Proposed Satellite Service for Ice-Edge and Storm warning using GNSS Reflectometry

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Biography

Martin Unwin heads the GNSS team at Surrey Satellite Technology Ltd, and is responsible for spaceborne GNSS receiver design and operation. He holds a BSc from Lancaster University and a PhD from the University of Surrey.

Philip Jales is a PhD student at Surrey Space Centre, The University of Surrey since October 2007. The main attention of his research is the study of GNSS-Reflectometry techniques, specialising in new receiver approaches. He received his MPhys degree in Physics from The University of Manchester.

Craig Underwood is Deputy Director of the Surrey Space Centre (SSC) and Reader in Spacecraft Engineering. He also heads the Planetary Environments Group within SSC. Craig joined the University in 1986 and has been responsible for designing remote sensing instrumentation for the Surrey satellites. He continues to research in these areas, and teaches on the Space Technology and Planetary Exploration programme.

Abstract

In addition to navigational positioning and timing, GNSS has found an important role in a number of remote sensing techniques, notably sensing of the atmosphere, but also now reflectometry off the Earth's surface. SSTL and the University of Surrey have demonstrated the feasibility of use of GPS reflections to detect ocean roughness and detect ice edges from space, using the UK-DMC satellite GPS Reflectometry Experiment. The attraction of this method over other remote sensing techniques is that only a GNSS receiver and antennas need be carried on the satellite, allowing the reduction in size down to a spacecraft of potentially only a few kilograms. This concept will see an improvement in coverage as signals from more satellites become available; GPS, GLONASS, Galileo, COMPASS, and SBAS can all be used. A constellation of satellites carrying these instruments is envisaged that can provide measurements valuable to scientists but also to marine navigators on a near real time basis. Cargo vessels are vulnerable to poor knowledge of weather when far from coasts and a regular update on the ice edges at both poles would be valuable information for navigators.

This paper presents the recent results of the reception of reflected Galileo signals and the detection of ice features from the UK-DMC GNSS-Reflectometry Experiment, that show the characteristics of reflected GNSS signals received in space. The possible architecture and implementation of an ice and storm service provision to mariners is discussed, and the scientific benefits of such a system are reviewed.

Keywords: *GPS, GNSS, Reflectometry, Satellite, Ocean hazard*

Introduction

The world’s oceans still suffer from limited or sparse meteorological measurements. There is a need for more measurements to support medium-term weather forecasts, climate models as well as storm warning. The Partnership for Observation of the Global Oceans (POGO), a group of scientists from the ocean research community have recently called for a stable network of satellites for ocean observation [1].

The future requirements for ocean sensing were discussed by an international community at the GAMBLE workshops [2]. The session on the marine operators' requirements reported that waves remain the major environmental factor for offshore structures. Ocean wave height is still the most important factor in offshore design, operations and planning. The knowledge of wave direction and wave period of long wavelength swells is also important for operations. The main priority was reported to be an increase in spatial and temporal sampling, to provide measurements ~200km every 6-12 hours. To achieve this sampling criterion a constellation of satellites with wide measurement swath would be required.

Current measurement of the ocean state from satellite has been with radar altimeters such as the Jason, TOPEX/POSEIDON satellites and ENVISAT's RA instruments. Ocean wave state is linked to current and past wind conditions, so measurement of the wind vector is also in use with scatterometers such as QuickScat. These active microwave instruments have primarily been possible only on large dedicated satellites. A large transmitter is required to illuminate the ground, which leads to an expensive mission. To be able to meet the sampling requirement a constellation of satellites is required. An alternative technique is needed that is cheaper and smaller so that a constellation can be realised.

An alternative technique makes use of the microwave transmitters already broadcasting to the ground, whether navigation or communication signals. Only a receiver is needed on the remote sensing satellite, which can be very small and low power. As this would not need a dedicated satellite, the instrument can be flown as a secondary satellite payload. The globe can then be covered by a greater number of sensors for monitoring rapidly changing features.

The global navigation satellite systems (GNSS) are almost ideally suited to this purpose due to their particular signal characteristics and worldwide coverage from an already existing constellation. The opportunity to use the GNSS signals for remote sensing can be applied to measuring the ocean sea state, also a mission could have secondary targets of soil moisture and polar ice extent retrieval amongst other uses.

