Online Journal of Space Communication

Volume 5
Issue 9 *Global Navigation Satellite System (Winter 2006)*

Article 20

Sensing Ocean, Ice and Land Reflected Signalsfrom Space: Results from the UK-DMC GPS Reflectometry Experiment

Scott Gleason

Mounir Adjrad

Martin Unwin

Sensing Ocean, Ice and Land Reflected Signals from Space: Results from the UK-DMC GPS Reflectometry Experiment

Scott Gleason, *Surrey Satellite Technology Limited*
Mounir Adjrad, *Surrey Space Centre*
Martin Unwin, *Surrey Satellite Technology Limited*

BIOGRAPHY

Scott Gleason received his B.S. degree in Electrical and Computer Engineering from the State University of New York at Buffalo and an M.S. in Engineering from Stanford University. Since September 2001, he has worked at Surrey Satellite Technology Ltd in Guildford, UK, where his duties include GPS, AODCS and Remote Sensing software development and applications research. He is presently researching a Ph.D. thesis in the area of GNSS bistatic remote sensing at the University of Surrey.

Mounir Adjrad received the State Engineering degree in electronics and the M.Sc. degree in signal processing and communication in 1999 and 2002, respectively, both from the National Polytechnic School of Algiers, Algeria. He is currently with the Surrey Space Centre, University of Surrey, as a Research Assistant.

Martin Unwin heads the GPS team at Surrey Satellite Technology Ltd, responsible for spaceborne GPS receiver design and operation. He holds a B.Sc. from Lancaster University and a Ph.D. from the University of Surrey.

ABSTRACT

The use of Global Navigation Satellite System (GNSS) signals reflected from the Earth's surface has progressed from its beginnings in the early 1990's to a demonstrated practical linkage of measurements to geophysical characteristics of ocean, ice and land surfaces.

A pioneering space-based experiment was carried on the UK-DMC satellite launched in September of 2003. The GPS receiver on the satellite was modified to accommodate a downward (nadir) pointing medium gain antenna and to send sampled IF data to a solid-state data recorder [1]. Since its launch it has been successfully used to target and detect specular reflections of GPS signals after scattering from the Earth's oceans, ice sheets and land surfaces. All data collections under a wide range of conditions have revealed reflected signals, including signals reflected off the ocean under reasonably rough ocean conditions. This demonstrates convincingly that GNSS Reflectometry (or GNSS Bistatic Radar) is a valid future technology for space based Earth remote sensing, even when using modest antenna gain configurations such as that deployed on the UK-DMC low Earth orbiting satellite.

This paper presents a summary of the signals collected from over the ocean, and an examination of the signal relationship to the ocean wind and wave conditions is presented. The preliminary results from ice and land surfaces reflection analysis are also described.

INTRODUCTION

The GNSS bistatic radar concept suggests that a similar technique to that of traditional bistatic radar remote sensing can be applied to reflected signals transmitted from global navigation satellites, such as those of GPS and in the future those of the Galileo navigation constellation.

Several near Earth experiments (from aircraft, balloons and towers) have been conducted and the results have shown successfully retrieved ocean wind speeds [2], ocean wind direction [3], ocean altimetry [4,5] and soil moisture sensing from land surfaces [6] to give just a partial list.

To test the bistatic technique from orbit, one member of a small constellation of imaging satellites, the UK Disaster Monitoring Constellation (UK-DMC) platform was equipped with an experiment and launched into 680 km sun-synchronous orbit in September 2003. On-board was the GPS Reflectometry Experiment, also known as the GNSS Bistatic radar experiment developed by Surrey Satellite Technology Limited (SSTL) with support from the British National Space Centre (BNSC). The initial goal was to investigate the feasibility of using ocean reflected GPS signals for remote sensing applications [1]. To accommodate the experiment, the GPS receiver on the

UK-DMC satellite was modified to accommodate a downward (nadir) pointing medium gain antenna, an interface to send sampled data to a solid-state data recorder and additional software to process reflected signals in real time.

