Reflecting on GPS

Sensing Land and Ice from Low Earth Orbit

Scott T. Gleason

GPS IS NOT YOUR PARENTS' POSITIONING SYSTEM. Today, GPS is being used in a variety of unconventional ways, likely unthought of when the system was being designed back in the early 1970s. With data from a network of geodetic-quality receivers, geodesists are monitoring the small fluctuations in the Earth's spin and the wobble of the Earth on its axis.

Other scientists use GPS data to measure the drift and flexure of the Earth's tectonic plates and the rise of sea level due to global warming and other causes. These applications rely on GPS to produce extremely accurate antenna positions — to better than a centimeter.

INNOVATION INSIGHTS
with Richard Langley

Analysis of reflected signals holds great promise for measuring ocean roughness, ice conditions, vegetation cover, and even soil moisture.

Other unconventional uses of GPS include studies of the Earth's atmosphere from the ground and from low-Earth-orbiting satellites. The radio signals emanating from the GPS satellites must travel through the ionosphere and the neutral atmosphere on their way to receivers on and near the Earth.

The propagation velocity variations the signals suffer due to the electrons and electrically neutral atoms and molecules they encounter allows scientists to determine ionospheric electron density for space weather studies and water vapor concentrations in the troposphere for moisture forecasts.

In this month's column, we look at yet another out-of-the-ordinary application of GPS: using signals reflected off the Earth's surface to sense land and ice, as well as the ocean surface, from low Earth orbit. Such reflected signals, weaker and with less coherence than ~~light~~-of-sight signals and with predominantly left-handed polarization, have been intercepted by a special receiver on the United Kingdom's Disaster Monitoring Constellation satellite.

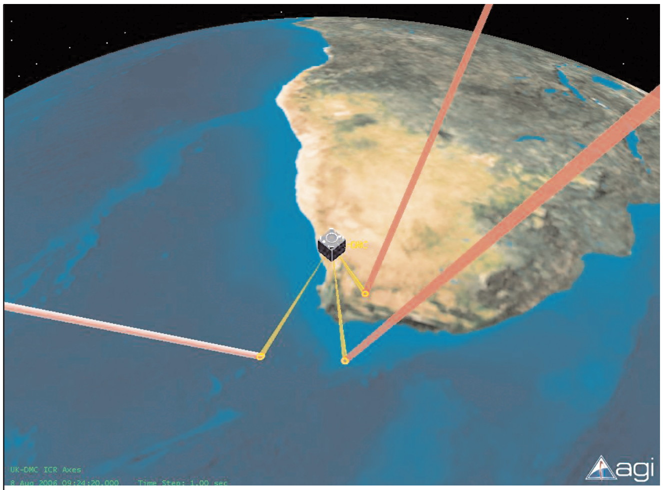
Analysis of these and other reflected signals holds great promise for measuring ocean roughness, ice conditions, vegetation cover, and even soil moisture from orbiting satellites! And you thought GPS was just a positioning, navigation, and timing tool. Read on.

"Innovation" is a regular column that features discussions about recent advances in GPS technology and its applications as well as the fundamentals of GPS positioning. The column is coordinated by Richard Langley of the Department of Geodesy and Geomatics Engineering at the University of New Brunswick, who welcomes your comments and topic ideas. To contact him, see the "Contributing Editors" section on page 10.

The signals from the GPS constellation satellites are constantly being scattered from the surface of the Earth. The usefulness of these signals for remote sensing applications was proposed over a decade ago when the European Space Agency's Manuel Martín-Neira suggested they could provide a new source for ocean altimetry measurements. Researchers in the U.S. demonstrated soon afterward that the signals from this bistatic radar technique, with separated transmitter (a GPS satellite) and receiver (on a host platform), could also be used to sense sea winds and waves.

As this concept advanced and good preliminary results were obtained from aircraft experiments, the attention turned to validating this technology from a space-based instrument, thereby opening up the possibility of global measurement coverage. The general concept of using reflected signals from a space platform is illustrated below in **FIGURE 1**. Notably, with a suitably designed instrument, it would be possible to track the reflections from all-in-view navigation satellites, making several parallel measurements (only three reflections are shown in the figure for clarity).

