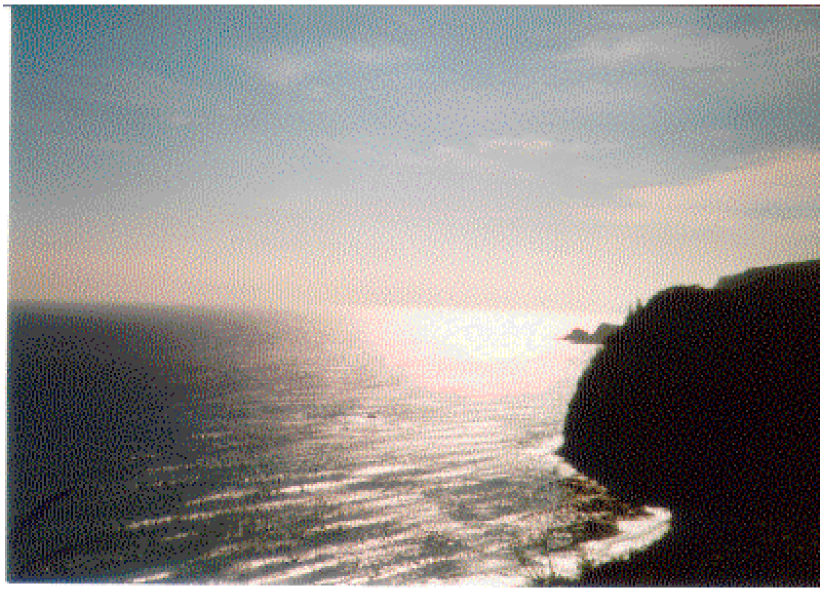
BNSC Service Mission Support (SMS) Programme

Ocean Currents from space



Using GPS reflections to detect Ocean Currents

Report for WP33 (Parasitic radars: GPS Reflectometry)

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Abbreviations

AODCS – Attitude and Orbit Determination and Control System
ESA - European Space Agency
GNSS – Global Navigation Satellite Systems – A generic term that includes all space based navigation systems (GPS, GLONASS, and Galileo).
GNSS-R Global Navigation Satellite Systems - Reflectometry
GPS – Global Positioning System
JPL – Jet Propulsion Laboratory
PARIS – Passive Reflectometry and Interferometric System
SGR – Space GPS Reciever
SSH – Significant Sea Height
SSTL – Surrey Satellite technology Limited
SWH – Significant Wave Height

1 Introduction

We present here a brief outline of the state of the art in passive GNSS altimetry. Using passive GNSS reflections as a way to perform ocean remote sensing has emerged as a rapidly growing and potentially valuable technology. This technology has undergone much analysis and several successful experiments but still remains somewhat of a mystery with many questions surrounding its feasibility at spacecraft altitudes. However, the theory works, and everyone is awaiting a convincing demonstration on a space platform. It is only a matter of time before this happens, but until then much of our assessment must rely on the results of simulations and low altitude experiments.

2 Brief History of GNSS-Reflectometry

A French aircraft acquired the first GPS Reflection from the sea surface during training exercises in 1991 [AUB94]. After post-processing on the ground it was determined that the signal was almost certainly sea reflected multipath with lower received power and additional noise. This fortunate discovery was followed by a proposal by the European Space Technology and Research Centre (ESTEC). The use of reflected GPS signals as a new means to perform sea science was put forward as part of the PARIS concept [NEIRA93]. Several years later they were able to demonstrate an altimetry application using GPS reflected signals at low altitudes by measuring the change in sea level as tides flowed in and out at a bridge “Zeeland Brug” near Rotterdam, Holland [NEIRA01].

Significantly, in 1997 researchers at the Jet Propulsion Laboratory (JPL) were able to detect an ocean reflected GPS signal from space by post-processing the data collected during a calibration of the SIR-C radar [LOWE01]. This is the only known detection of a reflected GPS signal from a space platform to date. Currently, researchers at JPL are conducting flight experiments to explore the application of GPS reflectometry at aircraft altitudes [LOWE02,ZAFF01,ZAFF02]. On a similar note but at slightly higher altitudes, reflections have been received from a balloon experiment off a calm sea conducted just recently over the Mediterranean [CARD01]. Several more experiments are in the planning phase using both airplanes and balloons in both the US and Europe.

