPS antennas into soil moisture sensors, which could help monitor droughts and validate data from satellites that are designed to retrieve soil-moisture data. The task, however, wasn't as simple as directly correlating the multipath signals with observations of soil moisture. Seasonality in the time series indicated that the ground-reflected GPS signals were also likely affected by water in overlying vegetation.

By combining numerical modeling and analysis of hundreds of field samples, the Colorado group successfully derived an algorithm that would estimate soil moisture near a geodetic GPS antenna. More than a thousand of those antennas were scattered throughout the western US and Alaska as part of the Plate Boundary Observatory network funded by NSF. Hundreds of the antennas could be used to derive soil moisture with a resolution of about the area of a football field. The outcome was a new array of GPS soil moisture sensors—one of the largest such networks in the world.[1]

A different kind of radar

In retrospect, it should not have been so astonishing that GPS signals are sensitive to water in the soil. After all, microwave radar had been used for years to detect changes in soil moisture and surface water. And GPS is a type of microwave radar system, albeit with a different scattering geometry. In traditional radar, both the transmitter and the receiver are located on the same platform, which means the transmitter sends out a signal, and the receiver records it after it bounces back to the platform. GPS satellites, however, have only a transmitter, not a receiver. Receivers are normally located in cell phones, on towers, or in airplanes.

Although the scattering geometry is different, GPS signals behave much like any L-band microwave signals, which lie in the 1–2 GHz frequency range. They are sensitive to water in the soil and on the surface because of the large change in dielectric constant between a dry and a saturated soil; a similarly large difference in the dielectric constant exists between a saturated soil and water. Wetter soils have higher dielectric constants, which causes the surface to reflect the incoming GPS signals more strongly.

In ground-based systems, the surface-reflected signal interferes with the direct signal, which travels from the GPS satellite straight to the antenna. The extent of the interference depends on the difference in path lengths that the two signals have traveled and on the properties of the reflecting surface. By measuring changes in the frequency, phase, or amplitude of the interference pattern relative to a bare, dry reference state, one can infer changes in the surface, be they from soil moisture, vegetation, or snow.

In many ways, GPS signals are ideal for remotely sensing the terrestrial hydrologic cycle. Because the circularly polarized L-band signals are unaffected by cloud cover or sunlight, they can see the surface no matter the time of day or atmospheric conditions. In addition, the wavelength of L-band signals—19 or 24 cm in the case of GPS—is relatively long compared with those of other microwave frequencies, such as the C or X band. That's important because the wavelength is directly proportional to how much vegetation a signal can penetrate. Longer wavelengths can better sense the surface conditions beneath a canopy.

Although L-band signals are less affected by vegetation, they are still attenuated by traveling through the canopy. The roughness of the surface can also greatly affect how reflective the surface is. Smooth surfaces produce much stronger reflections than rough surfaces, which can scatter the signal in directions away from the receiver. Those confounding factors are by no means unique in the remote-sensing world, although they can and do complicate the analysis of GPS reflections.

Capturing reflections in space

Surface-reflected GPS signals don't just bounce around incessantly from buildings to trees to cars. A fraction of the signal eventually finds its way back into space. Despite the relatively weak transmitted signal, ground-reflected GPS signals can be observed from low Earth-orbiting satellites with receivers specially designed to record the reflections. Given the success of ground-based GPS receivers in capturing soil moisture and other variables, it is natural to wonder whether the retrieval could be done from space, as data from satellites could increase the spatial coverage from point measurements to global observations.

