The SGR-ReSI and its Application for GNSS Reflectometry on the NASA EV-2 CYGNSS Mission

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Abstract— **As part of the EV-2 Cyclone Global Navigation Satellite System (CYGNSS) mission team, Surrey will be providing the Delay Doppler Mapping Instrument (DDMI) for eight Observatories designed and built by the University of Michigan and Southwest Research Institute (SwRI). Following the success of the GPS Reflectometry Experiment on the UK-DMC 1 satellite launched in 2003, Surrey has developed the SGR-ReSI as a move towards operational reflectometry and other applications. The Space GPS Receiver Remote Sensing Instrument (SGR-ReSI) is a COTS-electronics based GNSS receiver which can support up to eight programmable front-ends. It allows collection of raw sampled data but also is capable of processing the reflections into Delay Doppler Maps in real time. The first flight of the SGR-ReSI will be on the UK TechDemoSat-1 to prove the instrument and its various applications. The SGR-ReSI on CYGNSS has a different configuration to that on TechDemoSat-1 which is needed to focus on the requirements for operational cyclone sensing.**

Key Words—**GNSS; GPS; Reflectometry; Satellite; Ocean Wind Sensing**

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1. INTRODUCTION - CYGNSS

CYGNSS (Cyclone sensing using Global Navigation Satellite Systems) was selected by NASA in June 2012 as a result of the Earth Venture-2 Announcement of Opportunity. The mission is led by the University of Michigan and will use a constellation of eight small satellites to take accurate measurements of ocean surface winds throughout the life cycle of tropical storms and hurricanes, which could help lead to better weather forecasting. Other partners include SwRI, and NASA Ames and SST-US. SST-US, the US subsidiary of Surrey Satellite Technology Ltd (SSTL), is providing the Delay Doppler Mapping Instrument for the CYGNSS Mission in conjunction with SSTL.

2. GPS REFLECTOMETRY AND UK-DMC

For some years, GPS receivers have been used to provide position, velocity and time knowledge to satellite platforms in low Earth orbit in a similar way to ground-based satellite navigation receivers. Surrey is a leading experimenter and provider of COTS-based GPS receivers for small satellites.

As well as navigation, GPS signals have been increasingly used for remote sensing. Signals at L-band with a 2-20 MHz bandwidth are being broadcast globally from a 20,000 km altitude and can be used to measure, amongst other things, tectonic plate motion and ionospheric and tropospheric parameters. Furthermore, signals from other Global Navigation Satellite Systems (GNSS) are becoming available, and there will soon be more than 120 signal sources in space.

Spaceborne GNSS Reflectometry uses GNSS signals that have been reflected off the Earth's surface to measure geophysical parameters. The potential for GNSS Reflectometry was demonstrated on the UK-DMC mission by SSTL and the University of Surrey in 2003 [1]. A nadir pointing antenna, just under 12 dBiC, had a 3 dB field of view of approximately 20° x 70°, permitting collection of as many as three reflected signals simultaneously. The primary mode of operation on the first experiment was the collection of sampled IF data into a data-recorder, typically 20 seconds, and downloading for post processing on the ground. The raw data was processed on the ground into Delay Doppler Maps (DDMs) using software receiver techniques to allow analysis of signal returns off ocean, land and ice. Two example DDMs are shown in Fig. 1; they measure the spread in energy away from the specular point, and the spread grows as the surface becomes rougher.

A substantial effort into the modeling of signal returns has been undertaken based on data from the first UK-DMC experiment with the intention to assess inversion of sea state parameters [2,3] and the retrieval of directional roughness information [4,5]. Although severely band-limited, the collection of reflected Galileo signals (from GIOVE-A) was also demonstrated. Moreover, the collection of signals over mixed sea and ice indicates the potential of GNSS Reflectometry for ice edge mapping. [6]. The UK-DMC experiment demonstrated the feasibility for many remote sensing applications but limited space-based data is available for robust assessment of the geophysical retrieval accuracy of GNSS-R.