GPS-Reflectometry for the determination of ocean roughness has been demonstrated from aircraft during experimental campaigns [3]. The next challenge is to demonstrate the technique can routinely retrieve ocean roughness measurements from space.

As a by-product the polar ice edge can be located. For ocean operations and climate monitoring there is a need to know the location of boundaries between ice and sea. The importance of this is increasing with the North West Passage beginning to open up for shipping. Routine measurements are taken by radiometers with frequent repeat but low resolution.

Spaceborne GNSS reflectometry

GNSS-R uses a bistatic geometry. The receiver utilises the signal transmitted from the GNSS satellites in medium earth orbit which has been scattered around a specular point on the ocean (Figure 1). The signal is both delayed in comparison to the direct signal and also distorted. From the time delay it is possible to determine the surface height. The distortion of the signal due to the scattering contains information on the surface roughness.

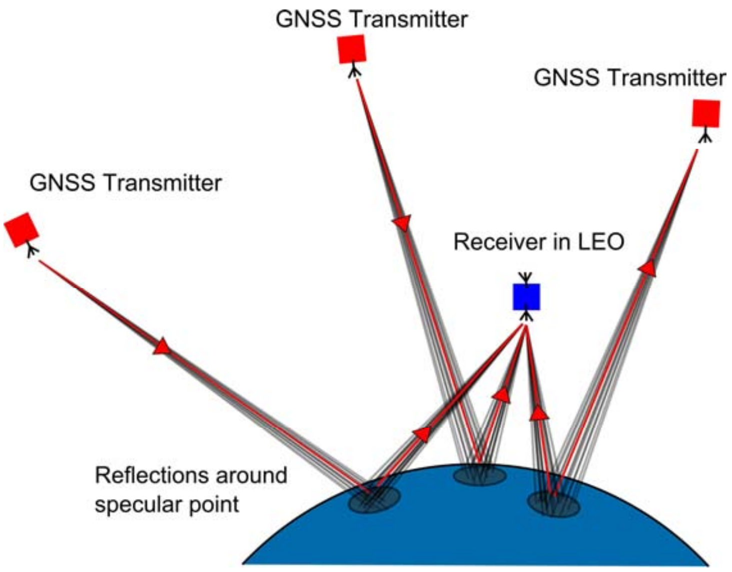

Figure 1 The geometry of GNSS reflectometry

This separation of transmitter and receiver makes a more economical remote sensor as the transmitting infrastructure is already in place. However the reuse of the signal for something other than the intended navigational function means that there is no control over its characteristics, we must make the best of what is available.

GNSS signals are much weaker than would normally be considered for active remote sensing as each GNSS satellite emits to the whole of the Earth's face, rather than just the region of interest. Also the usual remote-sensing definition of the instrument measurement swath is not appropriate as sensing is possible only where the specular reflection falls within the receiving antenna beamwidth. To increase the density of the sampling either more remote sensing satellites are needed or each receiver can target more GNSS transmitters. There are a number of opportunities, in the near future, brought about by the new signals available from GPS and Galileo systems, China's COMPASS system and the modernisation of Russia's GLONASS constellation.

With the aim of driving the development of affordable oceanography measurement from space, Surrey Satellite Technology Ltd (SSTL) built an experimental GPS reflectometry receiver into its UK-DMC satellite [4]. In 2003 the UK-DMC satellite was launched as part of the international disaster monitoring constellation. The satellite has now successfully exceeded its designed life and is still being used for GNSS-R experiments. This experimental receiver was configured as a data recorder; the raw signal is stored for 20 seconds and transmitted to the ground for post-processing. Using this equipment, reflections of GPS signals were detected from all types of surfaces on the Earth. Some recent results from UK-DMC are presented in this paper.

Ocean roughness measurement

The technique for determining the sea state using spaceborne altimeters and backscatter radars has been long established. Although the models for GNSS Reflectometry are still immature, the technique is a form of bistatic-radar and much expertise exists in very similar modelling and inversion processes. The simplest method of inversion is to measure the return of the peak of the signal – the calmer the ocean, the stronger the returned peak. Other methods under consideration include evaluation of the shape, the spread in Doppler and quantifying the statistical distribution. Figure 2 shows an example of the peak strength as seen under calm and rougher ocean conditions.