With the launch in October 2003 of the bistatic GPS experiment on the United Kingdom's Disaster Monitoring Constellation (UK-DMC) satellite, a unique instrument has existed to test the feasibility of monitoring reflected signals from low Earth orbit. The UK-DMC satellite is one of the small, low-cost satellites built by Surrey Satellite Technology Ltd. (SSTL) to provide daily images for a variety of applications, including global disaster monitoring. It is also a test vehicle for state-of-the-art technologies such as those associated with the bistatic GPS experiment. The results obtained so far from the experiment have shown that this is a viable technique for remotely sensing ocean roughness, and holds promis-



▲ **FIGURE 1** Illustration of the bistatic reflection geometry for signals from three GNSS satellites as received in low Earth orbit

ing potential to make useful scientific measurements in numerous other fields of research, including land and ice sensing applications.

The UK-DMC instrument includes a downward-looking antenna interfaced to SSTL's Space GPS Receiver (SGR) and a backup data recorder. The SGR-10, a single frequency (L1) C/A-code receiver, which normally uses two space-facing antennas and provides general platform navigation information, was upgraded to interface to a higher gain (12 dB) Earth-facing antenna. Additionally, a raw data sampling capability (for a single space-facing and the Earth-facing antenna) was added, which logged the downconverted intermediate-frequency signal into a spare data recorder at 5.714 MHz. This data could then be transmitted to the ground and processed using a software receiver, as described below. The Earth-facing antenna is left-hand circularly polarized to capture more signal power from the predominantly left-handed circular polarization, which the signal acquires on reflection. Raw data sets, up to 20 seconds in length, have been repeatedly captured, downloaded, and processed with a ground-based software receiver. The reflected waveforms discovered to date have demonstrated the potential of this technology as well as highlighted some of the difficulties unique to spacecraft altitudes. Significant validation has already been performed in the area of space-based ocean wave sensing. However, this article will concentrate on two of the UK-DMC experiments' latest revelations: that GPS signals reflected off land and ice surfaces are easily detectable from a spacecraft and that the power levels observed can be connected to surface features.

Land Applications. The most likely candidate for the application of GNSS bistatic remote sensing from land is sensing the water content in the top layer of soil. Soil-moisture sensing is emerging as an important and often lacking parameter in numerous fields of research and this technique has been successfully demonstrated using near-Earth platforms such as aircraft. The known applications of soil moisture measurements include better determination of crop yields; flood prediction, drainage, and run-off estimation (urban planning); inputs into weather prediction models; and the study of chemical and nutrient transport in environmental investigations. Additionally, the L-band frequency of GNSS signals has been shown to be sensitive to surface soil moisture, which provides us with an additional motivation.

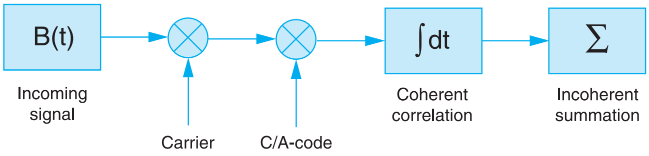
Ice Applications. An accurate knowledge of the coverage and thickness of the Earth's sea ice is a key input parameter into determining the extent of global warming. Measurements from GNSS reflections could be used to help monitor the seasonal variations in ice around the polar regions, where good global sea ice information is critical to understanding the changing climate.

In addition to climate change, there are other applications and possible end users concerned with the Earth's ice coverage. These include the sea ice impact on shipping routes, which is of crucial interest to marine navigators and the global shipping industries. The relatively low cost and wide coverage of the GNSS bistatic technique would make it a good candidate to contribute alongside the more advanced established instruments (such as the Canadian Space Agency's RADARSAT-1 and forthcoming RADARSAT-2 satellites) in observing the Earth's cryosphere.