A detailed assessment of the initial results and processing required for application of this technique from low Earth orbit was initially presented in [7,8,9] and will be summarized in part by this paper. To date, the UK-DMC experiment has been successful beyond expectations. Numerous data sets have been downloaded with ocean-scattered signals being recovered on every occasion under a wide range of ocean conditions, as well as over ice and land surfaces.

Using these results, software is now being developed and tested to operate on the spaceborne GPS receiver to detect and track reflected signals in real-time using the spare 12 C/A code channels available. The ultimate goal, either on this or future satellites, is to map and invert the signals on-board. If this can be achieved, it would represent the first in a class of a new instrumentation that can provide global coverage for ocean, ice and land remote sensing measurements. To what accuracy various geophysical parameters can be measured using this technique is the subject of on-going research.

DATA COLLECTIONS

The UK-DMC satellite is in a near-polar orbit, and so experimental operations potentially could be scheduled anywhere over the whole globe over the course of a few days. However, the data collection process is limited by the experiment's lower priority with respect to the main camera payload, and also by a data recorder restriction that permits only collections during an orbit that passes the ground station. It is anticipated that a work-around for this problem will soon permit data collection over all regions of the globe.

Initially it must be determined that a specular reflection of one or more GPS satellites will be within the antenna footprint on the ocean surface using the tool described in [1]. Additionally, the presence of independent measurements at the time and location of the data collection is considered. Independent measurements could come from stationary buoys from the National Buoy Data Center (NDBC) or even intersections with other ocean remote sensing satellites such as QuikSCAT or JASON. When a desirable data collection time is found using the ground utilities, a request is made to the satellite operations team and an attempt is made to schedule the data capture on the satellite.

Table 1 show a partial list of the data collected from the UK-DMC satellite. These collections, other than the ice and land collections, coincide with NDBC buoys to within 10 minutes and 50 km in most cases. Additional data collected have been described in [7] and other data sets have been scheduled for the coming months.

Table 1, UK DMC Data collections from Sept 04 to Sept 05 (times are approximate). All ocean collections have NDBC in-situ buoy comparisons unless otherwise noted.

	Date d/m/y	Time (UTC)	PRN	Region
R10	03/09/2004	07:25:15 AM	17	Northwest Pacific
R11	08/11/2004	07:49:80 AM	15	Northwest Pacific
R12	16/11/2004	07:54:46 AM	22	Northwest Pacific
R13	26/11/2004	07:36:36 AM	22	Northwest Pacific
R14	14/01/2005	10:23:58 AM	13	Alaska Pacific
R15	30/01/2005	09:05:21 AM	13	Hawaii
R16	30/01/2005	10:24:04 AM	13	Alaska, Ice
R18	04/03/2005	08:27:16 AM	27	Hawaii
R19	11/03/2005	07:46:09 AM	13	Northwest Pacific
R20	21/03/2005	07:29:56 AM	13	Northwest Pacific
R21	02/05/2005	09:16:11 AM	29	Hawaii
R22	17/05/2005	08:50:40 AM	26	Hawaii
R23	25/05/2005	08:50:13 AM	27	Land, N America
R24	29/05/2005	06:26:39 AM	28	Southwest Pacific
R25	03/06/2005	06:29:27 AM	31	Southwest Pacific
R27	15/06/2005	08:57:01 AM	9	Hawaii
R28	23/06/2005	11:15:30 AM	*	Antarctica, Ice
R30	24/06/2005	09:29:08 AM	5	Alaska Pacific
R31	07/07/2005	09:33:39 AM	5	Hawaii
R32	22/07/2005	09:08:07 AM	30	Hawaii
R33	24/07/2005	08:44:36 AM	5	Hawaii
R34	09/08/2005	10:21:14 AM	15	Alaska Pacific
R35	10/08/2005	07:46:07 AM	30	Northwest Pacific
R36	12/08/2005	09:07:31 AM	30	Hawaii

*R28 is a collection targeting several reflections between ice and sea using a 180-yaw spacecraft manoeuvre. It has not been extensively analyzed yet although signals have been found.