At the University of Colorado there has been significant progress into the detection and recovery of sea wind surface speed and direction as well as extensive modelling of the reflected signal environment [ARM01]. At the University of Colorado/NOAA they have also studied the use of the reflectometry technique to determine the age of ice flows [KOM02] as well as significant attempts at modelling the electromagnetic characteristics of GPS signals reflected off various surfaces including the ocean [KOM01]. Equally, in Spain a group of researchers (Starlab) have developed a comprehensive signal simulator and done extensive research into the characteristics of the reflected signal [RUFF01].

There has been progress on the many different techniques that could be used to extract the information after the signal has been received and correlated. A useful technique has already been developed in this regard and is that of Delay-Doppler Mapping [ELF01,ELF02].

There have been numerous proposals regarding the use of GPS reflectometry and its applications. These include proposals to determine the sea winds and ionospheric delay [GAR98,KATZ96]. The application of this technology is relatively still in its infancy. People are working diligently on proposals to perform experiments on satellites such as the Student Reflected GPS Experiment (SuRGE) by the University of Colorado [EMERY01] and others [SSTL01]. There currently exists the CHAMP satellite that has a downward facing antenna and could theoretically be configured to acquire GPS Signals but has yet to do so. There have also been simulations done of a wind retrieval system from space [GAR01] as well as research done into the development of GNSS receivers that are capable of tracking reflected signals [SSTL02,SUST01].

SSTL is actively involved as well. There is a downward looking antenna on the UoSat-12 Satellite that has been used to test signal detection algorithms [SSTL02], however like CHAMP it has not been designed to retrieve reflected signals and it may prove difficult doing so. Also, the miniPetrel Proposal [SSTL01], presented at Navitec 2001 ESTEC, put forward an idea to build a nanosatellite for the sole purpose of collecting data for extracting GPS reflected signals both on the ground and in real time on the space platform. Currently, we are trying to modify an existing earth monitoring satellite with a downward pointing antenna. When a convincing demonstration is realised from a space platform much of the uncertainty surrounding this technology will be significantly diminished.

This applies even more strongly for the application of space based altimetry using GNSS. It is generally assumed that high accuracy altimetry is the most obvious way to invert to ocean currents. A demonstration needs to be realised at spacecraft altitudes to waylay many of the doubts and uncover critical issues. The obstacles encountered during ground testing have provided significant challenges and it can be assumed that in space the number of these challenges will increase. Issues such as signal strength and signal tracking, as well as a host of others, need to be accounted for. To date, ground experiments have been completed using both C/A code altimetry and more precise carrier phase determinations. These two experiments give valuable insights into the technical details involved and we will delve into more detail in the body of this report.

3 Concept and Physical Principles

3.1 Overview

As mentioned above, this concept was first proposed as a tool for ocean science back in 1993. The basic idea is rather straightforward. As is the case of most new science, the problems have been emerging in the details. Shown below is an illustration at the visible wavelength of the basic concept.