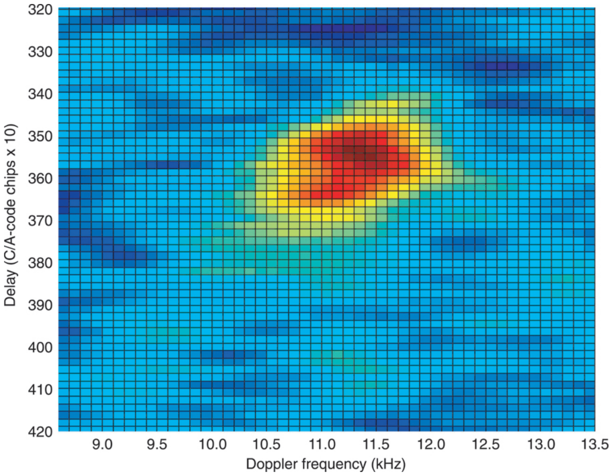
Signal Processing

In processing Earth-reflected GPS signals, the traditional GPS signal correlation process needs to be understood in a different context. As with most GPS signal processing, a coherent correlation over each 1 millisecond of data is performed with an internally generated local signal at a trial C/A-code phase delay and frequency. However, in most bistatic scenarios, the signal will be diffusely scattered from numerous facets on the surface, thus introducing speckle or fading noise to the received signal. The original phase information and navigation data modulated onto the signal is normally lost during the scattering process (unless the signal is reflected off a very smooth surface or the receiver is located close to the scattering area, in which case there may be original phase information present). Thus, a coherent correlation is performed on the resulting scattered signal received at the receiver, where normally no navigation data is present or needed. This diffuse signal remains coherent for only about a millisecond, determined mostly by the changing geometry but also the movement of the surface (in the case of the sea), thus preventing long coherent correlations to increase the signal levels.

Subsequently, consecutive averaging of these single-millisecond correlations is needed to reduce speckle noise and determine the true scattered signal power at a given C/A-code delay and Doppler frequency. I used a ground-based software receiver to process sig-



▲ **FIGURE 2** Reflected signal processing block diagram. The signal is normally processed over numerous C/A-code delays and Doppler frequencies.



▲ **FIGURE 3** Delay Doppler map for the December 7, 2005, data collection over land. The normalized power received for PRN18 after 1 second of incoherent averaging is indicated by a color scale.

nal samples as outlined in **FIGURE 2**, but it would also be possible to run such a software receiver on board a satellite.

The process shown in Figure 2 represents only the signal power detected at a single delay and Doppler frequency. To capture the necessary information resulting from the surface interaction, we usually had to repeat this process over a range of delays and Doppler frequencies near the point of specular or dominant reflection.

At different points over the scattering area on the surface, or glistening zone, the path delays and Doppler frequencies change significantly. This scattering of the signal over the surface results in a spreading of the signal power in the time and frequency domains that is fundamentally different from the characteristics typically observed during normal navigation GPS signal processing and tracking. This spreading can be clearly seen in a delay-Doppler map in which the signal power is plotted as a function of delay and Doppler frequency. An example of such a map for a land reflection is shown in **FIGURE 3**. In the figure, the signal-power spreading over several C/A-code chips and the increase in Doppler bandwidth after 1 second of non-coherent averaging are clearly evident. (Note that the delay indicated on the vertical axis is not the same as a distance on the surface. See Further Reading suggestions for more details on how delay and Doppler map to the surface.)

Land Sensing

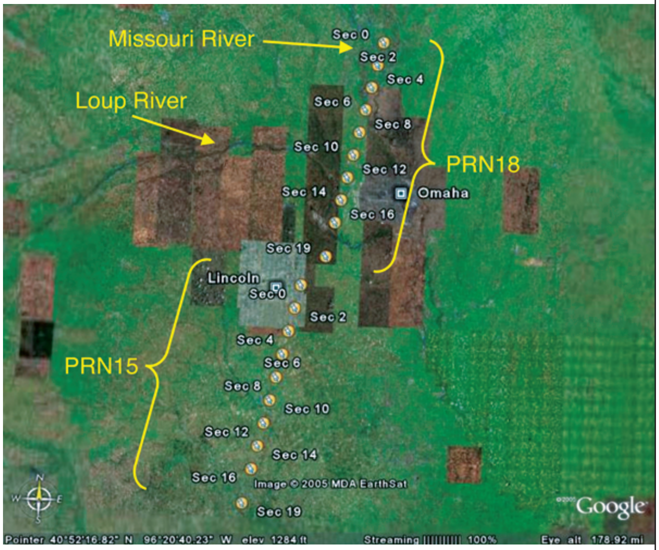
Previous research into the possibility of using GPS reflections for sensing soil moisture has been undertaken primarily at the University of Colorado in Boulder and the NASA Langley Research Center in Hampton, Virginia. Their experiments were performed using measurements taken during aircraft flights and from other near-Earth-based platforms. This research has demonstrated both the possibilities and difficulties of this technique over land surfaces.