Scientists have known for years that GPS signals reflecting off the ocean surface can be recorded by satellites and used to infer the roughness of the water, which itself is related to the surface wind speed. The first robust demonstration came from the Disaster Monitoring Constellation's UK satellite *UK-DMC1* in the mid 2000s. The satellite carried an experimental receiver designed to capture GPS reflections, although many researchers were skeptical it could actually work. They were wrong, and *UK-DMC1* proved that ocean-reflected signals could indeed be consistently recorded by a downward-looking GPS antenna onboard a satellite.[2]

The signals' sensitivity to roughness and, by extension, wind speed motivated NASA to fund a new mission in which a constellation of eight satellites would collect GPS reflections. The Cyclone Global Navigation Satellite System (CYGNSS) was launched in December 2016 to measure hurricane wind speeds, with the ultimate goal of learning how to better predict the storms' intensities.[3] Since its launch, CYGNSS data have been successfully used to map winds during numerous hurricanes, including Harvey and Irma. Those data have been assimilated into numerical weather prediction models to improve forecasts of a storm's track and intensity.

Even though CYGNSS was designed for collecting data over the ocean surface, the satellites also collect information over land. Before CYGNSS, there had been hints as to what GPS reflections would look like over land. The *UK-DMC1* experiment produced a handful of observations over Nebraska[2] in the mid 2000s. A subsequent satellite, the UK's *TechDemoSat-1*, showed in 2014 that discernable reflected signals could be obtained over a wide variety of land cover types and surfaces.[4] The data were still much too sparse to fully image the land surface, but they left researchers hopeful, although with only inklings of what the true potential of the new technology could be.

After the launch of CYGNSS, researchers quickly began mapping the reflections coming from the land surface to determine whether the data were at all responsive to changes in surface hydrology. To their surprise, the data appeared to be incredibly sensitive to extremely small surface-water features. For instance, researchers easily imaged the Amazon River's tributaries, some as small as 25 m wide, using data from CYGNSS, as shown in figure 2. And they observed significant sensitivity to soil moisture when they compared the data with retrievals from operational soil moisture satellites.[5]