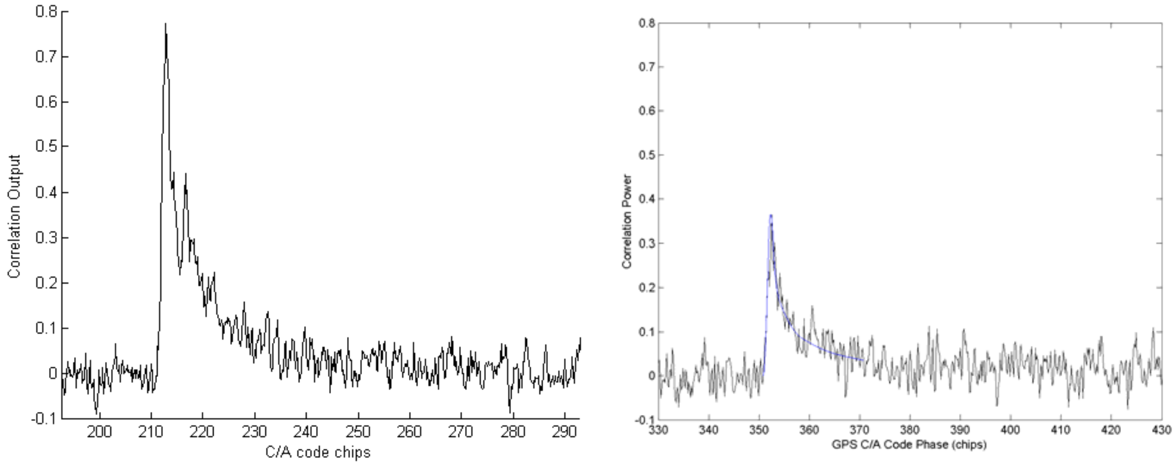

Figure 2 Two reflections in delay domain collected by UK-DMC showing change with sea state, a) 10/08/05 Calm conditions: 5.0 m/s wind, 0.7 meter waves, b) 03/09/04 Rougher conditions: 10 m/s wind, 3 metre waves

Only a compact fixed gain antenna can be accommodated on small satellites and a trade-off has to be made between gain and coverage. A stronger signal can be received if a higher-gain antenna is used, but this leads to a corresponding smaller ocean sampling area (Figure 3). Additional gain can be achieved through optimising the receiver and processing techniques. Work on determining the optimal trade-off for the required coverage and signal level is ongoing.

Due to the wavelength of the GNSS signals, the parameter that is measured most directly by the GNSS-R is the *mean squared slope (mss)*, a statistical measure of the average slope of facets of the ocean which are 20cm or larger. While the *mss* does not correspond directly to wind speed and wave height, it is closely related and could be used as an indicator for mariners. The *mss* parameter is used by the ECMWF (European Centre for Medium-Range Weather Forecasts) in their ocean modelling and feeds into global weather forecasts.

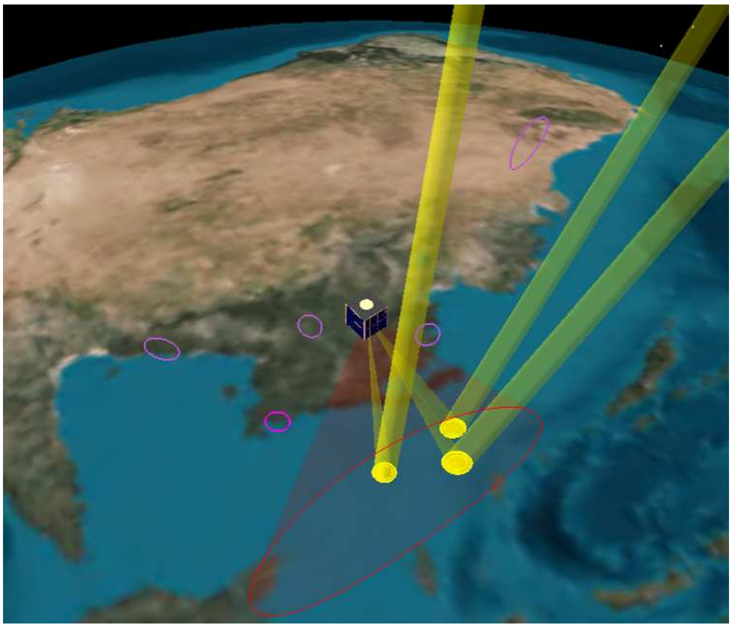

Figure 3 Specular points are indicated on the ocean as circles, by expanding the receiver antenna beamwidth more measurements can be taken, although at the expense of signal to noise ratio.