A useful summary of the GPS bistatic technique over land is the Ph.D. dissertation by Dallas Masters from the University of Colorado at Boulder (see Further Reading). The results presented in his research showed that the GPS surface reflections were responding to surface moisture and displayed sensitivity to field boundaries and differences in land cover. However, sensing soil moisture or terrain cover from low Earth orbit is expected to be challenging, specifically due to the larger scattering region (or glistening zone) and changing local-terrain roughness and surface cover.

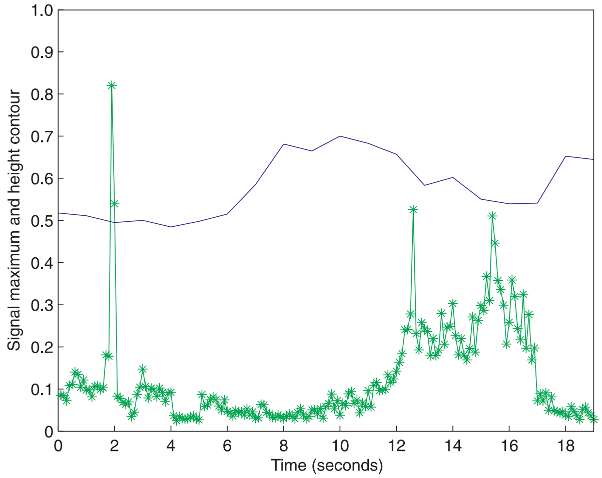
Example Data Collection. On December 7, 2005, a 20-second-long data set was collected over North America, near the city of Omaha, Nebraska, on the west bank of the Missouri River. This data collection included two satellite reflection points within the antenna surface footprint, both of which were open-loop tracked across the entire data collection at the locations shown in **FIGURE 4**. Interestingly, it is known to have snowed in the days before the data collection. Open-loop tracking (in contrast to conventional closed-loop tracking in which code and phase correlation peaks are tracked by a feedback process) is accomplished using the known locations of the transmitting satellite (from the International GNSS Service orbit data) and the receiver (from the SGR-10 navigation solution), from which the C/A-code delay and Doppler used in processing can be calculated and adjusted for the duration of the data.

Variations in the Signal Magnitude. I processed the signals across several C/A-code delays and Doppler frequencies using the approach illustrated in Figure 2. To mitigate the effects of speckle noise, the single 1-millisecond correlations or "looks" were summed together into 100-millisecond combined measurements across the entire duration of the data collection. The variations in signal magnitude are plotted in **FIGURES 5** and **6** as a function of time for the two reflections mentioned above.

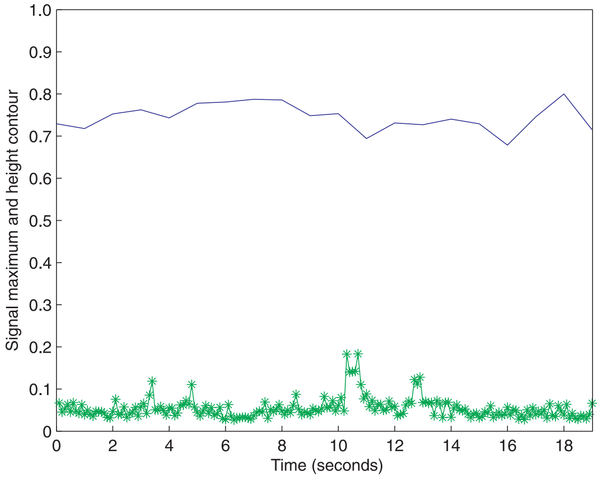
The geometry differences between the two reflections will have a small impact on the overall signal magnitudes, but over the short interval of the data, we can make some general comparisons. Over the interval shown in the figures, I believe the fluctuations in signal magnitude come



▲ **FIGURE 4** Google Earth image of the December 7, 2005, reflection locations for GPS satellite PRN15 (to the south) and PRN18 (to the north).



▲ **FIGURE 5** Signal maximums (arbitrary scale) and height contour over the entire 19 seconds of data, December 7, 2005, for GPS satellite PRN18 (eastern Nebraska). A general normalized height contour (as indicated by Google Earth) is shown as a reference. Additional land collections from the UK-DMC satellite showed weak correlation with the surface contours. The spike at 2 seconds is the signal crossing of the Missouri River.