That finding was surprising because before the launch of

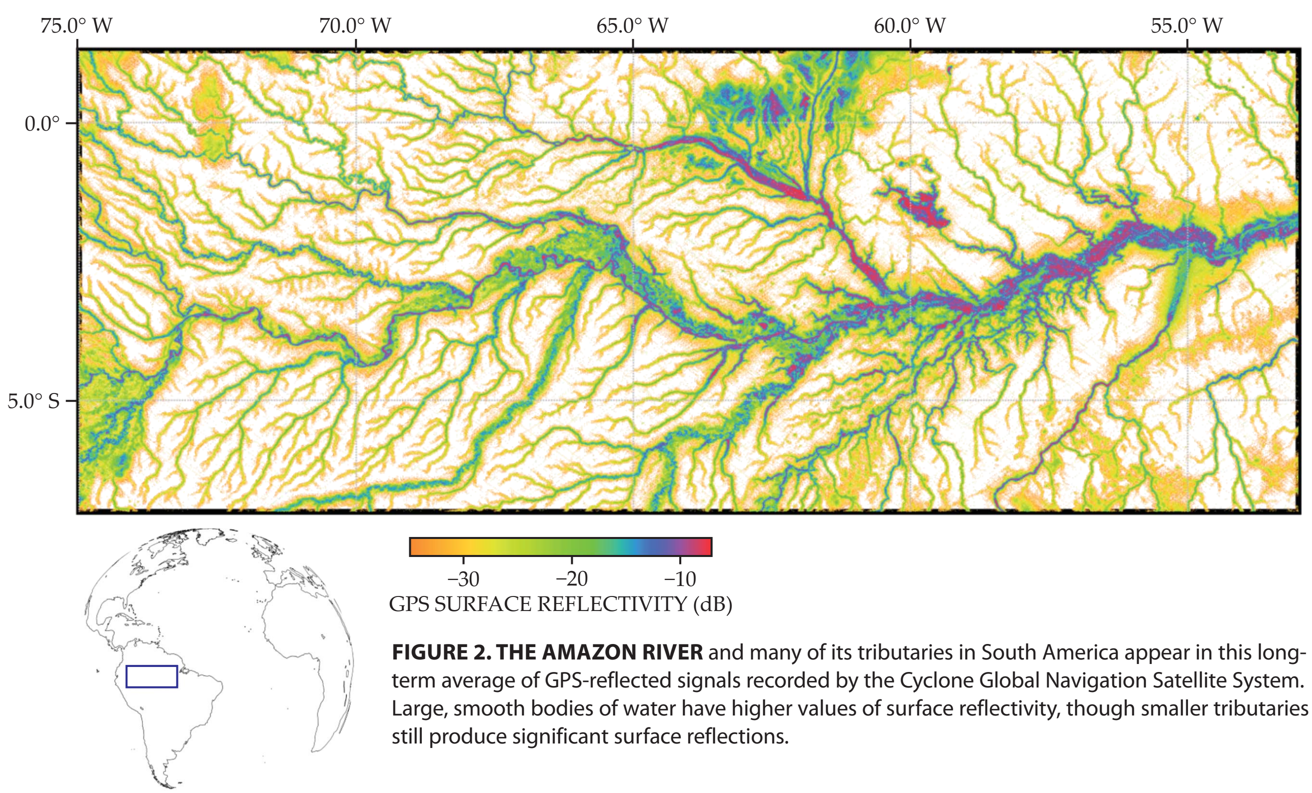


FIGURE 2. THE AMAZON RIVER and many of its tributaries in South America appear in this long-term average of GPS-reflected signals recorded by the Cyclone Global Navigation Satellite System. Large, smooth bodies of water have higher values of surface reflectivity, though smaller tributaries still produce significant surface reflections.

CYGNSS, the vast majority of the research pertaining to spaceborne GPS-reflection data came from theory and modeling that assumed a rough ocean as the scattering surface. The roughness produces a weakly scattered signal coming from an area of about 25 km × 25 km. Most researchers had assumed that the land surface would be much more electromagnetically rough than the ocean surface. Surely, they thought, hills and trees were rougher than the average ocean wave, and they had anticipated even weaker reflected signals as a result. What they found instead was that inland water bodies sheltered from the wind are smooth enough to produce coherent reflections, which result in a strong signal from a relatively small area, about 0.5 km^2.

Cost and constellations

The discovery that the land surface can produce powerful reflections at a relatively high spatial resolution has spurred interest in how GPS-reflected signals recorded by CYGNSS or future satellites like it could map flooding, changes in soil moisture, and other variables, such as the freeze-and-thaw state of the soil[6] and even sea-ice extent.[7] Several other remote-sensing satellite techniques and instruments can retrieve the same information, but the GPS reflection technique stands apart for its cost-effectiveness. Because the technique essentially recycles signals that already exist, no expensive transmitters need to be built, and their absence decreases the size and mass of each satellite.

Other microwave instruments, including passive radiometers and active radar, cost hundreds of millions of dollars to launch in a single satellite. For example, in collaboration with the Indian Space Research Organisation, NASA is scheduled to launch the *NASA–ISRO Synthetic Aperture Radar* (*NISAR*) spacecraft in early 2023. *NISAR* will fly a combined L- and S-band active radar and cost approximately $1.5 billion. By comparison, CYGNSS cost a total of $150 million for the eight satellites.

The financial benefit alone is compelling, given the always uncertain funding for Earth science. But the relatively economical nature of the technique opens the door for launching constellations of instruments, as CYGNSS has already demonstrated. Constellations of satellites decrease the temporal repeat period: You get data from one particular spot more often with many satellites than with only one. For many applications, having frequently updated data is key. In the case of flooding, affected communities require rapidly updated flood maps to know where and how to get resources. Because floods are usually associated with significant cloud cover, they are often mapped using data from microwave instruments. (See the box on page 47 for an example.) Currently, the instruments with the fastest repeat time are passive radiometers, which collect naturally emitted microwave radiation from the surface. The repeat time, once every three days, comes at the expense of spatial resolution, which makes it difficult to pinpoint where the flooding actually is.