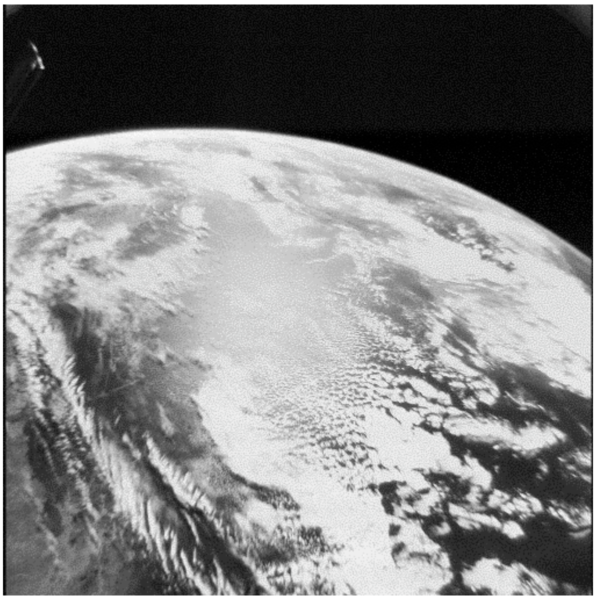

Figure 1, Uosat-12 Sun Glint Image

As part of a BNSC instrument development study we demonstrated our ability to steer SSTL's UoSat-12 camera at a predicted sun reflection. The theory stems from the visible parameters contained in that reflection. If we measure the size of it, this will give us an indication of the sea state around the specular point (possible at some distance away as well). If we could time the delay the suns rays needed to reach the camera we could calculate the height of the reflection surface (at the centre and at concentric rings emanating from the centre). For light waves this is not possible but the GPS signals are designed for these kinds of measurements (in addition, they also traverse clouds).

This list of advantages is somewhat short and the difficulties soon make themselves apparent. GPS was designed for calculating distances between transmitter and receiver but as the signals undergo scattering and reflection many of the physical principals the system was based on become complicated. Anyone who has ever spent time at sea can easily imagine that the ocean surface is not exactly an easily predictable reflection surface. However, the changes that the signal undergoes during the reflection process hide clues about the sea surface (and below). This information often requires painstaking persuasion to reveal itself. The extracting of this information has been the task at hand for the past 10 years.

The ability to make range measurements from a reflected signal will allow for a calculation of the height of the reflecting surface. In this case the spread of the signal is a nuisance in that the signal arrives at the receiver at slightly different delays from concentric circles around the specular reflection point. By contrast, this spread contains useful information on the sea state. So it can be seen that how the information in the reflected signal is used depends on what you are looking for. For the case of Ocean currents we are primarily concerned with altimetry measurements from ocean gradients from which currents can be estimated. GPS range measurements are confined to 2 main categories. That of lower resolution C/A code measurements (derived from a modulated code on the GPS carrier providing metre level accuracy) and carrier phase measurements (centimetre precision).

The primary obstacle one encounters when researching the subject of Space GNSS-Reflections is that all of the real experiments (with one notable exception) were performed below spacecraft altitudes. To better illustrate the state of GNSS altimetry we will concentrate on 2 experiments performed over the past few years.

The 2 experiments we chose to focus on were:

1) The Zeelund Brug Experiment. Performed by ESA, they were able to measure the flowing and ebbing of the tide from atop a bridge in Holland by using height measurements. [CAP01]
2) The Crater Lake Experiment. Performed by JPL, they were able to make altimetry measurements and address the dominate contributing error sources [ZAFF03]

These 2 experiments provided valuable data into the feasibility of GPS altimetry.

It is theoretically possible that current information can be deduced from the Doppler information of the reflected waveform. From our discussions we ascertained that in theory it is possible to measure the current directly by analysing the Doppler shift closely but no empirical evidence was uncovered that led us to suspect that this has been demonstrated.

Our primary concern with this study was to focus on the use of GPS Altimetry, from which ocean current information could be derived. The issues as we understand them are outlined below.

3.2 Signal Strength

An effort was made to verify that the level of the reflected signals would actually be detectable given the general parameters of the envisioned space platform. The equation for the link margin for the reflected signal has been derived as follows in dB:

S/N = Transmitted Power + Transmitter to Reflection Point Path Loss + Radar Cross Section + Reflection Area + Reflection Point to Receiver Path Loss + Receive Antenna Gain + Noise Term

Our analysis was based on the fact that the Surrey Space GPS Receiver can detect signals at –165dB. This is before the addition of the noise term. In other words we are interested in the signal only as it arrives at the SGR. In this way we can determine if the signal is detectable at the antenna input. This is similar to the approach in "Understanding GPS: Principals and Applications" by E.G. Kaplan. When considering GPS it is necessary to realise that the signals are actually being pulled up from below the noise through correlation. Therefore the equation can be adjusted as follows:

S/N = Transmitted Power + Transmitter to Reflection Point Path Loss + Radar Cross Section + Reflection Area +
Reflection Point to Receiver Path Loss + Receive Antenna Gain + **165**

This includes all path and reflection losses and will tell us with respect to our detection level if we will be able to separate signal from noise for different path delays. This analysis did not encompass a calculation of the radar cross section nor a detailed model of the reflecting surface. Estimates for these values where made in both cases based on previous research [CAP01, ZAFF04]. A set of runs was completed where all possible elevations for the GPS satellites were tested and the resulting Signal to Reference ratio was computed and plotted according to the method above. The following figure shows for comparison the results obtained using both a 700km and 500 km orbit as well as a comparison with the corresponding direct signal power levels. The nadir antenna "good antenna" was simulated as having a 12 dB gain while the normal antenna for the direct signals was assumed to have a 5 dB gain. It can be seen that although the signals are very weak they can be detected by using non-coherent integration techniques (1 second assumed in this case).

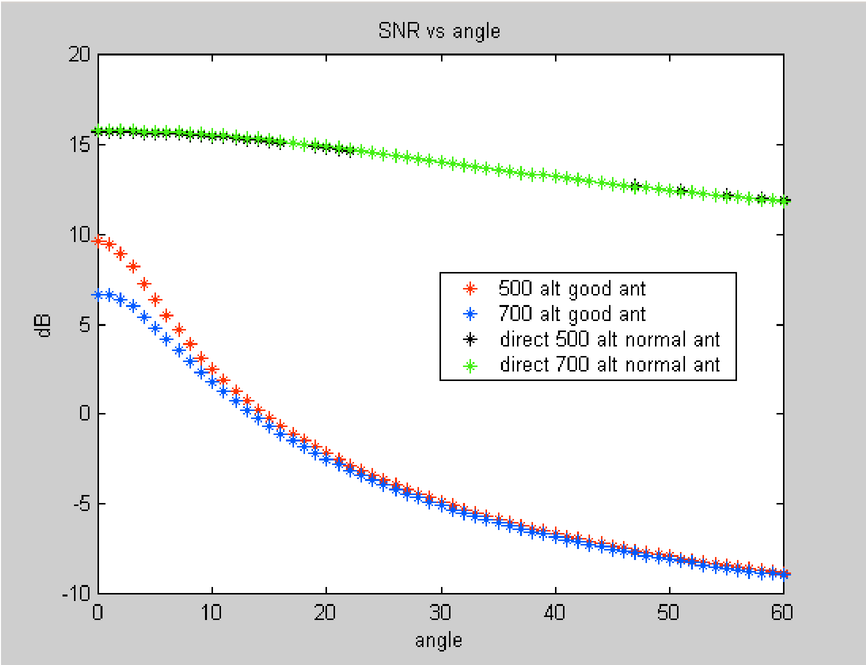

Figure 2, Estimated Signal to Reference Levels

3.3 Spatial Coverage

As illustrated below, GPS reflections can theoretically provide both single continuous measurements concentrating on one satellite or multiplex over several channels to extract measurements from several reflection points simultaneously. As SSTL's UoSat-12 (green trace) approaches Europe it is initially following only one GPS reflection point using all available mapping channels. It then switches to a multiple satellite mode and distributes 4 possible reflections across it's mapping channels. As can be seen this provides for better ground coverage but a host of issues float to the surface when this type of operating scheme is attempted.

The first is obviously the increased demand placed on the processor to continually calculate the statistics of the various specular points. It can be observed that the spacing of the specular point tracks (yellow) are farther apart in the multiple satellite mode. During single satellite tracking the specular point statistics are calculated every 2 seconds, while in multiple satellite mode the calculation must alternate among the available GPS satellites resulting in delays of up to 20 seconds between individual satellite calculations. However, given a more powerful processor it is desired to be able to calculate statistics for each specular point every second.