▲ **FIGURE 6** Signal maximums (arbitrary scale) and height contour over the entire 19 seconds of data, December 7, 2005, for GPS satellite PRN15 (eastern Nebraska). The slight increase in signal power after 10 seconds corresponds to the reflection passing near Beatrice, Nebraska (see Figure 4).

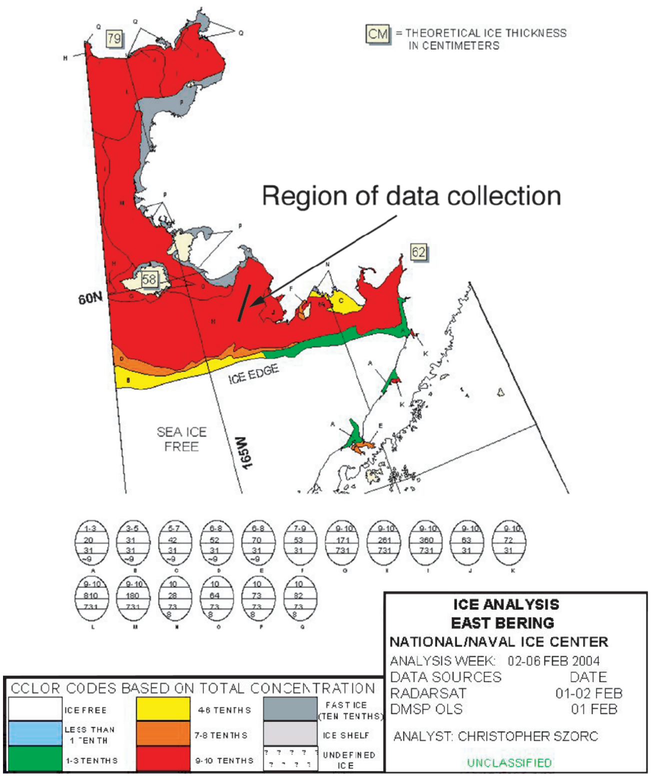
mainly from the scattering surface.

From examining the fluctuations in the reflected signal with respect to the terrain, we can observe several interesting links. The first is the obvious spike in the signal magnitude as the reflection point crosses the Missouri River (at 2 seconds in Figure 5). As the signal passes over water, one would expect it to increase in magnitude. I also suspect that the increase in signal magnitude at 12 seconds in Figure 5 may be due to the presence of rivers to the west of Omaha. In Figure 6, we see a slight increase in signal power at 10 seconds as the reflection passes to the east of Beatrice, Nebraska. This could also be due to the presence of a nearby river, but the exact cause is unknown and better in-situ ground information would be needed to confirm this.

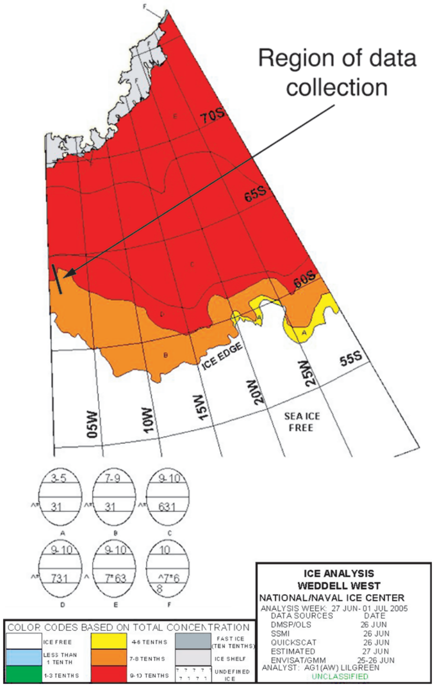
Ice Sensing

Researchers have shown that scatterometers, single-instrument radars for measuring reflected signals such as the SeaWinds instrument on the QuikSCAT satellite, can be used to remotely sense sea ice, including tracking icebergs and monitoring the ice shelves of Greenland. This would lead one to believe that using GNSS signals in a bistatic scatterometry configuration to sense the Earth's cryosphere is also possible. Previous research by Maria Belmonte-Rivas, again at the University of Colorado at Boulder, has shown that ice-reflected GNSS signals contain information useful in the determination of ice classes, by measuring the ice permittivity and roughness. The limited number of data sets collected from the UK-DMC experiment has shown that this technique is also applicable from low-Earth orbiting satellites.