On the other hand, active microwave radar instruments, such as *NISAR*, have a high spatial resolution, on the order of tens of square meters. Their temporal repeat period, however, is quite long—more than 10 days—which implies a significant risk of the instrument missing the entire flooding event. And even if the satellite doesn't miss the entire incident, the snapshot of data it collects may not capture the maximum flood stage.

Launching constellations of either passive or active microwave instruments to decrease the temporal repeat period is an expensive proposition. For example, the European Space Agency currently has in orbit two C-band radar satellites, which make up the Sentinel-1 constellation. And it plans to launch two additional satellites in the coming years at a cost of more than €200 million ($226 million) per satellite, or more than €800 million altogether for the four-satellite constellation.

Unique obstacles

Although launching constellations of inexpensive GPS reflection satellites is an attractive proposition, the technique is not without its own challenges. The collection strategy characteristic of spaceborne GPS reflection observations may appear a bit strange to those familiar with traditional remote-sensing data. Usually, satellite remote-sensing missions are designed to collect observations over a particular area at a particular rate. Someone interested in soil-moisture data for Dallas, Texas, for example, can have confidence that NASA's *SMAP* (*Soil Moisture Active Passive*) satellite, an L-band radiometer, will provide those data every three days at 6:00am central time. The timeline for spaceborne GPS reflection data, however, is murkier. Because the positions of the GPS transmitters and GPS reflection receivers are constantly changing, so are the reflection points on Earth's surface.

The result is a set of observations pseudo-randomly positioned across the landscape, as can be seen in the box figures on page 47. Over Dallas, two subsequent GPS reflections might be collected within a few hours of each other, followed by several hours or days without data. The temporal gaps, however, can be shortened with the addition of more low-cost satellites. Recording data from the other constellations of navigation satellites, such as the European Union's Galileo or Russia's GLONASS, could also increase the density of observations without the need to launch more satellites. GPS reflection receivers that do that are already in development.

In addition, one of the greatest advantages of the GPS reflection technique—its use of freely available transmitted signals—comes at a cost: a lack of signal control. Despite being widely used by the civilian population, the constellation of GPS transmitters is fundamentally a military operation. And the military can and does change the power of its transmitted signals. A more powerful transmitted signal will result in a more powerful reflection. But without knowledge of the changes in transmission power, changes in the reflection power could be mistaken for a change in the surface hydrology. Those jumps in power level can be mitigated by observing the power of the direct signal, which travels from the GPS transmitter to the receiver without first reflecting off the ground. Future GPS reflection satellites will likely perfect that mitigation strategy.