The second and more important point concerns the antenna beam pattern of the nadir pointing antenna or antennas. In order to achieve the gain necessary to do carrier phase altimetry it may be required to point (physically) or steer (electronically) the beam of the antenna at the reflection. This could make the task of taking consecutive measurements much more complicated. If the satellite must be physically oriented toward each reflection, this would greatly limit the number of measurements that would be possible. Should the beam steering be electronically controlled it would be possible to make quick measurements from vastly separated reflection points. This introduces other problems in that the great advantage of GNSS-R is its relative hardware simplicity (with most of the work done in software). A larger beam steerable antenna is a significant payload, while a smaller omni-directional antenna is the prefered solution from a system design perspective.

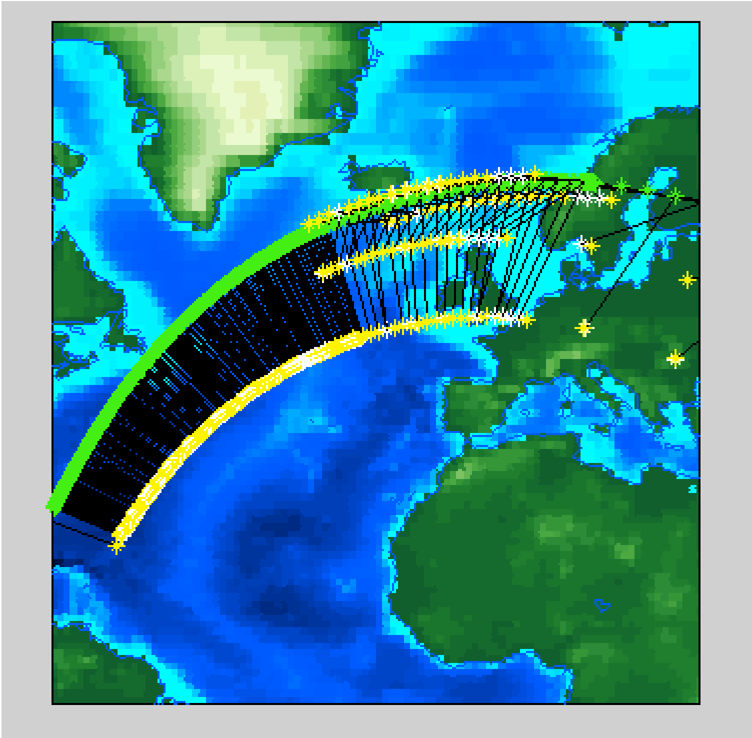

Figure 3, Satellite and Specular Point Ground Tracks

The total earth coverage provided by a variety of different scenarios was simulated in depth at the University of Colorado [ARM01]. They showed that for a polar orbit and an omni-directional antenna total ocean coverage was possible on a daily basis. The reality will almost certainly be less than that (at least initially) but without any real empirical evidence it is difficult to say with any certainty.

For altimetry the measurements will ideally correspond to arcs displaced from the spacecraft ground track as shown above [Figure 3]. These derive from the intersection of the iso-doppler and iso-code loci and trace approximately the arcs shown above (receiver shown in green and the various specular points represented in yellow) [CAP01]. However, for SWH measurements the swath width will vary depending on the sea state. If the sea is rough then power from the reflected signal will be received at points farther from the specular point thus providing information over a greater area. In contrast, for a smooth sea the reflection will be concentrated in a smaller footprint, due primarily to less backscatter. The sea state at points outside the footprint may be deduced to some degree, this will result in a larger total swath width. The antenna beam pattern could also be a significant factor in determining the swath width. Additionally, the drop off of the main antenna lobe will limit the greater reflection area.

3.4 Measurement Accuracy

The results of the two experiments mentioned above are listed below. The ESA experiment relied solely on C/A code range difference measurements, which yielded metre level accuracies. These are likely to be insufficient for determining ocean currents, where between 5 and 10 cm is considered acceptable [GOMM01]

Measurement accuracies obtained

Zeelund Brug – 3.46 metres std, using C/A code estimation only.
Crater Lake – 10 cm with ~8 seconds averaging and 1 cm with ~ 37 seconds averaging.