Example Data Collections. Using the UK-DMC GPS experiment, reflected signals have been detected off sea ice on two occasions. On February 4, 2005, the UK-DMC experiment collected 7 seconds of data off the coast of Alaska, including a GPS reflection in Kuskokwim Bay. The approximate collection location is shown in **FIGURE 7**. It is worth noting that this reflection contained a coherent phase component (that is, no incoherent averaging was necessary, and navigation data bit transitions were observed). We suspect that the ice surface was very smooth, thus resulting in a coherent reflection from the sur-



▲ **FIGURE 7** Data obtained from the U.S. National Ice Center indicating that Kuskokwim Bay was frozen over on February 4, 2005. The loci of the GPS reflections are shown as a short black line.



▲ **FIGURE 8** U.S. National Ice Center data indicating that the Antarctic ice shelf extended over the reflection location during the week after June 23, 2005. The north direction is approximately downwards. The loci of the GPS reflections are shown as a short black line.

face instead of the normally observed rough surface scattering.

The second ice collection was 9 seconds of data collected on June 23, 2005, near Antarctica in the Southern Ocean. This collection targeted an ice shelf off the coast of Antarctica and is shown in **FIGURE 8**.

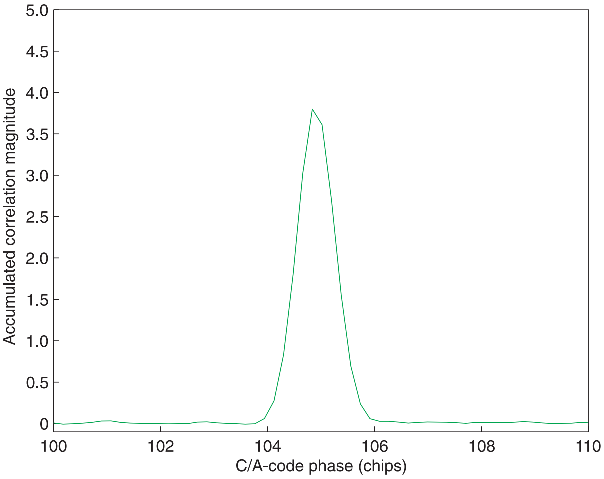
The conditions at the reflection locations at the time of the two data collections were determined by analysts at the U.S. National Ice Center (NIC, *www.natice.noaa.gov*), as shown in Figures 7 and 8.

The NIC validation data indicated that as the February 4 (Alaska) reflection moved across the ice surface, it remained within a region of 9/10 total concentration of first-year ice, between 30 and 70 centimeters thick, for the entire 7 seconds. (The total concentration is a measure of the amount of sea surface covered by ice as a fraction.) A concentration of 9/10 for floating ice or so-called "very close ice" in this case) is slightly below that of 10/10 compact or consolidated ice sheets. In simple language, this means that the region in question was more than 90 percent covered with very densely packed ice flows, with possible small gaps between them. In contrast, the NIC ice data for the June 23 collection (Antarctica) revealed that the sea was covered with between 8/10 and 7/10 ice. This presence of less compact sea ice resulted in a noticeably different reflected signal.

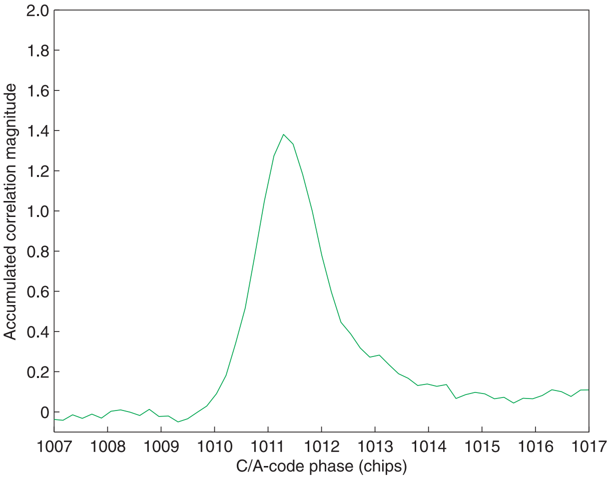
Signal Response. A comparison can be done using the February 4 data from 9/10 sea ice and the June 23 data where only 7-8/10 sea ice was present. This comparison demonstrates a noticeable difference in the C/A-code spreading of the processed signals.