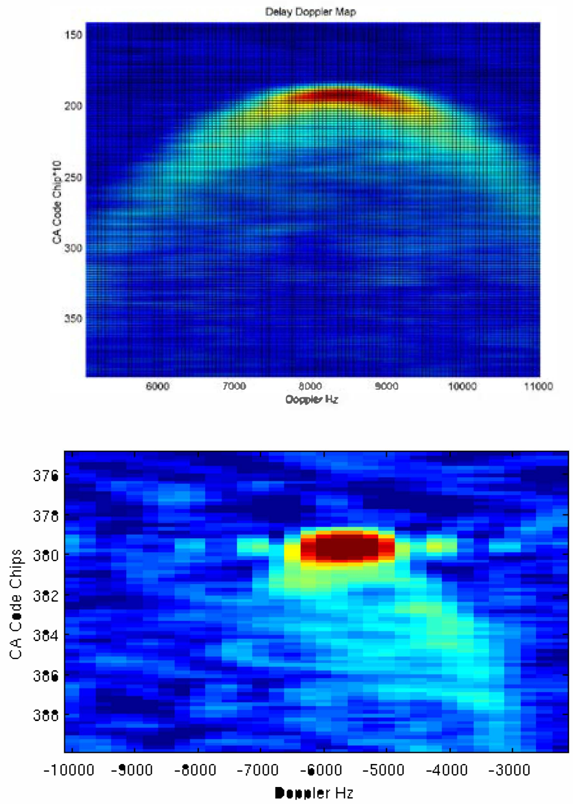

Fig. 1 Example Delay-Doppler Maps from UK-DMC GPS-R Experiment a) Ocean reflection, b) sea ice / water reflection

3. DEVELOPMENT OF THE SGR-RESI

The UK-DMC experiment highlighted the potential that a microsatellite-compatible passive instrument may be able to make valuable geophysical measurements using GPS reflectometry. A future experiment would be necessary to continue the demonstration and gather a larger quantity of data. If possible, the instrument should be capable of processing the raw data into Delay Doppler Maps in real-time.

Surrey teamed with National Oceanographic Centre in Southampton and with other partners, University of Surrey, University of Bath, and Polar Imaging Ltd to develop a new GNSS Reflectometry instrument for this purpose.

A schematic of the SGR-ReSI (Space GNSS Receiver – Remote Sensing Instrument) [7] is shown in Fig. 2. The SGR-ReSI in effect fulfils in one module what might be handled by three separate units on previous spacecraft.

a) It performs all the core functions of a space GNSS receiver, with front-ends supporting up to 8 single or 4 dual frequency antenna ports.
b) It is able to store a quantity of raw sampled data from multiple front-ends or processed data in its 1 GByte solid state data recorder
c) It has a dedicated reprogrammable FPGA co-processor (Virtex 4).

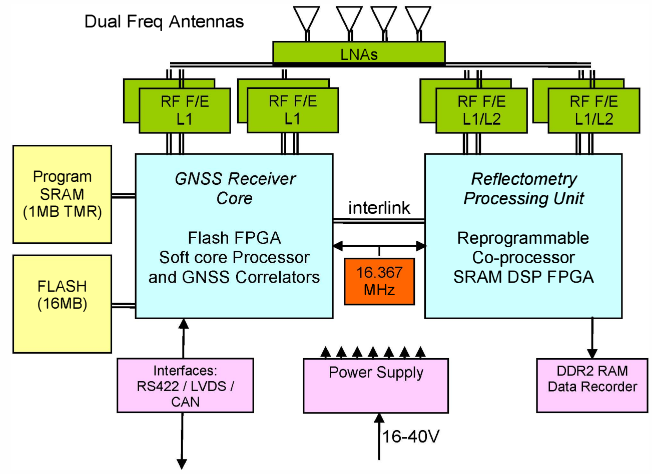

Fig. 2 GNSS Reflectometry Instrument Configuration

The co-processor was specifically included for the real-time processing of the raw reflected GNSS data into Delay-Doppler Maps (DDMs) However, it has flexibility to be programmed in orbit as required for different purposes, for example to track new GNSS signals, or to apply spectral analysis to received signals.

