A Global System for Dangerous Sea Monitoring Using Space Based GPS Bistatic Remote Sensing

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ABSTRACT

Global Navigation Satellite System (GNSS) bistatic remote sensing involves studying the signals transmitted by navigation satellites, such as those of the Global Positioning System (GPS) and in the future those of the Galileo constellation after they have reflected from the Earth's surface. These signals are constantly being scattered off the seas and land, and they contain valuable and varied information on the Earth's surface. Ground-based and airborne applications of this method for ocean, land and ice sensing have been explored in both theoretical and experimental studies. A significant step towards assessing this technique in space came with the launch of the designated GPS reflections experiment on the UK Disaster Monitoring Constellation satellite in 2003.

GPS reflected signals are now being detected regularly from low Earth orbit using the experiment on board the UK-DMC. Many in the scientific community are convinced that this is a viable method for ocean sensing at satellite altitudes. It is now possible that dangerous seas can be distinguished from passable ones thus enabling a very useful low-cost application. A low-cost constellation of this sort could be used to backup or augment the existing systems of dangerous sea detection already in place.

This paper will examine ocean reflected GPS signals received by the UK-DMC under different roughness conditions and make comparisons with in-situ buoy measurements. Additionally, a plan will be presented proposing how this technology could provide a low-cost system capable of good spatial coverage and quick measurement repeat times in helping to prevent maritime accidents caused by dangerous sea conditions.

1. INTRODUCTION

This remote sensing concept proposes that techniques similar to those of traditional radar remote sensing systems can be applied to the bistatically reflected signals transmitted from global navigation satellites, such as those of Global Positioning System (GPS).

Over the last two decades Earth-reflected GPS signals have become an attractive tool for remote sensing, applicable to a variety of existing applications. Several near Earth experiments (from aircraft, balloons and platforms) have successfully retrieved ocean wind speeds[1], ocean wind direction[2], ocean altimetry[3,4] and surface water content over land surfaces[5] to give just a partial list.

To test this technique from low Earth orbit, the United Kingdom Disaster Monitoring Constellation (UK-DMC) platform was equipped with an experiment and launched in September 2003. On-board was a GNSS bistatic radar (or GNSS Reflectometry) experiment developed by Surrey Satellite Technology Limited (SSTL) with support from the British National Space Centre (BNSC). Its initial goal was to investigate the feasibility of using reflected GPS signals for remote sensing applications in low Earth orbit. The experiment operations and hardware configuration are described in detail in [Ref. 6 and 18]. The GPS receiver on the UK-DMC satellite has been modified with a downward (nadir) pointing medium gain antenna and a solid-state data recorder. The recovered signals shown below were all detected using down-linked data processed with a software receiver on the ground.

Initial results of the UK-DMC experiment and the processing required for application of this technique from low Earth orbit were presented in [Ref. 7,8] and will be expanded on in this paper.

The results of this work are applied to a constellation design intended to detect dangerous sea conditions on a global scale and provide warnings to mariners. We will start by highlighting the possible human and commercial benefits that such a system could provide. Then, to provide a solid technical foundation, bistatic radar cross section (BRCS) measurements have been made and compared over a range of sea conditions. From these measurements it is clear that dangerous sea conditions could be detected using this technique. Subsequently, two low-cost platforms will be put forwards, followed by an analysis of the coverage over a high risk target area. Finally, a proposed interface to marine users is presented.

2. MOTIVATION

There are obviously many things that can cause an accident at sea and most are usually attributable to an unlucky or negligent combination of several factors. Among these factors, sea conditions have played a part in several of the recent ferry accidents in recent years[9]. As an example we can consider the tragic ferry disaster that occurred of the coast of west Africa in 2002[10]. In this case, if the Senegalese or Gambian port authorities knew that there was a high probability of disaster before the Joola passenger ferry [Figure 1] left port, the disaster may have been avoided. Obviously, if other important factors are neglected accidents will still occur. For example, this particular disaster may have been avoided by limiting the number of passengers to what the ferry was designed to accommodate. Our aim is to provide ocean knowledge on which to base decisions and in parallel to encourage work to eliminate the other factors that often equally contributes to these catastrophes.