In theory measurements to this accuracy are obtainable on a spacecraft but there are several critical issues specific to spacecraft altitudes that impact the inversion to observable information that are discussed below.

3.5 Inversion to Ocean Currents

Ocean surface topography measurements obtained would be converted to ocean currents by way of cross track circulation velocities [ELAC01]. This procedure has been used with conventional altimeters. GNSS-R has the possibility to provide greater repeat coverage than normal altimetry but the amount of averaging required could be a significant obstacle. Given the satellite is unlikely to be able to focus on a single spot for 37 seconds to achieve 1cm accuracy (for example a satellite in a 700km circular orbit will traverse approximately 250km on the ground in 37 seconds) it is probable that lower resolutions are more realistic. A reasonable guess is that given the appropriate antenna and ground post-processing the SSH can be estimated to approximately 5-10 cm not withstanding any future technological advancements.

Theoretically, it is possible to achieve better than that estimated above. Analysis done by Starlab in Barcelona shows that using averaging of the C/A code alone, the SSH can be determined to within about 20 cm. This work was detailed as part of ESA's PETREL Earth Observer proposal and assumed an advanced AODCS system [RUFF02].

The actual resolutions obtainable using GNSS-R as an altimetry instrument are still subject to much debate and simulation. It is anticipated that within the next 5 years there will be a significant space experiment which will answer many of the existing questions, until then we are forced to speculate based on the results from land experiments.

3.6 Inversion to Sea State and Ocean Winds

Sea State Inversion seems to be the most straightforward of the extractable parameters. Sea State and SWH are functions of the total received power and the incident angle of the reflection predominately. Wind speed is slightly more complicated in that a second measurement is needed from a different direction to resolve the 180 degree ambiguity in the direction vector.

4 Spacecraft and System Attributes

4.1 Dual Frequency Receivers

As the GPS signal traverses the atmosphere it is subject to delays introduced by the atmosphere. The most notable of these errors is that of the ionosphere or lower atmosphere. The error introduced by the ionosphere varies temporally and depends on the amount of atmosphere the signal crosses on it's way to the receiver (signals from low elevation satellites therefore traverse a larger portion of low atmosphere and are more susceptible to large ionospheric delays).

The general solution to this problem is to use a dual frequency receiver. In this case the effect of the ionosphere can be calculated by comparing the propagation delays of the 2 signals at different frequencies. However, dual frequency receivers are more complicated and not widely available for space applications. SSTL's Space GPS Receiver, for example, uses only a single frequency and would be unsuitable for GNSS-R altimetry applications.

4.2 Antennas

As the preliminary Signal strength analysis above illustrates, the signals as they arrive at the receiver will be very weak and all methods at our disposal will be needed to extract them from the noise. For the simulations above a 12dB antenna was assumed but for phase level range measurements it is probable that an antenna of at least 25dB gain will be needed. This was the antenna size for the PETREL proposal submitted as part of ESA's Earth Explorer mission of opportunity [RUFF02].

To translate that into real numbers using basic formulas we can predict that a 25dB antenna would have a primary lobe width of approximately 10 degrees and an aperture diameter of 93 centimetres at the GPS L1 frequency, the illustration below gives some idea as to how this would be accommodated on a space platform. Keep in mind that it may be possible to more efficiently design the antenna, possibly by using phased helices. In contrast, assuming a desired gain of 15dB, that required for SWH and wind speed applications, the primary lobe width works out to be 30 degrees with an aperture of a more manageable 10 centimetres.