SIGNAL DETECTION AND PROCESSING

To detect the reflected signals, the traditional GPS signal correlation process needs to be adapted [7]. As with most GPS signal processing, a coherent correlation over each 1 ms of data is performed with an internally generated local signal at a trial code phase delay and frequency, where *coherent* means that the signal is processed using both its in-phase and quadrature signal components. Beyond 1 ms, the signal loses its coherence due to speckle and fading noise from the relative motion and interaction of the signals with the ocean surface (unless the signal is reflected off ice, in which case it may remain coherent). The consecutive non-coherent averaging of coherent 1 ms correlations is then employed to bring out the weak signals from the noise (see Figure 1).

The correlation magnitude is a measure of the total power received from an area on the ocean surface corresponding to the delay and Doppler selected by the trial signal. This process is then repeated at different delays and frequencies until the ocean's "glistening zone" of scattered power is processed into the Delay Doppler Maps (DDM) shown later. The peak magnitude of the signal power is closely related to the sigma-0, the radar cross-section term from radar theory.

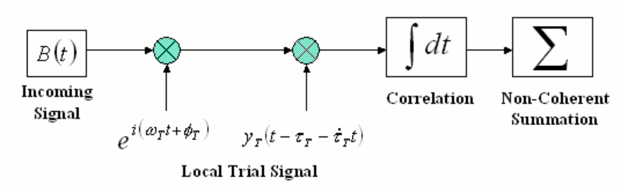

Figure 1 Reflected signal processing block diagram

Two examples described in Ref [7] clearly show the signal emerging from below the noise during the process of non-coherent summation.

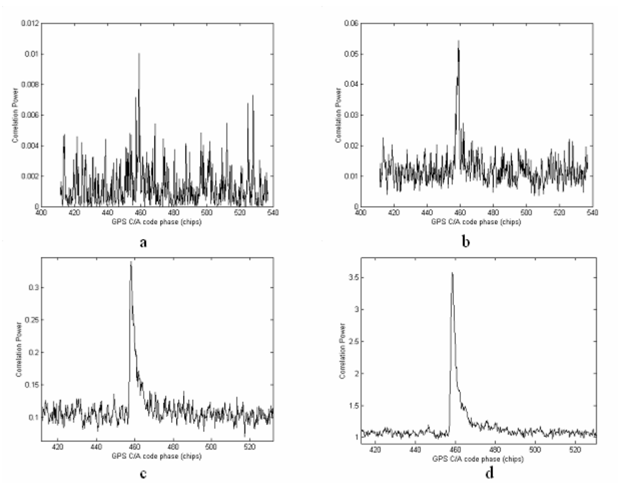

Figure 2 Calm seas: Signal found using non-coherent integration times of: (a) 1ms, (b) 10ms, (c) 100ms and (d) 1s. The horizontal axis is code delay, and vertical axis is correlation magnitude.

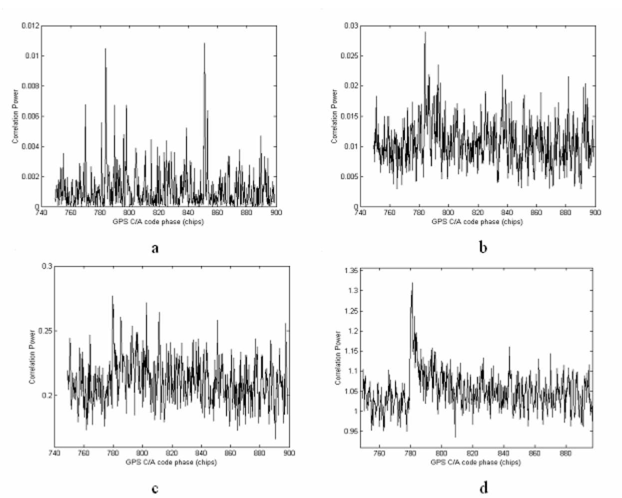

Figure 3 Rough seas: Signal found using non-coherent integration times of: (a) 1ms, (b) 10ms, (c) 200ms and (d) 1s.

The signal shown in Figure 2 was collected under calm ocean conditions. In contrast, Figure 3 shows a signal reflected off rougher ocean conditions that requires more than 200 milliseconds of integration before it can be seen.