Interestingly, the February 4 signal reflected from a higher ice concentration had a consistently stronger peak (even with less averaging) and showed less spreading in delay and Doppler. Examples of the two signals' power waveforms as a function of delay are shown in **FIGURES 9** and **10** where the lower signal power levels and greater spreading in delay is clearly evident for the June 23 signal from lower ice concentration. To better observe the power spreading in the June 23 signal, we performed 1-second non-coherent averaging.

The greater spreading in delay is most likely due to surfaces reflecting power toward the receiver from distances away from the point of specular reflection. In other words, the greater presence of water surfaces could be resulting in a larger total glistening/scattering zone. However, the roughness of the reflecting sea ice (in addition to the increased presence of open water) will also have an effect on the correlation magnitude and spreading. Additionally, the unique geometry of each reflection will alter slightly the magnitude and the spreading observed. The February 4 signals were observed at roughly 30 degrees incidence and the June 23 signals at 19 degrees. However, we believe that the difference in signal magnitudes between the two signals is due primarily to the reflecting surface and is only slightly distorted by their different incidence angles.



▲ **FIGURE 9** The February 4, 2005, sea-ice-reflected signal delay waveform.



▲ **FIGURE 10** The June 23, 2005, sea-ice-reflected signal delay waveform.

Conclusions and Future Work

Conclusively, the only thing being sensed for certain in the land data discussed in this article is the Missouri River. Following this very preliminary demonstration, a more thorough validation campaign needs to be carried out involving data collections over large areas in parallel with in-situ measurements, possibly in Africa, North America, or the U.K. These measurements could then be studied with respect to reliable in-situ ground truth information and compared to models to determine if the reflections are responding to a useful surface observable, such as soil moisture or surface vegetation cover.

Concerning the ice-sensing results, it has been shown that GNSS signals can be detected after reflection from sea ice. Additionally, the different power returns and spreading in delay from different total ice concentration reveal this as a promising technology in sensing the sea ice total concentration. However, as in the case of land sensing, a more thorough validation campaign is needed to accurately determine what is being sensed and what usefulinformation may be contained in the signal power returns.

Acknowledgments

Primarily, I would sincerely like to thank all those at Surrey Satellite Technology Ltd. involved in the design, implementation, and operation of the UK-DMC bistatic radar experiment, without whom none of the work discussed in this article would have been possible. The British National Space Centre is due thanks for providing partial funding for this research, including the realization of the spacecraft experiment. I would also like to thank Pablo Clemente-Colon and John Woods at NIC for providing the ice validation maps. This article is based on the paper "Land and Ice Sensing from Low Earth Orbit Using GNSS Bistatic Radar" presented at ION GNSS 2006, the 19th International Technical Meeting of The Institute of Navigation, held in Fort Worth, Texas, September 26–29, 2006. ⊕

Manufacturer

The *Space GPS Receiver* and the *UK-DMC Bistatic GPS Experiment* were built by **Surrey Satellite Technology Ltd.** *(www.sstl.co.uk).*

SCOTT GLEASON received his B.S. degree in electrical and computer engineering from the State University of New York at Buffalo, an M.S. in engineering from Stanford University, and a Ph.D. from the University of Surrey. He has worked in the areas of satellite design and GNSS for more than 15 years, including stints at NASA's Goddard Space Flight Centre and Stanford's GPS LAAS Laboratory. Over the past decade, he has contributed to various GNSS-related projects at several companies in the U.K., including Surrey Satellite Technology and Astrium, the European Aeronautic Defence and Space Company (EADS) subsidiary. He is currently working for QinetiQ Ltd. while collaborating on remote sensing research with the National Oceanography Centre, Southampton (U.K.), the University of Minnesota, Twin Cities, Minneapolis-St. Paul and others.

FURTHER READING

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"Bistatic Scattering of Global Positioning System Signals from Artic Sea Ice" by M. Belmonte Rivas, Ph.D. dissertation, University of Colorado at Boulder, 2007.

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