Figure 1, Image of the capsized Senegalese passenger ferry "Joola", where an estimated 1800 people died. Rough seas were partially responsible.

In addition to the Joola disaster, the damaged caused by the worlds ocean is impressive. For example the following statistics, taken from [Ref. 11], indicate the pressing need for new systems to monitor ocean conditions.

1. Bad weather causes on average of one ship of over 500 tonnes to sink somewhere on the globe every week.
2. In 1998, the marine insurance industry paid out over $2.5 billion in claims for weather related accidents.
3. In November 1998, a single ship lost containers with a value of $100 million in a storm in the North Pacific.
4. Since 1990, over 15, 000 lives have been lost at sea.

The weight of this evidence presents a challenge to the world science community to commence development on creative solutions to make the world's oceans safer.

3. THE OCEAN ROUGHNESS MESAUREMENT

The most basic observable of a GPS bistatic application is the bistatic radar cross section (BRCS). This is simply the bistatic version of the extensively used traditional backscatter normalized radar cross section (NRCS). A BRCS estimate of the surface scattering can be performed over a physical area on the surface as shown below.

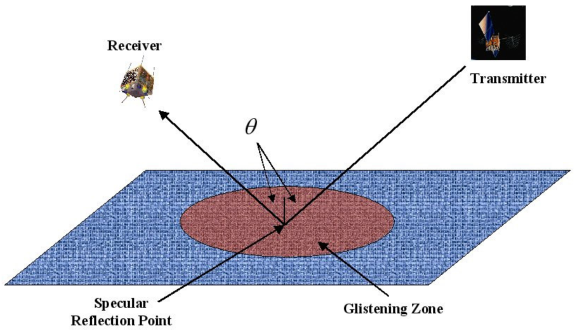


Figure 2, Basic reflection geometry. The incidence angle is shown as theta above. Power is returned in a region around the reflection point in what is often called the glistening zone.

Details of this calculation are included in [Ref. 12,18] and involve integrating the received signal power over the surface while taking into account non-surface related effects, such as those of the transmit and receive antenna gains and transmission paths.

It would be expected, and has been shown to be the case, that contrary to a backscattered radar cross section, the forward scattered radar cross secions decreases as the sea roughens. For under conditions of rough sea, the waves act to scatter the power more widely, thus decreasing the power received at the receiving satellite.

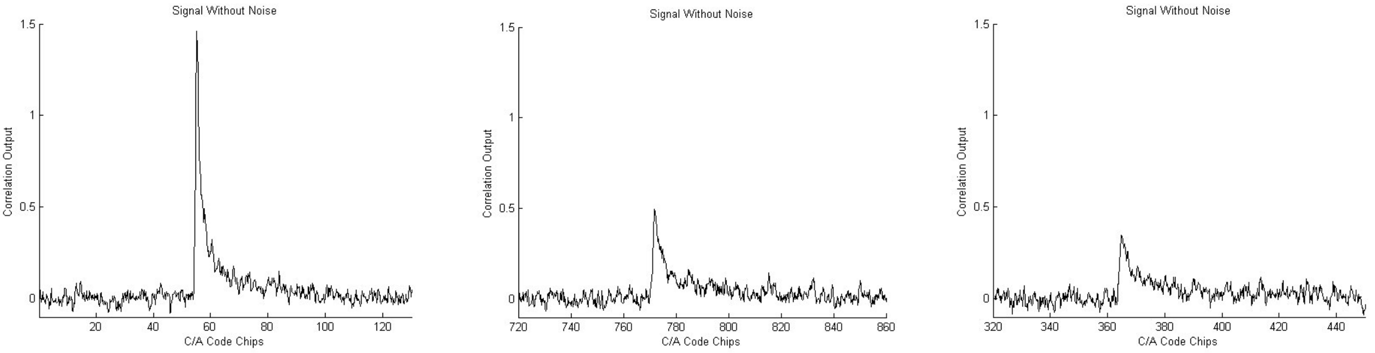


Figure 3, Delay power waveforms of the signals with noise after 1 second of averaging for the March 23rd 2004 (left), March 4th 2005 (centre) and September 3rd 2004 (right) ocean reflected signals.