If after 1 second of averaging the signal is still too noisy to make an accurate measurement, it may be necessary to use even longer integration times. The limit will occur when the reflection point has moved a distance where significantly different ocean conditions are possible (roughly 50km, or 8 seconds).

More information about the ocean-scattered signals can be extracted from a Delay Doppler Map. This shows the correlated signal power (coloured from blue to red) with respect to Doppler frequency (horizontal axis) and time delay (vertical axis). Shown in Figure 4 is a DDM for the March 21st 2005 signal (R20) under the conditions of 3.6 m/s winds and 4.1 metre waves. The low winds and high waves are unusual and suggest the presence of significant swell [10].

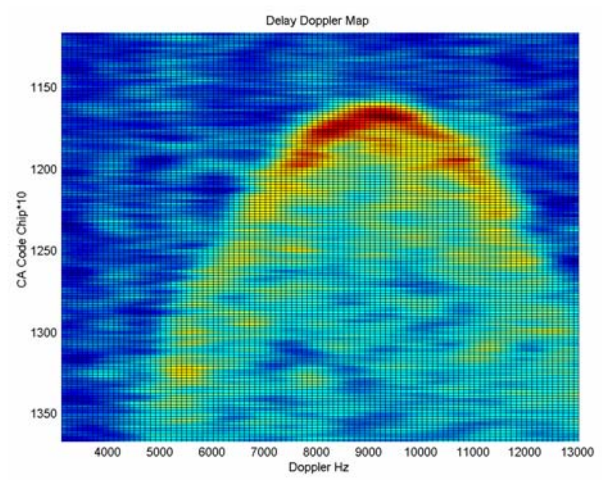

Figure 4 Delay Doppler Map, 21/03/05 (R20), wind speed 3.6 m/s, wave height 4.1 m. (Increasing power of signal represented by colours from blue to red.)

The horseshoe shape is a function of the iso-range and iso-Doppler lines on the surface and is the most convincing proof that this signal was indeed scattered from the ocean surface as it agrees with the outputs from Zavorotny and Elfouhaily models [11,12].

OCEAN REFLECTED SIGNALS AND THE CONNECTION TO WIND AND WAVES

Since the first signals were retrieved, a significant effort has been made to link these to the known conditions on the ocean surface. Theory suggests that we should expect a close relationship between the retrieved measurements and the surface mean square slope (a statistical descriptor for the ocean roughness). Unfortunately the obtainable in-situ measurements are largely restricted to wind speed and significant wave height values from buoys. There is clearly a connection between wind, waves and the Delay Doppler maps but less direct, and the models may yet need to be refined using results from orbit.

General trends have been shown between the peak reflected power and the winds, and likewise the Doppler spread and the waves in Ref [8], and attempts are being made to construct empirical models that describe these relationships. The connection between ocean reflected GPS signals and the wind and wave conditions on the surface is best demonstrated using two contrasting examples (from Ref [8]).

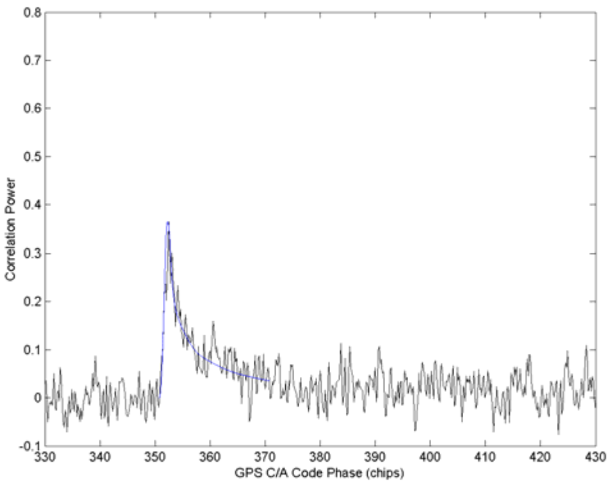

Figure 5 Delay map, 03/09/04 (R10), wind speed 10 m/s, wave height 2.8 m. High winds lead to relatively low peak correlation power.