Galileo Reflectometry

A multi-system receiver, capable of receiving the Galileo and GPS systems will effectively fill in the gaps between the measurements from one system alone. Galileo has the same design goals as GPS, however the signals have a different structure. One of the challenges in GNSS-R instrument design is extracting comparable information from both types of reflection, despite the differences in signal structure. The UK-DMC experiment can be used to assess the signal models compared to real reflections. Unfortunately the experimental receiver was optimised for the narrower bandwidth GPS signals so the receiver distorts the Galileo signals. Despite pushing at the limits of the experiment, the collection of real signals is valuable as the distortion separately quantified.

A data collection was scheduled for UK-DMC targeting reflections from the Galileo test satellite, GIOVE-A over the Arafura Sea, off the North Australian coast. The ECMWF weather forecast for the time predicted wind speeds of ~15km/h. This is a relatively calm ocean and hence a flat surface, leading to a reduction in the size of the scattering zone, and a stronger reflected signal.

An ocean reflected signal was successfully detected despite the receiver limitations and the GIOVE test signals being lower power than that from GPS. The signal magnitude with respect to path delay for the full 20 second data collection is shown in Figure 4. This was detected by combining two channels on the L1 frequency provided by the Galileo structure [5].

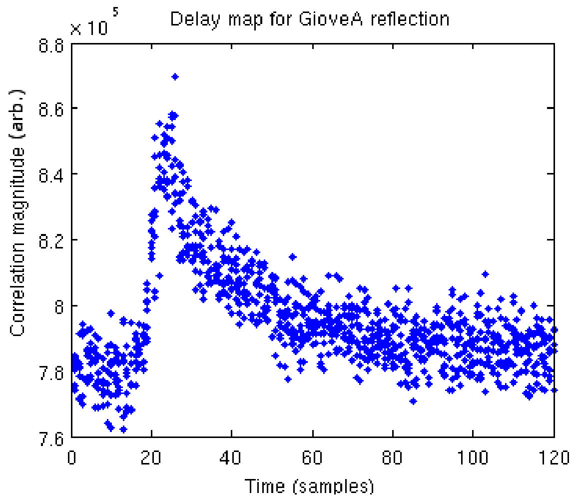

Figure 4 The signal magnitude vs. delay for the fixed Doppler at the centre of the specular point. Shown are 20 seconds of data, overlaid, each made up of 2 second integrations.

Ice edge sensing

An application within the capabilities of this type of instrument is the detection of the boundary between the ocean and polar ice. Here we show an outlook to a service providing ice-sea boundary mapping.

The physical parameters that could be measured using GNSS reflectometry are the presence of ice, the ice roughness and the surface height. There has also been research into ice age and thickness [6]. Simulations of theoretical scattering models have been investigated by Wiehl, Legresy and Dietrich [7]. Signals recorded from orbit are demonstrated in this paper.

The resolution of the edge detection depends on the microwave power reflected from the ice. This reflection is much stronger than that of the ocean principally due to the smooth surface of ice. A strong reflection requires a shorter integration time to achieve the required SNR threshold, so the radar cross-section at the specular point can be reported more frequently than for the ocean. The signal reflected from ice is strong enough to be detected after approximately 10ms integration, which corresponds to a ground track of just 75m.

We can analyse the other limits to spatial resolution using the Hajj and Zuffada geometric optics model [8]. Operating in the simplest mode, measuring the radar cross-section, the resolution would be limited by the size of the footprint. The footprint is an ellipse on the surface of the earth, centred on the specular point and bounded by the surface that has one code chip delay from the specular path, Figure 3. The size of this annulus zone is the limiting factor for the resolution rather than the integration time.