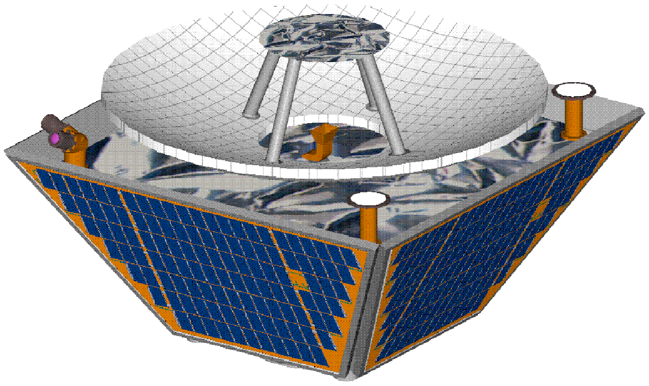

Figure 4, Model of GNSS-R Capable Satellite with 93cm Dish

4.3 Mass/Power

Since GPS receivers are becoming standard equipment on most spacecraft the predominant mass and power loads would be due to the antenna. The size of the antenna could make it unmanageable as a secondary payload. For GPS altimetry the antenna size would be a significant driver in the design of the spacecraft structure. The rough size of a 25dB antenna was calculated above to be just under a metre in diameter. Using an electronically steerable phased array antenna and/or more advanced techniques it would be possible to improve the weight and footprint, nevertheless it would remain a serious system driver. For other parameters such as winds or sea state a smaller antenna could make the experiment more workable.

4.4 Orbit and Attitude Requirements

To perform adequate referencing for altimetry measurements fairly precise orbit and attitude knowledge is required. If we desire to achieve accuracies down to the centimetre level it will be necessary to have orbit knowledge to within a couple centimetres. Since GNSS-R altimetry is performed using path differences with respect to the receiver, the exact location of the receiver is of great importance. Traditionally the GPS receiver itself will provide raw position measurements to approximately one metre accuracy. These will need to be refined and filtered on the ground using advanced orbit fitting methods [PALM01].

The preliminary mission proposals for a space demonstration of this technology involved satellites at rather low orbits (500 km) [EMERY01]. The reason for this is that this decreases the path loss of the reflected signal. It is desirable for an initial mission to concentrate on the detection of the signals. However, at 500km the drag on the satellite would significantly limit the life of the project. It is estimated that a satellite in a circular 500km orbit would decay at the rate of approximately –7.86 km/year [WERTZ01], this would result in a relatively short mission for a simple platform. For future experiments, after the lessons learned from the demonstration missions are absorbed, the altitude and the life of the satellite will certainly increase. A reasonable guess is that satellites at about 600 to 650km will provide an adequate lifetime without adding an unreasonable amount of path loss to the reflected signal.

The pointing requirements of the satellite are strict as well. Although the antenna pattern will be narrow to achieve higher gains, the signal can still be extracted with slight pointing errors as long as the phase of the GPS carrier is recognisable. If it is desired that the signal be tracked as it traces out the curved paths shown above [Figure 3] the pointing knowledge will need to be sub-degree level, on the order of 0.1 degree control and 0.05 degrees knowledge [RUFF02].

4.5 Data Delivery and Distribution

Currently months pass before data is extracted from the raw data collected. This will of course improve as the methods of signal processing and data inversion improve. At SSTL we are researching algorithms to perform real time data inversion on the satellite before download. This is ambitious and we are only concentrating on coarse indicators of SWH at the moment. Concerning GNSS-R the primary focus has been on signal extraction with little development into how the data will be distributed when a system is finally realised.

5 Summary of Key Issues

5.1 Link Margin

Preliminary calculations made by ESA, Starlab, University of Colorado, JPL and SSTL [CAP01,RUFF01,ARM01,LOWE01,SSTL02] indicate that the signal should be detectable given the appropriate antenna. For sea state parameters and wind speed this would need to be approximately 15dB, for altimetry this would need to be 25dB. This is using current GPS signals. It is envisioned that the next generation GPS satellites and possibly the European Galileo constellation will transmit at higher power levels thus easing slightly our antenna requirements.

A 25dB antenna steer able antenna represents a significant payload and puts the technology beyond the category of a complimentary secondary mission. It is envisioned that one of the future advantages of GNSS-Reflections will be the modest hardware and power requirements as compared to conventional methods.