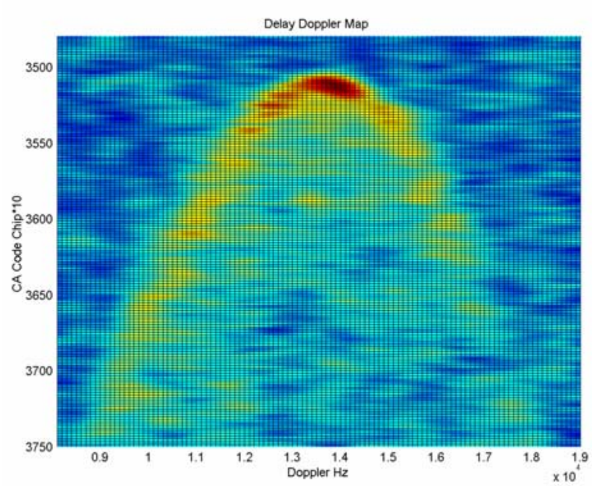

Figure 6 Delay Doppler Map, 03/09/05 (R10). Doppler spreading is related to larger wave slopes and indirectly to the wave heights.

The first signal was collected under conditions of relatively high winds and waves on September 3rd 2004 (R10). The data from the NDBC buoy indicated a wind speed of 10.3 m/s and wave heights of 2.8 meters. The delay map (a slice of the DDM at the maximum correlation frequency) and the DDM are shown in Figure 5 and Figure 6, respectively.

In contrast to these conditions a second data set was collected under low wind but similar high wave conditions on November 8th 2004 (R11). In this case the NDBC buoy indicated 3.9 m/s winds and 3.0 meter waves. The delay waveform and DDM are shown below in Figure 7 and Figure 8 for comparison.

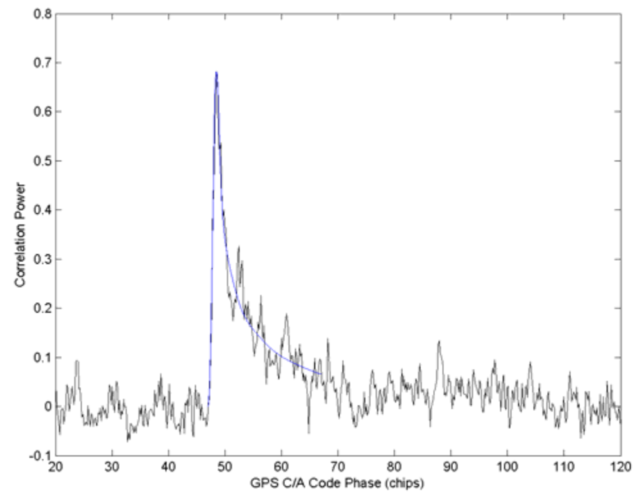

Figure 7 Delay map, 08/11/04 (R11), wind speed 3.9 m/s, wave height 3.0 m. Lower winds yield higher peak correlation power than R10 despite similar wave heights.

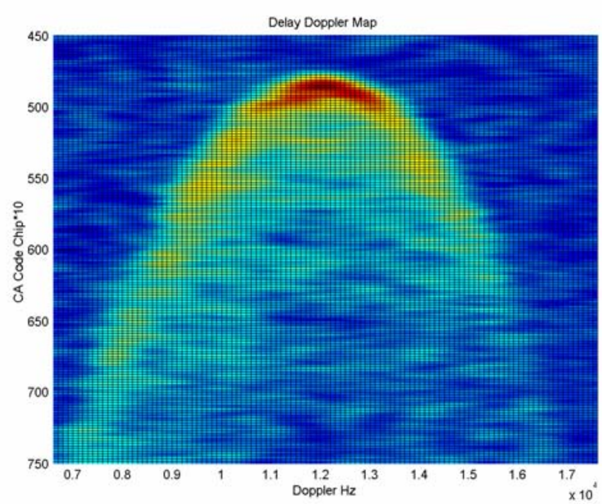

Figure 8 Delay Doppler Map, 08/11/04 (R11). Spreading of Doppler comparable to R10 with similar wave heights.

