TOWARDS LONG-TERM SUSTAINABLE OBSERVATIONS OF OCEAN WIND AND WAVES WITH GNSS SIGNALS OF OPPORTUNITY

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1. ABSTRACT

Global Navigation Satellite Systems (GNSS) such as Global Positioning System (GPS) or Galileo provide ubiquitous signals, which can be exploited for Earth Observation. Successful use of reflected GPS signals to measure ocean wind and waves was demonstrated recently for the first time with data from a dedicated receiver on a Low Earth Orbiting (LEO) satellite. The GPS-R receiver onboard the Surrey Satellite technology Ltd (SSTL) UK-Disaster Monitoring Constellation (UK-DMC) satellite was a small, low-power, low-cost instrument ideally suited for deployment on small satellites. The method offers improved sampling of ocean wind and waves by means of a very modest instrument that could easily be fitted on more satellites. Combined with high accuracy satellite data, this technique could provide long-term sustained observations of ocean wind and waves with high spatio-temporal resolution, relevant to both climate and operational applications.

2. REFLECTED GNSS SIGNALS FOR OCEAN REMOTE SENSING

The scientific usefulness of Global Navigation Satellite Systems (GNSS) signals for Earth Observation is already well established for atmospheric sounding, where GPS signals can help recover tropospheric temperature, pressure and humidity and provide near real-time ionosphere total electron content data. A less well-known application of GNSS signals for Earth Observation is Surface Reflectometry, or GNSS-R, which relies on the detection of signals from GNSS satellite constellations such as GPS, GLONASS or Galileo after they are reflected from the Earth surface, and yield information on various geophysical properties of the Earth surface. The principle of the technique is illustrated in Figure 1.

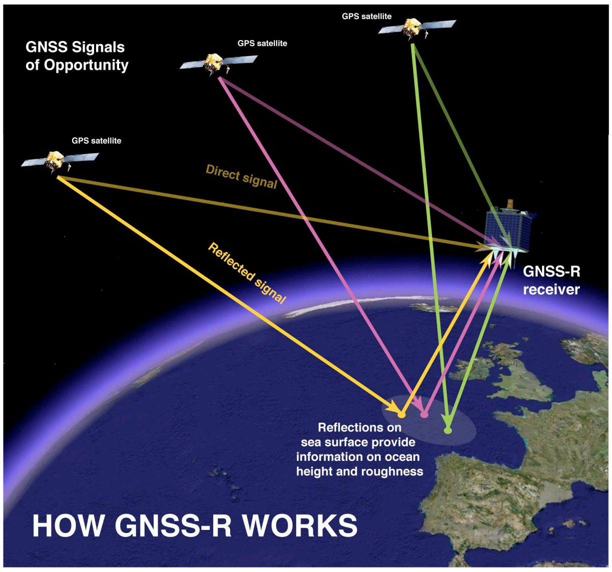

Figure 1: Measurement principle of Global Navigation Satellite Systems Reflectometry (GNSS-R) for Earth Observation.

Over the ocean, GNSS-R basically equates to bi-static altimetry, and, as in conventional ocean altimetry, the reflected GNSS signals contain information about the altimetric height of the ocean (sea surface height) and the roughness of the ocean (wind and sea state estimation). Both sea surface height and ocean roughness have been retrieved with GNSS-R with satisfactory accuracy using airborne receivers, but so far only ocean surface roughness retrieval has been successfully demonstrated from a space borne receiver. A more detailed discussion of the retrieval of ocean surface roughness with GNSS-R is presented in Section 4.

3. HOW CAN GNSS-R CONTRIBUTE TO THE GLOBAL OCEAN OBSERVING SYSTEM ?

The GNSS-R technique offers several advantages that make it an attractive cost-effective way of delivering sustainable high-density Earth Observation data. Being based on signals of opportunity from GNSS satellite constellations, GNSS-R receivers have no need to transmit signals. The instruments thus tend to be small, with low power requirements, which can easily be accommodated on small satellites or piggy-back on satellites of opportunity. All this contributes to substantial reduction in the overall cost of placing such a receiver in space.