5.2 Signal Coherence

As the GPS signal forward reflects off a large area of ocean the signal only remains coherent for a brief period of time before the signal becomes unrecognisable. The coherence time for the direct signal should be relatively long, on the order of several seconds, while the reflected signal, due to the motion of the satellite through the scattered signals far field, will be on the order of 1.6ms [LOWE01].

5.3 Phase Tracking

In order to achieve carrier level range measurements it is necessary to lock onto the carrier phase of the reflected signal. It is straightforward to visualise some of the problems involved in attempting this. The GPS wavelength at L1 is only 19cm. If we are trying to measure the range from transmitting satellite-to-specular point-to- GPS receiver to an accuracy of a signal wavelength, the possibility of mixing from signals around the specular point (due to ocean conditions or simply geometry) that would distort the true phase become obvious. This drives the need for a higher gain antenna where integration is not needed to extract the signal information, and the signal can be followed for long enough to resolve the 19cm integer ambiguity inherent in phase ranging [ELAC01].

5.4 Post Processing

All of the experiments to date (with the exception of those performed by SSTL) have involved enormous amounts of data sampled at the output of the RF front end (8 bit resolution at 89.99424 Mhz for JPL's SIR-C space experiment and 8 bit resolution at 6.25 Mhz for the Zeelund Brug experiment, for example). This data was then processed on the ground afterwards using software correlation algorithms. Initially it was a significant time before any waveforms were found, this delay is perfectly acceptable considering the scope of the data and state of technology. It will eventually be desirable to provide data quickly, SSTL has spent time addressing this but unfortunately the only information derived from GNSS-Reflections is for the moment contained in publications and on the PC's of the experimenters. This area remains open for further research and advancements involving real-time processing. Streamlining the data generated will be crucial for future operational systems. SSTL hopes to perform additional analysis using real time processes on larger amounts of data. In addition to increasing the number of measurements it is desirable to have continuous measurements at a given location to compare with in-situ measurements. This will allow us to validate various aspects of the reflection modelling with empirical data.

6 Conclusions

It becomes obvious quickly: there are a lot of questions that need to be answered before GNSS-R altimetry becomes an accepted tool in the field of remote sensing. It hold great promise as an emerging technology but still needs to undergo several phases of verification before the results are useful to the oceanography communities. Many of the difficulties arise from attempting to isolate and track the reflected carrier phase. Deriving wind or sea state parameters looks much more feasible at this point than altimetry. The complexity that is added varies significantly. From increasing the antenna size to increasing the AODCS requirements by an order of magnitude, the practicalities of implementing such a system would require quite a bit of systems engineering. This is not to imply that it is not worthwhile to attempt such an experiment. Compared to altimetry satellites along the lines of ERS-1 or TOPEX a system utilising GNSS-R altimetry could provide valuable complimentary measurements. Ideally, this technology will be adaptable as a secondary payload (yet providing the same capability). However, the current state of GNSS-R restricts any space based altimetry into the model of larger scale projects along the lines of existing altimeters. As the technology advances it will surely become easier, antennas will become smaller and more powerful and the exponential rise of on-board processing power will make real time processing more promising. Therefore, as an existing technology GNSS-R altimetry is too young for general use, but as a future possibility it holds great promise. Applications involving derived sea state or sea winds could appear much earlier than a working space based GNSS altimetry system.

The future of GNSS-R can be broken down into the short and long term goals.

1. In the short term, a space-based demonstration will eventually be realised and this will clarify the picture as to how future satellites or constellations will be designed and used. In the mean time advancements will proceed in the areas of signal detection, processing and data distribution.
2. In the long term, it is envisioned that this system will be capable of providing measurements of several natural land and ocean parameters (including ocean currents) as both a primary and as a much cheaper simpler secondary payload. The advancement of antenna technology and processor capability will drive these improvements. On the other hand Galileo and the next generation GPS satellites will hopefully improve the possibilities even further.

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