The two most important parameters from these DDMs are the peak power levels and the Doppler spreading. The wave heights in these examples are similar, but because the wind was lower on November 8th, the lack of wind driven waves results in a stronger signal. This suggests that at the frequency of the GPS L1 signal (relatively low compared to other satellite radar measurements) there is a scattering dependence on the near surface wind velocity. Secondly, because the overall wave heights are similar (~3 meters) the Doppler spreading is comparable. This is an indication that some larger scale surface wave features are contained in the Doppler information as has been previously discussed in [13].

Traditional backscatter techniques, such as employed on QuikSCAT, use collocated transmitter and receiver, and see an increase in signal return as the wind increases and roughens the sea surface. Conversely, bistatic radar techniques (such as GNSS Reflectometry) see the strongest signals when the ocean is calm. As the wind and waves increase, the sea becomes rougher and the power scattered towards the receiver will decrease; the peak of the signal (effectively the scattering cross section, or sigma0) decreases as more power is scattered away from the receiver. At the same time, the reflection area increases and power is received from points further and further from the point of specular reflection, as can be seen in the DDMs.

ICE REFLECTED SIGNALS

On 4th February 2005, the detection of GPS signals reflected off ice was demonstrated using the UK-DMC experiment over the Kuskowkwim Bay Alaska [14]. Data from the U.S. Naval Ice Center revealed that the region of specular reflection was covered with ice between 30 and 70 cm thick.

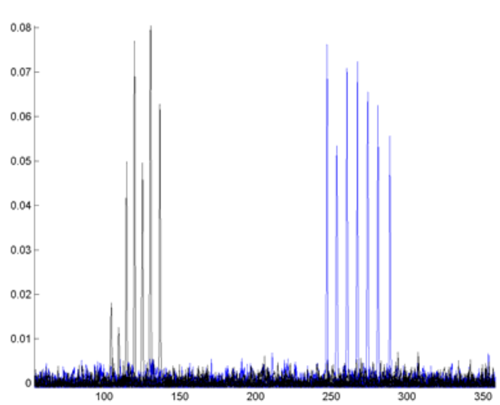

Figure 9 Ice reflected signals (left, black), and direct signals (right, blue) over 7 seconds, collected 04/02/05 over frozen Alaskan sound. Horizontal: GPS C/A code chips, Vertical: correlation magnitude (1 ms). The two signals are at different C/A code phases, Doppler frequencies and move at different rates with respect to the changing geometry.

The signal detected was noticeably strong and coherent without the characteristic spreading in delay and Doppler seen in ocean-reflected signals. To verify that this was indeed a reflected signal, the reflection geometry was examined closely, and the corresponding direct signals were recovered from the data for comparison. Figure 9 shows the reflected signal plotted at 1 second intervals over the course of seven seconds as the code delay changes with range. The simultaneously received direct signal is shown for comparison.

To investigate the potential of coherent phase range recovery, the phase from the signal was unwrapped over 50 consecutive milliseconds (Figure 10). With more precise frequency alignment the phase should return to the same point (0 degrees) at each millisecond. Even with the small frequency error present the carrier phase coherency of the signal is evident over short periods (between the 1st and 30th ms). Coherent phase measurements over ice could potentially be used for altimetry with 10 cm or better accuracy.

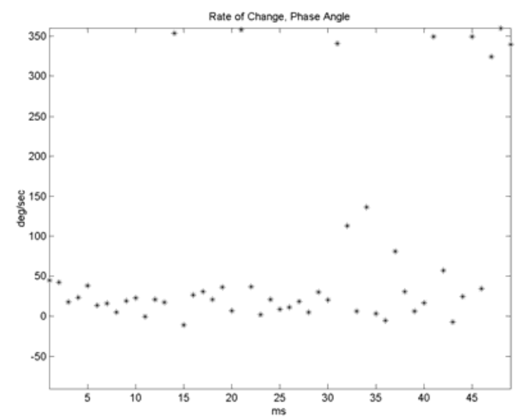

Figure 10 Phase unwrapping of reflected signal over 50 ms of data. Coherency evident for 30 ms, then less stability, possibly due to changes in the ice surface.