For a satellite in a low earth orbit of 700km, with the specular reflection in the plane of motion the size of the annulus zone is 20km. If the wide-band Galileo E5a/b signal were to be utilised then the footprint reduces down to 5-10km. In reality this resolution can be reduced still further by deconvolving the signal ambiguity function. This is possible as the high frequency components of the signal structure are retained upon convolution with the ocean scattering function due to the characteristic triangular function for PSK or BOC modulated GPS signals. Data from UK-DMC will be analysed below, to assess whether a greater spatial resolution than the annulus zone is actually possible.

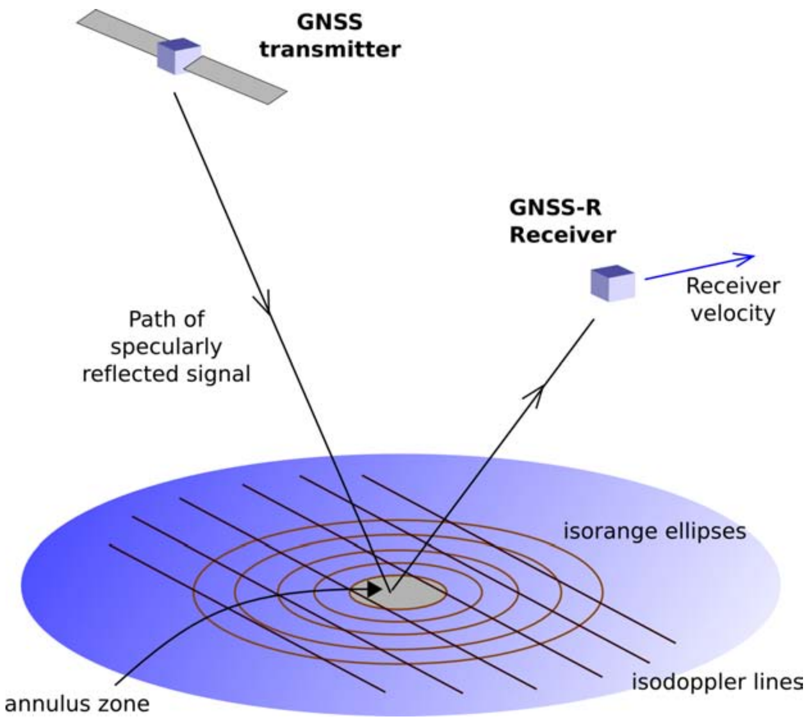

Figure 5: Geometry of the scattering arrangement. The ocean surface is split into cells where the signal is scattered with different doppler frequency and signal range delay

To give a very brief view of the potential of the data, we present a reflectometry data collection from UK-DMC over Antarctica in January 2008. The data collection was scheduled using GPS signals, rather than Galileo, near to the UK Halley research base. Several days previously the ENVISAT ASAR instrument, captured an image of the area, which was used to tie up the GNSS-Reflectometry signals with a ground truth. The 20 second data collection had 3 specular points within the area of the receiving antenna: one on sea ice, one on the snow covered ice shelf and one in a small sea containing icebergs and bounded with sea ice. Whether a reflection is from ice or ocean can be determined from the shape of the delay-Doppler waveform or from the reflected signal power.