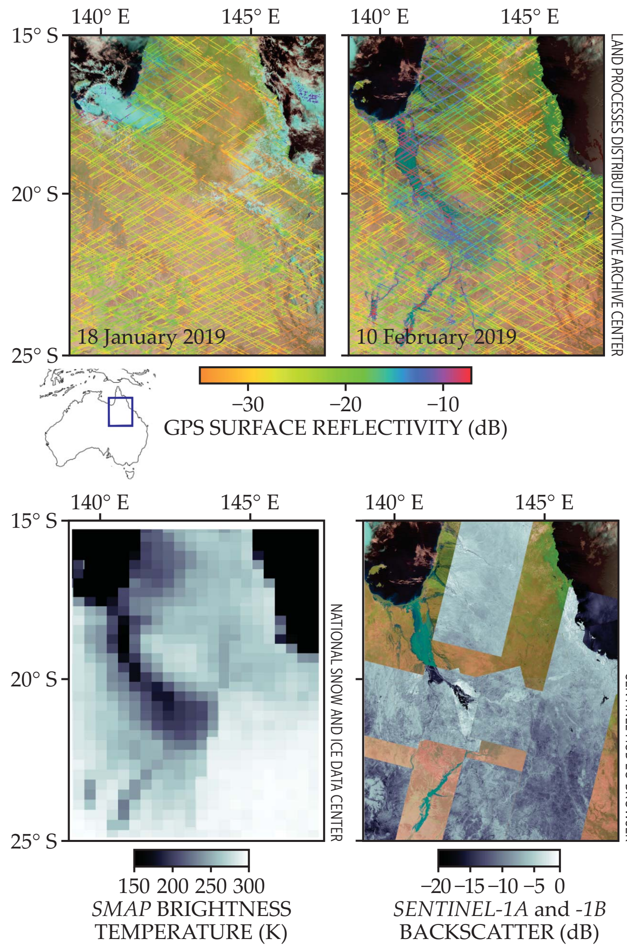
Carving out a niche

The unique advantages of the GPS reflection technique still do not make it a one-stop shop for every hydrologist's remote-sensing needs. The superior spatial resolution of active radar data is useful for mapping inundation in a single neighborhood, for example. And the repeatable swaths of measure-

IMAGING A FLOOD

Heavy rain in late January 2019 brought wide-scale flooding to the state of Queensland in northeastern Australia and helped to end a long drought. Ground-reflected GPS signals recorded by the Cyclone Global Navigation Satellite System (CYGNSS) constellation captured the extent of the flood, as shown in the top panels. Researchers used cloud-free images from the MODIS (Moderate Resolution Imaging Spectroradiometer) instruments aboard the *Terra* and *Aqua* satellites to confirm the flooded area. CYGNSS data (superposed as colored stripes) in the flood's boundary show a significant increase in the power of the reflected signal (right) relative to that observed before the flood (left). Large increases in the reflected signal strength could ultimately be used to map flooding at spatial and temporal scales not currently available with other methods.

The CYGNSS satellites were not the only microwave instruments to record data during the flood. Images from an L-band microwave radiometer on NASA's *SMAP* (*Soil Moisture Active Passive*) satellite and a pair of C-band radars on the European Space Agency's *Sentinel-1A* and *Sentinel-1B* satellites are shown in the bottom panels. Each satellite can provide complementary information when creating a timeline of a flood. At left, the *SMAP* satellite captured average brightness temperatures on 8–12 February 2019 during the Queensland flooding event. Although *SMAP* data cover the region entirely, its resolution is quite coarse. At right are aggregate data recorded by *Sentinel-1A* and *Sentinel-1B* during the same time period. Those satellites captured less area, but their record is richly detailed.



ments and consistent, global coverage of radiometer observations make them well suited for assimilation into numerical weather and climate models.

Instead, GPS reflection technology can provide data that are complementary to those that already exist from other microwave instruments, and it can help fill a gap in our knowledge of how hydrologic events evolve over short time scales. For instance, scientists could map short-term changes in soil moisture in environments more heterogeneous than a typical 36 km radiometer pixel, and the CYGNSS data have already shown promise in that regard. Recently, data from CYGNSS were used to help map high-resolution soil moisture in East Africa during a severe locust outbreak. Locusts tend to hatch in environments with a specific soil moisture range, and by mapping the current soil moisture conditions, scientists were better able to identify the location of the locusts' likely breeding grounds.[8]

What's more, satellites that record GPS reflections have the potential to offer moderate (0.5 km^2) spatial-resolution maps of flooding within a matter of days of the event. If more low-cost GPS reflection satellites are launched, the gaps in observations, as highlighted in the box, could be filled, so that maps akin to the one shown in figure 2 could be available daily. The improvement could revolutionize how satellite data are used—not only to monitor but also to respond to events in near-real time.[5,9]

Whether significant investment into GPS reflection technology will actually be made by government agencies remains to be seen. The recent announcement of *HydroGNSS*, a reflection-satellite concept, as the second European Space Agency scout mission is certainly encouraging. And if recent investments into reflection research by commercial satellite companies are any indication, the field is likely to continue growing. It is only a matter of time before the full potential of GPS signals is realized, and given the field's rapid advances in just the past five years, we may not have long to wait.

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