LAND REFLECTED SIGNALS

A large amount of satellite data is being used to generate near daily ice maps in the Polar Regions. In contrast, there is a pressing need for more information on the Earth's hydrology and related systems, including measurements of soil moisture and surface water [15].

Another welcome opportunity came when the UK-DMC was available and the conditions were right to collect data over land, in this case along a short stretch of land between Nebraska and Colorado in North America [14]. The delay response of this land reflected signal is shown below in Figure 11 and the corresponding DDM in Figure 12. The signals shown below have a very strong and detectable peak and noticeable spreading in the time domain.

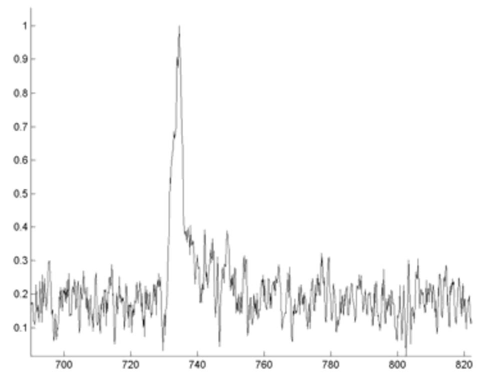

Figure 11 Reflected signal delay map over mix of bluff, hills, and farmland in North America. Horizontal axis is C/A code phase, vertical axis is correlation magnitude after 100 non-coherent summations.

The overall power returned from the land was surprisingly strong across the 7 seconds of data collected. A possible explanation was significant rainfall in the days before the collection leaving the ground very wet and more reflective to GPS signals.

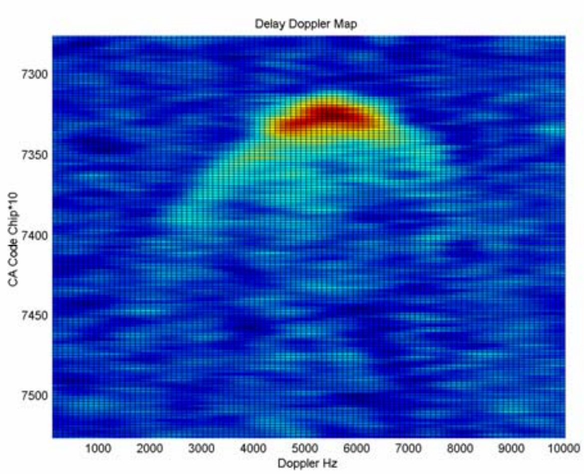

Figure 12 Land-reflected Delay Doppler Map across 7 seconds of data. Increasing magnitude of the signal represented by colours from blue to red.

The familiar horseshoe shape of the ocean reflected signal is present but less pronounced. This will be dependant on the local surface topography, which is unknown at present but possibly retrievable using USGS aerial images. For other DDM's the signal shows more or less "hooking" around the centre, indicating that there is power being received over a distributed area on the surface. With enough analysis and in-situ data this feature could be used to sense other land characteristics other than just the water content (which is believed to dominate the received power levels [6]).

More data sets are needed to quantify the range of conditions under which the signals can be detected from low Earth orbit and to what accuracy. Most importantly there is a need to assess whether dry land reflects signals sufficiently to be detectable.

CONCLUSIONS

In spite of the presence of some scepticism about the feasibility of the technique prior to launch, the UK-DMC GPS Reflectometry experiment has successfully and repeatedly detected from space GPS signals reflected off ocean, ice and land surfaces. Work is ongoing to gather more data from orbit with corresponding in-situ measurements, although experimental operations are naturally limited by the main UK-DMC imaging activities.

Existing theory and models indicate that there are connections between ocean state and GPS bistatic measurements, and some trends between wind and waves and the Delay Doppler Maps have been presented in this paper. However, many more data sets and more work on the models are required before the full value of this emerging technology can be realised.