GNSS signals are emitted at microwave frequencies around 1.3 GHz (L-band), offering day and night operation without detrimental sensitivity to adverse weather. Driven by their commercial imperative for real-time global positioning capability anywhere any time, the spatial coverage is dense and truly global. For GPS alone, over 12 different satellites are in direct view of any point on the surface at any given time. Consequently, one space borne GNSS-R receiver could simultaneously detect multiple reflections on the surface, spanning over a broad swath and dramatically increasing the space-time sampling of one sensor.

Finally, GNSS services are now hugely popular and have become highly profitable commercial enterprises. It is inconceivable that GNSS will not continue for the foreseeable future to provide free ubiquitous signals of opportunity. Such guaranteed long-term continuous provision is very rare for Earth Observation and a key issue for climate monitoring with satellites.

4. HOW GOOD ARE GNSS-R MEASUREMENTS OVER THE OCEAN ?

Research in GNSS-R for ocean remote sensing suggests application to both altimetry (e.g. Ruffini et al., 2004) and scatterometry (e.g. Garrison et al., 1998) with satisfactory levels of accuracy, but based on mostly airborne experiments. Key issues relating to the capabilities of the technique to contribute to global monitoring revolve around the suitability of the GNSS signal characteristics (e.g. chip code, limited bandwidth) and the degradation of the signal/noise ratio with increasing receiver altitude due to the relatively low power levels of GNSS signals.

Nevertheless, the first space-based detection of ocean reflected GNSS signals was reported by Lowe et al. (2002) who chanced upon these signals in data acquired from the US Space Shuttle. The possibility to perform global monitoring with GNSS-R from LEO satellites was confirmed in 2004, when an experimental GPS-R receiver was placed onboard the UK-DMC satellite, orbiting at an altitude ~ 680 kilometres. As well as providing the first glimpse of the capability of GNSS-R for global land and ice remote sensing, the UK-DMC dataset contained 24 samples over the ocean, supported by ancillary wind speed and sea state data from *in situ* stations and other satellites. To date, this remains the only GNSS-R dataset obtained onboard a satellite.

In that experiment, GPS signals reflected off the ocean were analysed to recover information linked to the surface roughness of the ocean. The analysis consists of cross-correlating the reflected signals with a local replica of the original GPS signal, followed by coherent and incoherent integration (for details about the processing, see Gleason et al., 2009). The reflected power is distributed in both time delay and Doppler frequency domains, as illustrated in Figure 2A. The geophysical information is extracted by fitting the data with a theoretical model that depends on geophysical properties of the surface.