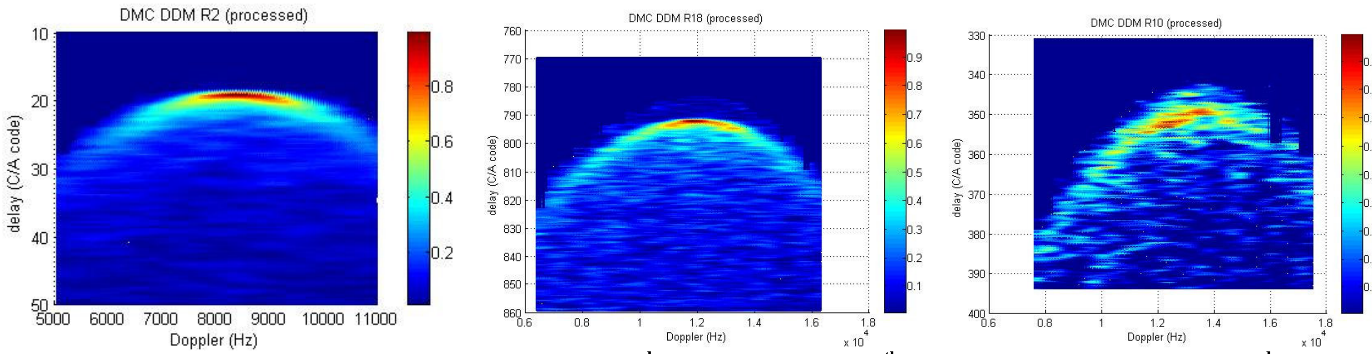


Figure 4, Delay Doppler maps for the March 23rd 2004 (left), March 4th 2005 (centre) and September 3rd 2004 (right) ocean reflected GPS signals detected using data from the UK-DMC experiment.

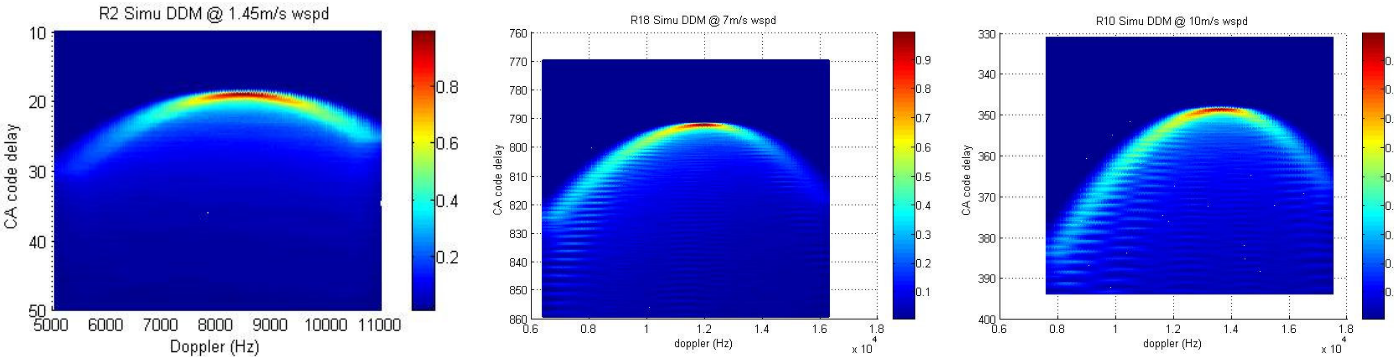


Figure 5, Simulated delay Doppler maps for the March 23rd 2004 (left), March 4th 2005 (centre) and September 3rd 2004 (right) ocean reflected GPS signals detected using data from the UK-DMC experiment.