Some empirical models are being examined that could be used to enable quick ocean-state recovery on-board a satellite. The GPS Reflectometry Experiment permits the uploading of software to potentially enable a coarse Delay Doppler Map recovery and potentially an inversion to sea wind/waves on the UK-DMC satellite. This would enable the continuous measurement of sea-state as the satellite orbits around the Earth.

The demonstrated feasibility for both ice and soil moisture measurements combined with the ocean state sensing capability from a low cost experiment on a small satellite highlight the importance of GNSS bistatic radar for the future of spaceborne remote sensing.

ACKNOWLEDGMENTS

The authors would like to thank all those at SSTL and the Surrey Space Centre who continue to believe in this research and have provided the funds and advice that have enabled this project to continue productively.

REFERENCES

[1] M.J. Unwin, S. Gleason and M. Brennan. "The Space GPS Reflectometry Experiment on the UK Disaster Monitoring Constellation Satellite". Proc. ION 2003. Portland, Oregon. September 2002.

[2] J. Garrison et al., "Wind Speed Measurements Using Forward Scattered GPS Signals." *IEEE. Trans. Geosci. Remote. Sens*., Vol. 40, No. 1, Jan. 2002.

[3] M. Armatys, "Estimation of Sea Surface Winds Using Reflected GPS Signals", PhD Thesis, University of Colorado at Bolder. 2001.

[4] S. Lowe, C. Zaffuda, Y. Chao, P. Kroger, L. Young and J. LaBrecque. "5-cm precision aircraft ocean altimetry using GPS reflections". Geophysical Research Letters. Vol. 29, No. 10, 2002.

[5] G. Ruffini et al, "The Eddy Experiment: Accurate GNSS-R Ocean Altimetry from Low Altitude Aircraft", Geophysical and Research Letters, Vol.31, L12306, 18 June 2004.

[6] D. Masters, "Surface Remote Sensing Applications of GNSS Bistatic Radar: Soil Moisture and Aircraft Atimetry". PhD dissertation, University of Colorado, 2004.

[7] S. Gleason et al., ``Detection and Processing of Bistatically Reflected GPS Signals From Low Earth Orbit for the Purposes of Ocean Remote Sensing." *IEEE. Trans. Geosci. Remote. Sens*., Vol. 43, no. 6, pp. 1229 –1241, Jun 2005.

[8] S. Gleason, M. Adjrad and M. Unwin. "Preliminary Attempts to Connect Ocean Reflected GNSS Signals Detected From Low Earth Orbit with Sea Winds and Waves". American Geophysical Union Fall Meeting, San Fransico, 2004.

[9] S. Gleason, M. Adjrad, "An Attempt to Sense Ocean Winds and Waves Empirically Using Bistatic GNSS Reflections in Low Earth Orbit", IGARSS05 conference, Seoul, Korea 25-29 July 2005.

[10] S. Gleason. "Exploring the Effects of Swell and Non-Gaussian Wave Slope Distributions on Delay Doppler Maps". GNSS-R Workshop, University of Surrey, June 2005. www.gnssr-05.com

[11] V.U. Zavorotny and A.G. Voronovich, "Scattering of GPS Signals from the Ocean with Wind Remote Sensing Application". IEEE Trans. Geosci. Remote Sensing, Vol. 38, pp. 951-964, March 2000.

[12] T. Elfouhaily, B. Chapron, K. Katsaros and D. Vandemark "A Unified Directional Spectrum for Long and Short Wind-Driven Waves". Journal of Geophysical Research, Vol. 102, No. C7, pp 15781-15796, July 15th, 1997.

[13] T. Elfouhaily, D.R. Thompson and L. Lindstrom, "Delay-Doppler analysis of bi-statically reflected signals from the ocean surface: theory and Application". *IEEE Transactions on Geoscience and Remote Sensing* Vol. 40, No. 3, (March 2002).

[14] S. Gleason. "Space Reflected GNSS Signals Detected off an Ice Sheet in an Alaskan Sound and from a Diverse Land Surface in the Plains of North America". GNSS-R Workshop, University of Surrey, June 2005.

[15] V. Lakshmi, E.G. Njoku, and T. J. Jackson. *Geotimes* Magazine, July, 2002.