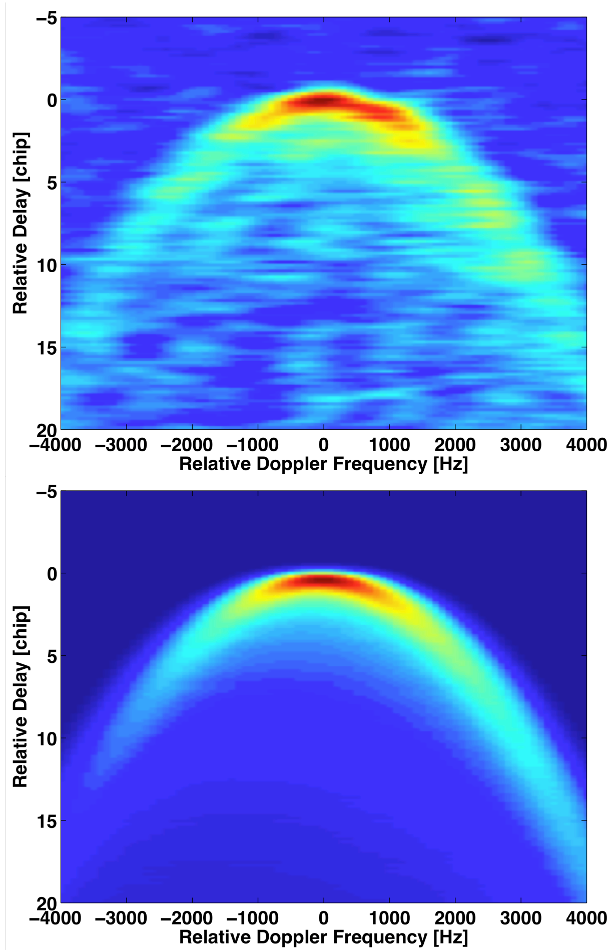

Figure 2: (A) Example of a measured Delay-Doppler Map of the reflected power from the UK-DMC GPS-R experiment. (B) Theoretical Delay Doppler Map used for fitting (see text for details).

Gleason et al. (2005) fitted the waveforms from the UK-DMC data over ocean in delay space only, to retrieve wind speed and the ocean height mean square slope variance. The theoretical model used for the fitting was the widely-used model by Zavorotny & Voronovich (2000) - based on Geometrical Optics electromagnetic scattering approximation - combined with the Elfouhaily et al. (1997) theoretical ocean spectra model to provide the link to ocean surface height statistics and wind speed. Wind speed and ocean height mean square slope variance were recovered and validated, with reasonable success, against in situ buoy measurements from the US National Data Buoy Centre. However, the small number of samples (< 24) and wide range of sea states experienced in the dataset did not permit a robust statistical evaluation of the overall retrieval error.

Four samples from the UK-DMC dataset were selected and recently re-analysed by Clarizia et al., (2009) to determine if further information could be recovered by fitting the full 2D Delay Doppler Maps. Using a 2D expression of the same theoretical model as used in Gleason et al. (2005), Clarizia et al., (2009) was able to show that it was possible also to retrieve directional information about the ocean surface roughness.

5. RELEVANCE OF GNSS-R OCEAN ROUGHNESS DATA TO SCIENCE AND OPERATIONAL NEEDS

High-density global measurements of directional mean square slope variance (dmss) have a multitude of uses for scientific and operational applications, which need proper characterisation of the state of the ocean/atmosphere interface.

Air-sea exchanges of gases, for example, are controlled by the dmss, so that better sampling would have a direct impact on our understanding of the magnitude and distribution of atmospheric CO2 uptake by the ocean. Equally, dmss is relevant to operational weather and ocean forecasting, with important applications in the prediction of extreme weather events, including hurricanes, dangerous sea states, risk of flooding and storm surges.

Finally, ocean roughness plays a supporting role for important climate-relevant Earth Observation techniques, for example IR SST where the wind history serves to quantify the degree of vertical stratification in the surface micro layer (the IR skin effect). Directional mean square slope variance from GNSS-R is particularly relevant to the ESA Soil Moisture and Ocean Salinity satellite, where it can provide the essential ancillary data needed to remove unwanted effects of ocean roughness on L-band brightness temperature to ensure accurate retrieval of ocean surface salinity.

6. THE NEED FOR NEW TECHNOLOGY & MORE GNSS-R DATA FROM SPACE

The GPS-R experiment onboard UK-DMC used a prototype receiver based on commercial off-the-shelf (COTS) components, which purpose was to demonstrate that reflected GNSS signals can be retrieved from space even with small, low-power, low-cost instruments. This kind of small payload is ideally suited for deployment on small satellites or satellites of opportunity (e.g. Iridium NEXT).

The UK-DMC demonstration dataset included just 24 measurements over the ocean with collocated buoy data, spanning a wide range of wind and sea state conditions. This precluded any meaningful statistical analysis of the retrieval capability from space. More space-based GNSS-R datasets are required in order to get estimates on retrieval accuracy, particularly in high wind/wave conditions.

Work is now underway at SSTL to optimise the design and performance of the instrument and antenna, to build the next generation of GNSS-R receivers (Fig. 7) for a future deployment on a space flight opportunities. The optimisation of the instrument aims to improve its performance and operability, while maintaining the low-cost, low power and lightweight advantages of the technique.

7. ACKNOWLEDGEMENTS

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