Date	$\hat{\sigma}^0$ (dB)	Incidence Angle (deg)	Wind Speed (m/s)
March 23rd 2004	44.17	9.4	<2
March 4th 2005	39.19	23.7	7
September 3rd 2005	36.90	22.2	10

Table 1, Estimated of the Bistatic Radar Cross Sections (BRCS) over the first iso-range ellipse, incidence angles and wind speeds for the three example signals shown above.

4. OCEAN REFLECTED SIGNAL MEASUREMENTS UNDER DIFFERENT CONDITIONS

In Figure 3 above the delay waveforms of three different ocean reflected signals are shown. These waveforms are achieved by holding the Doppler frequency constant during processing and searching for power as a function of delay across the surface. The slow tailing off of the signal is due to the decreasing power at locations away from the specular reflection point. For the three signals shown, the signal peak is highest for the calmest seas and decreases for the other two examples under rougher conditions. The sea conditions as indicated by collocated ocean buoys are listed in Table 1 above.

Following in Figure 4 are maps of the received signal power over a wide range of delays and frequencies. These are then compared with the simulated received power delay and frequency distribution in Figure 5 and shown to be in general agreement. The shifting of the power to one side in the Doppler (horizontal) axis is often due to the satellite antenna patterns which needs to be corrected for when making measurements of the BRCS. These simulation were run using the Zavorotny and Voronovich scattering model[13] and inputs from the bidirectional wave spectrum of Elfouhaily et al[14].

The estimated BRCS $\hat{\sigma}^0$ for the three signals shown above are included in Table 1. The range of measurements is approximately 7 dB between very calm seas and those with 10 m/s winds. This is a useful but not an extraordinary sensitivity and is believed adequate for sea state sensing.

5. DETECTING SIGNALS UNDER DANGEROUS CONDITIONS

Signals have been successfully retrieved in the presence of greater than 3-meter waves but we have yet to encounter an ocean state that could be uncontroversial deemed dangerous. However, it is possible to use the existing UK-DMC data sets and existing analysis of the NSCS measurements at very high wind speeds to make predictions. It has been shown that for existing scatterometers, such as QuickSCAT, as the wind speed increases to the point of creating dangerous ocean conditions (> 20 m/s winds) the backscattered NRCS tends to level off near a maximum value[15]. Similar to the case for the NRCS it is also reasonable to expect a similar but opposite phenomenon for the BRCS, with the level of the NRCS measurements not going below a minimum value. The value of the BRCS is expected to saturate as the winds increase and the sea roughens, permitting signal detection under all conditions.

6. MISSION REQUIREMENTS

The top-level mission requirements of a dangerous seas monitoring system can be summarized simply, and are listed below. In addition to the main mission objectives, it would be possible to use the satellites in this constellation as the basis for validating other GNSS bistatic applications, thus blurring the distinction between an operational and an experimental instrument. The operational mission requirements for a GNSS bistatic dangerous seas warning constellation could be as follows,

1. Generate a system for providing advanced warnings to marine users based on a simple color coded system; green – sea safe, yellow – sea rough but not dangerous, red – dangerous sea conditions present, black – no information available.
2. Provide measurements 24 hours a day, 7 days a week over the Earth's major oceans and seas. Provide at least one measurement in every 10-degrees longitude by 10-degrees latitude box on the Earth's surface each day.
3. Provide at least one measurement within a defined high-risk region that is always less than 1 ½ hours old.

These represent the minimum requirements for a marginally useful system. The constellation can then be scaled up depending on the available resources.

7. POSSIBLE SATELLITE PLATFORMS

A system of global sea state monitoring was proposed several years ago, that of the GANDER constellation[16], and this design could be easily revived and improved. We propose two possible LEO satellite platforms, both with flight heritage that could be used to construct the necessary constellation at a relatively low cost.