For the co-processor to generate Delay Doppler Maps of the sampled reflected data, it needs to be primed with the PRN, the estimated delay and the estimated Doppler of the reflection as seen from the satellite. These are calculated by the processor in conjunction with the main navigation solution - the data flow for this is shown in Fig. 3. Direct signals (from the zenith antenna) are used to acquire, track GNSS signals. From the broadcast Ephemerides, the GNSS satellite positions are known. Then from the geometry of the position of the user and the satellites, the reflectometry geometry can be calculated, and hence an estimate of the delay and Doppler of the reflection.

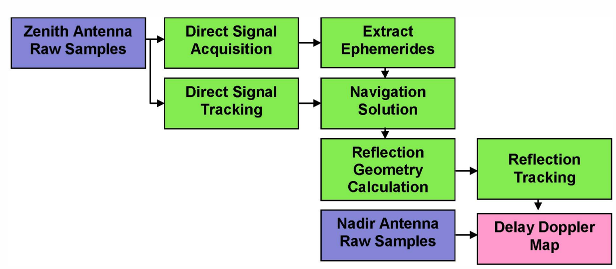

Fig. 3 GNSS Reflectometry Dataflow

The processing of the Delay Doppler Map is performed on the coprocessor using data directly sampled from the nadir antenna (Fig. 4). In common with a standard GNSS receiver, the local PRN is generated onboard the co-processor. As an alternative to synchronising and decoding the reflected signal in a standalone manner, the direct signals can be used to feed the navigation data sense, and assist the synchronisation. The sampled data is multiplied by a replica carrier and fed into a matrix that performs an FFT on a row by row basis of the Delay Doppler Map, to achieve in effect a 7000 channel correlator, integrating over 1 millisecond. Each point is then accumulated incoherently over hundreds of milliseconds to bring the weak signals out of the noise.

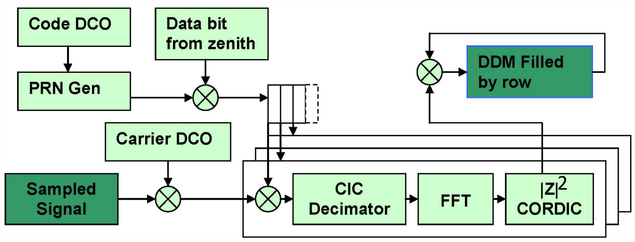

Fig. 4 Delay Doppler Map Processing

This processing is performed in real-time onboard the satellite and greatly reduces the quantity of data required to be stored and for the satellite's downlink, enabling a larger number of reflections to be captured across the globe. Initial implementation has been to predict and track a single reflection from a single downward pointing antenna. It is planned, however, to implement in the Flight Model (Fig. 5) the prediction and mapping of four reflections simultaneously from two nadir antennas giving an increased swath.

Fig. 5 SGR-ReSI Flight Model

4. TESTING THE SGR-RESI

Performing an end-to-end test of the operation of the SGR-ReSI in reflectometry mode is quite a challenge as no simulator has been available to date that could generate the full GPS signals with appropriate delay and Doppler spread as expected once reflected off a rough ocean. However, tests can be performed that thoroughly exercise different parts of the instrument in an orbital representative way.

1) The RF sampling and GNSS positioning function can be tested using live signals, or using a Spirent multichannel GPS simulator as if the receiver were in orbit. This tests the signal acquisition, tracking and data logging from different antennas.

2) When under simulation or connected to live signals, the raw sampled data can be stored into the data recorder for 1-2 minutes. This data can then be processed using a Matlab-based software GNSS receiver to evaluate RF and noise performance.