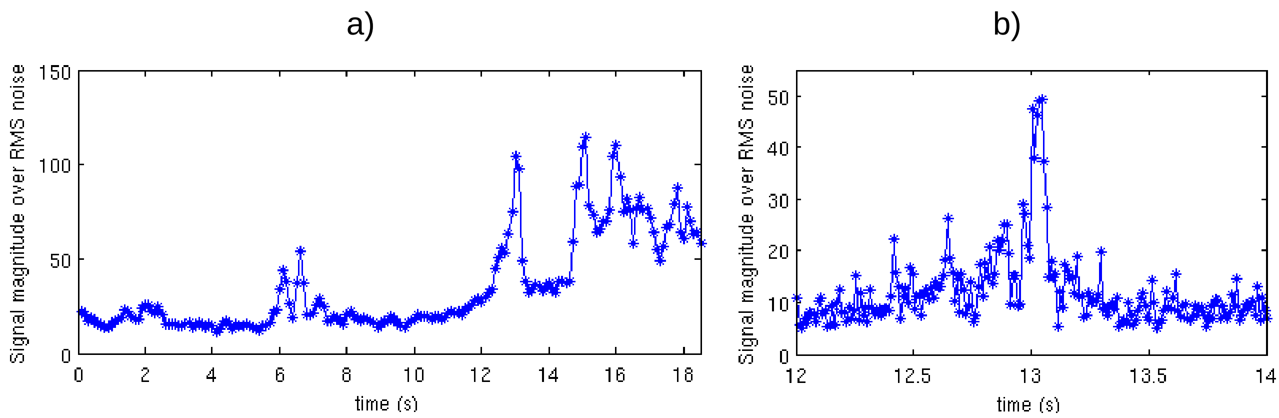

Figure 6 a) Reflected signal power from a GPS reflection as the specular point moves over sea (~0-10seconds) and icebergs (>12seconds) Integration time 100ms. b) A subset of the data between 12-14seconds. Integration time 10ms.

The specular reflection that followed a path over what appeared to be a small sea surrounded by ice, and containing icebergs was the most interesting. The reflected power at the specular point increases significantly at times, which is thought to be the specular point passing over icebergs, Figure 6a. The minimum feature size of the signal can be explored to give an indication of the spatial resolution achievable. In Figure 6b the integration time has been set to just 10ms. The smallest feature size is determined to be around 50ms. This corresponds to a distance travelled on the ocean of 350m which is smaller than the annulus zone. The shape of the delay Doppler waveform can also be used for determining the surface properties. The 'horseshoe' characteristic of a rough ocean (Figure 7a) changes to bright points thought to be the ice reflections. Work is ongoing in utilising the full delay-doppler map so that the measurement swath can be increased to the roughly 1000km wide scattering zone.

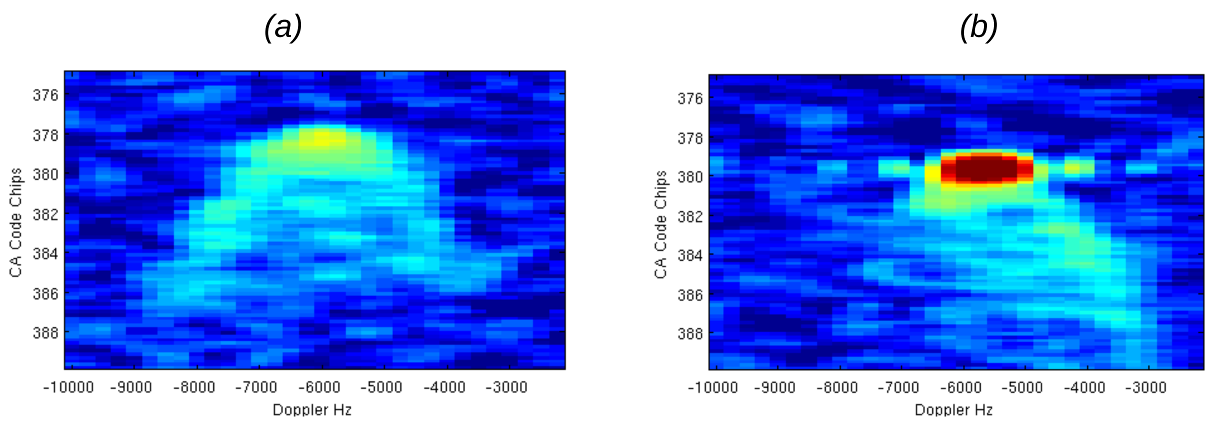

Figure 7 Delay-Doppler map at two points in the same collection as Figure 6. Integration time 300ms. Colour is proportional to the logarithm of the signal magnitude. a) Reflection at 0.3 seconds into collection, shows characteristic shape of ocean reflected signal. b) Reflection at 13 seconds.

The delay Doppler map for the ice reflection in Figure 7b shows some interesting features: there is a strong peak at the specular point from a very strong reflection, the ‘horseshoe’ shape of the ocean reflection remains, but is one sided, implying partial ocean and partial ice. To the left and right of the very bright spot are a set of spots which must not be confused with the response of the ocean but are the *sinc* shape of the ambiguity function.