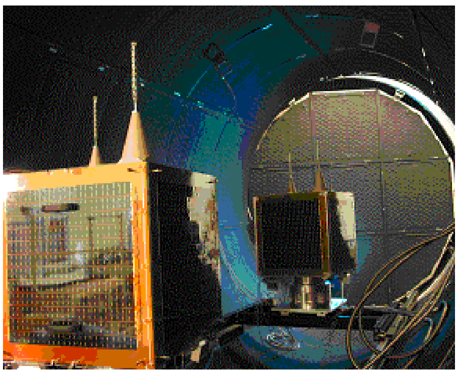


Figure 6, UK-DMC and NigeriaSat-1 satellites during environmental testing.

The existing UK-DMC platform, shown above in Figure 6 could be modified to perform only bistatic ocean measurements. This would involve replacing the imager with an enhanced antenna configuration to maximise the measurement swath. This has the advantage that it is not dependant on developing new technology and could be accomplished with existing off the shelf components using a proven design.

The second platform possibility is a 3-axis controlled nanosatellite, such as that of SSTL's very low cost SNAP-1. Significant modifications of the original design would need to be made to accommodate the bistatic ocean sensing instrument. A conceptual drawing of the SNAP satellite modified to accommodate a ocean sensing capable antenna is show in Figure 7.

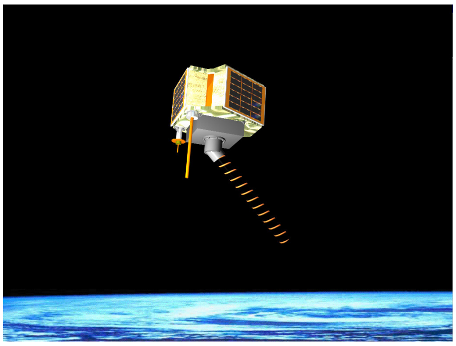


Figure 7, Model of SSTL's "SNAP-1" satellite, modified to carry an antenna suitable for making bistatic ocean roughness measurements.

8. COVERAGE AN ANALYSIS

As a representative study area we have chosen the ocean region between the Cape of Good Hope and Antarctica. The reason being that ships making the passage around the southern points of Africa, and in the Southern Oceans generally, often encounter dangerous conditions and there is only sparse and often unreliable knowledge of the ocean conditions available to them. During a typical descending pass of a GPS satellite, the path of available measurements will cut vertically across the corridor in a north-south arc. To better quantify the spatial and temporal coverage in the above passage, it can be broken down into 4 unequal divisions, all 10 degrees in latitude high but varying in width (1 degree in longitude at this latitude is approximately 200 km). A suggested arrangement is as shown below in Figure 8.

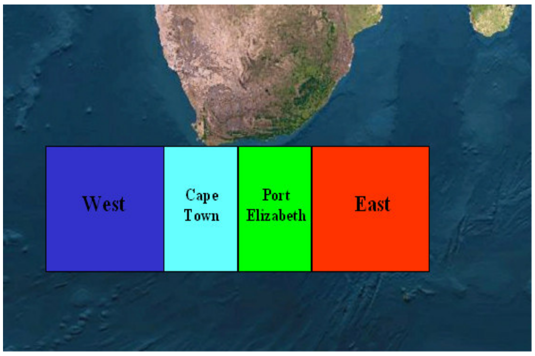
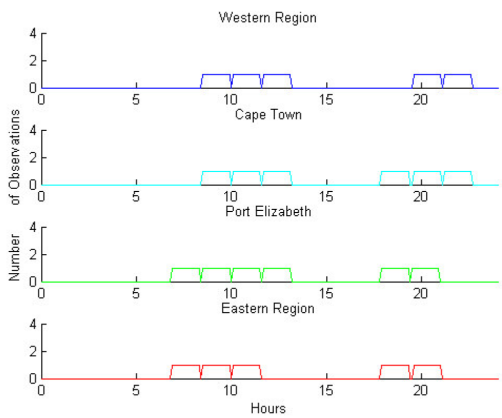


Figure 8, The Southern Ocean corridor broken into 4 watch regions. In this case, 2 narrower strips to the south of Cape Town and Port Elizabeth South Africa and two larger areas to the east and west.

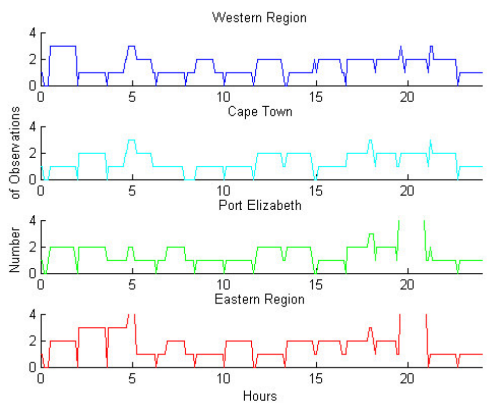
The total coverage achievable for different numbers of satellites in the constellation can be examined using a simulation. The following simulations examine the coverage achieved over a period of 24 hours in each of the above sub-regions. The simulations were run (using existing orbit propagators and NORAD orbital elements) over an arbitrary 24 hours with multiple satellites in nearly identical orbits, but spaced in longitude using a variable right ascension angle. The reference orbit was chosen to be that of the UK-DMC. All the satellites are orbiting in a 680 km sun-synchronous orbit, with an orbit period of slightly less than 90 minutes.



[1 satellite simulation] Time over 24 hours where one or more valid measurements exist in each of the 4 defined regions. Measurements were assumed to be valid for 1 ½ hours. The abrupt but brief losses of coverage are due to the satellite orbit period being slightly shorter than 1 ½ hours.

Figure 9

For the case of a four-satellite constellation the satellites are spaced from the original by 45,90 and 135 degrees.



[4 satellite simulation] Time over 24 hours where one or more valid measurements exist in each of the 4 defined regions.

Figure 10

[Note: The often erratic nature of the measurement point locations means that there will be slight differences in the optimal configuration from day to day. The above strategy is presented to act as a general guide only].

As is evident from the results above, it is possible to provide continuous coverage within the entire Southern Ocean using a constellation of 4 satellites or less. The results above benefited from the low latitude and large area of the target area and will decrease for regions near the equator or if tighter restrictions are needed near the targeted location[18].

9. DISTRIBUTION TO END USERS

Several methods of communication already exist for the distribution of weather information to ships at sea. Currently, a typical ship can rely on several sources of data and communications interfaces for charting a course around the world's oceans. A partial list of these services include: Top Karten, Weather Online, UK Met Office, Local near shore radio stations, Iridium Weather Service and GRIB files. The expanding reach of the Internet will make accessing these services in the open seas easier in the coming years.

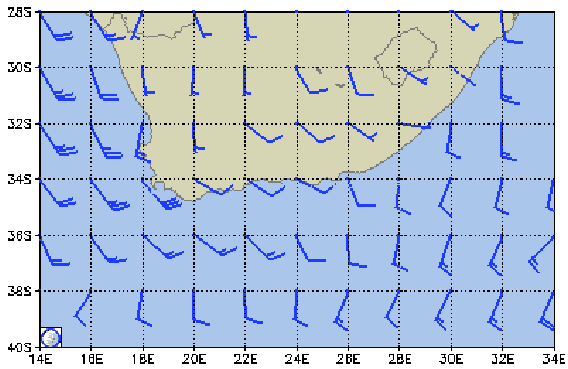


Figure 11, Example of a wind information chart from WeatherOnline in the regions around South Africa. Simple charts such as this one are commonly used by sailors at sea.

It is envisioned that data could be accumulated centrally and updated continuously into simple colour coded maps (green, yellow, red and black as per requirements) like that shown in Figure 11 above, available on the Internet. A service could easily be provided, where users can request maps of specific world regions to be sent regularly by one of the existing or future global distribution services mentioned above.

10. SUMMARY AND CONCLUSIONS

The experiment on-board the UK-DMC has provided a valuable verification platform for space based bistatic radar remote sensing. To date it has collected over 50 data sets, mostly from the ocean but also from land and ice surfaces[17, 18]. This data has been critical in evaluating the possible applications of this technique.