To compare well with current ice observation techniques a resolution of better than 10km is required with a daily update. From preliminary analysis GNSS-R appears to be able to provide data for the niche with a resolution of better than 400m. GNSS reflectometry would not be able to compete in many respects with an active synthetic aperture radar instruments. However it can provide a complementary technique capable of providing low-cost sensing of ice movements with frequent revisit times.

Satellite and instrument design

With a passive instrument like this there are two routes into space that could achieve the required constellation of sensors. Firstly dedicated nano-satellites could be used, with multiple satellites in one launcher. The second route puts the instrument as a secondary payload on satellite of opportunity. The requirements for the data-rate, mass and power are similar for both routes, to fit in a ~10kg satellite or introduce minimal impact on a larger, primary satellite.

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Figure 8 The RapidEye constellation of 5 satellites undergoing final testing at SSTL.

The most likely route into space is through putting the receiver onto satellite constellations built for other purposes. Surrey Satellite Technology will have launched 7 multi-spectral imaging satellites for the Disaster Monitoring Constellation by early next year and in August 2008 the five RapidEye satellites were launched successfully from a single rocket (Figure 8). There are other possible constellations such the 29 Orbcomm and the 66 Iridium communication satellites. The next generation Iridium communication satellites are offering to carry remote sensing instrumentation.

Instrument Specifications	
Mass	2kg
Power	<10W
Nadir Antenna	12 x 30 cm 12dBi
Data rate	40kbps continual

Table 1 Proposed instrument characteristics

The instrument concept is based on a GNSS navigation receiver, with additional antenna and reflection coprocessor, so it can double up as the navigation receiver for the host satellite, reducing mass or adding redundancy making the instrument more attractive for selection as a payload.

Data Transmission

To provide storm warning information to mariners, the complete path from sensor to user needs to be considered. A minimum in communication delay is required, implying the need for more than one ground station or the use of intersatellite links. The infrastructure would already exist if the instrument was carried on the communication satellites. Measurements would be collated at a control station, where the warning messages would be prepared for dissemination.

Existing communication channels can be utilised by linking into the Global Maritime Distress Safety System which sets the international communication requirements for ships [9]. The communication channel depends on the sea area. NAVTEX is used within about 400 miles of the shore. These low cost receivers operate at a very low data rate on Medium Frequency radio (MF) and continually record the transmitted text message to an internal printer or display. Further from the coast, the Inmarsat-C geostationary satellite transmits text-based messages to a SafetyNET receiver. Alternative channels include the Iridium, Orbcomm and Globalstar constellations which would provide a global coverage. For ice monitoring, a daily update may be adequate.

Conclusions

The UK-DMC GPS-Reflectometry experiment has demonstrated the measurement of ocean roughness and ice boundaries from space. The data collections have shown that the reflected signal characteristics are linked to the ocean roughness. The sensing of ice edges has been demonstrated and the resolution achievable has been considered from the initial analysis of the UK-DMC data.

Employing a constellation of receivers would enable measurement with global coverage and rapid revisit for the ocean and ice environments. Due to the small size and low power of a GNSS-R receiver, a sensor constellation could be achieved cost effectively by deploying nano-satellites or instruments as secondary satellite payloads. The increase in sampling frequency over current sensors would allow access to new applications in real-time storm measurement and warning.

The greatest future challenge is in demonstrating the precision and resolution of ocean roughness measurement. For this the current models and inversion techniques need to be extended from the airborne data and shown to work on signals from space. This work is ongoing but requires an extended measurement campaign with in-situ recording of the ocean surface for validation.

A further challenge will be in utilising multiple GNSS systems, generating results that are comparable between systems. The primary benefit of targeting multiple GNSS systems is the additional coverage possible by targeting GPS, Galileo and any other constellations.

To provide a storm warning service, the information needs to be made available to the end-user in a timely and appropriate format. The dissemination route for storm and ice warnings needs to be considered in particular by collating user requirements.

Surrey is preparing an instrument for a forthcoming satellite that will permit collection of data for further validation and demonstration of a prototype service.

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