Sensing dangerous seas and providing warning messages to marine users is only one in a number of valuable applications being explored. This technology is still being actively developed and the accuracy of the measurements that are being made is still under investigation. However, in the case of dangerous sea sensing we are less limited by the many complicated issues involved in providing an ocean product to the scientific community. We can demonstrate that a very rough sea is distinguishable from one that would be passable by most marine vessels. This lessens our requirements to the point were a very useful application can be advocated with confidence. In Summary,

1. There is a pressing need to reduce the loss of life caused by dangerous sea conditions and better protect the goods and crews of commercial shipping operations.

2. Bistatic radar cross sections are being calculated over a range of ocean conditions

using the UK-DMC bistatic radar experiment. These measurements can be used to sense dangerous sea conditions.

3. Existing satellite technology can be used to design a low cost constellation providing global coverage of the World's oceans.

4. Warnings and alerts can be provided to marine users using the present advancements in communications, resulting in safer marine navigation for all sea navigable ships.

A summary of the current state of this technology and more detail on the BRCS measurements and achievable coverage please contact the lead author for a copy of a useful Ph.D. dissertation on the subject [Ref. 18].

11. ACKOWLEDGEMENTS

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 productively continue. We would also like to thank the British National Space Centre for their support for this research.

12. REFERENCES

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

2. M. Armatys, "Estimation of Sea Surface Winds Using Reflected GPS Signals",PhD Thesis, University of Colorado. 2001.

3. 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.

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

5. D. Masters, "Surface Remote Sensing Applications of GNSS Bistatic Radar: Soil Moisture and Aircraft Altimetry". PhD dissertation, University of Colorado, 2004.

6. 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.

7. S. Gleason et al., "Detection and Processing of Bi-statically 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, "An Attempt to Sense Ocean Winds and Waves Empirically Using Bi-static GNSS Reflections in Low Earth Orbit", Proceedings from the International Geoscience and Remote Sensing Symposium, Seoul, South Korea, 25-29 July 2005.

9. S. Gleason "A Proposal for Preventing Marine Accidents Caused by Dangerous Seas using Emerging Bi-static Radar Technology" American Geophysical Union Fall Meeting 2004, San Francisco, USA.

10. Associated Press, "Naufrage du Joola: Environ 350 Corps Retrouver", September 2002.

11. Satellite Observing Systems web site. www.satobsys.co.uk/GANDER/webpages/ganstorm.html

12. S. Gleason and V. Zavorotny, "Bistatic Radar Cross Section Measurements of Ocean Scattered GPS Signals From Low Earth Orbit", Proceedings from the International Geoscience and Remote Sensing Symposium, Denver, Colorado, U.S.A, 31 July – 4 August, 2005.

13. V.U. Zavorotny and A.G. Voronovich, ``Scattering of GPS Signals From the Ocean with Wind Remote Sensing Application". *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 38, pp. 951-964, March 2000.

14. T. Elfouhaily, B. Chapron, K. Katsaros, and D. Vandemark, "A Unified Directional Spectrum for Long and Short Wind Driven Waves," *J. Geophys.Res.*, vol. 102, pp. 15 781–15 796, 1997.

15. D. Fernandez et. al. "C and Ku band Ocean Backscatter Measurements Under Extreme Wind Conditions". ", Proceedings from the International Geoscience and Remote Sensing Symposium, Anchorage, Alaska. September 2004.

16. A da Silva Curiel et al. "The GANDER Constellation for Maritime Disaster Mitigation". Acta Astronautica, Vol 44, Nos 7-12, pp685-692, 1999.

17. S. Gleason, M. Adjrad and M.J. Unwin,. "Sensing Ocean, Ice and Land Reflected Signals From Space: Results from the UK-DMC GPS Reflectometry Experiment". Proc. ION 2005. Long Beach, California. September 2005.

18. S. Gleason. "Space Based Remote Sensing of Oceans, Land and Ice Using Bistatic GNSS Reflections". Ph.D. Thesis, University of Surrey, 2006.