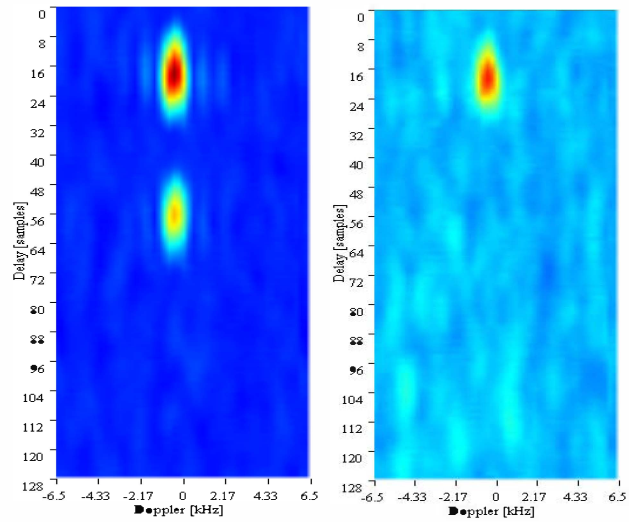

Fig. 6 SGR-ReSI Real-time Delay Doppler Map of a) Simulated Direct GPS Signal plus Multipath Reflection, b) Live direct GPS signal

3) The simulator can be configured to output a signal with a multipath signature. This allows the testing of delay Doppler Map generation in real time, albeit showing a limited range in delay and no dynamic Doppler spread (see Fig. 6a).

4) To confirm that the behaviour is still going to be valid with real GPS signals, the same exercise was tested using live GPS signals from the rooftop (see Fig. 6b).

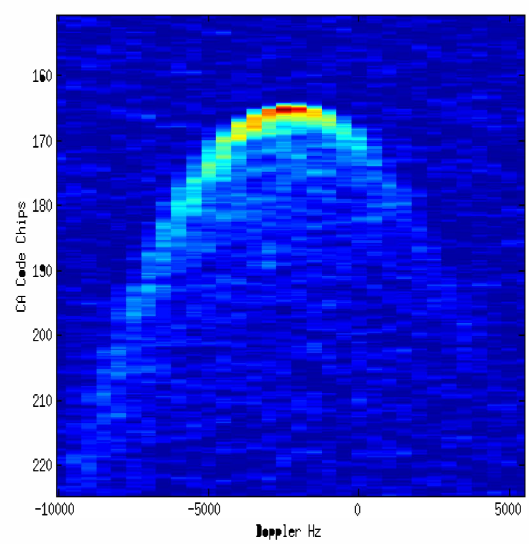

Fig. 7 UK DMC Data Delay Doppler Map Processed by SGR-ReSI

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5) The simulator cannot be used to test the prediction capability and the signal processing of a Delay Doppler Map as seen from orbit. Instead, in-orbit data from the UK-DMC GPS experiment has been used as a digital simulation. The SGR-ReSI has a unique record and storage capability allowing raw data to be uploaded and played back through the receiver. First the UK DMC data must be prepared and resampled for the SGR-ReSI as the sampling rates do not match. Then the data can be loaded into the Data recorder and played back through the SGR-ReSI. For this test, the Ephemerides are obtained from the internet, and the direct sampled data is used to predict the Delay Doppler of the reflected signal, which is then used to prime the DDM processor to generate its Delay Doppler Map. (Fig. 7).

These tests together are useful for identifying anomalies in the SGR-ReSI and giving confidence in correct operation once launched on TechDemoSat-1.

5. Demonstration on TechDemoSat-1

A technology demonstration satellite, TechDemoSat-1 (see Fig. 8), is being developed in the UK under sponsorship of the recently formed UK Space Agency and with contributions from the payload suppliers. It is intended to be the first of a series of UK technology satellites aiming to provide a rapid affordable means of testing and proving the next generation of space hardware in orbit. TechDemoSat-1 is based upon a standard SSTL design, the SSTL-150. With its 8 payloads, the satellite is approximately 160 kg. It is capable of accommodating around 52 watts of orbit-average power and can store up to 128 GBytes of payload data. It has S-Band and X-Band downlinks capable of operating with experimental downlink speeds up to 400 MBps. It has 4 wheel slew agility, and new generation star trackers, gyros, magnetometers and torquerods.

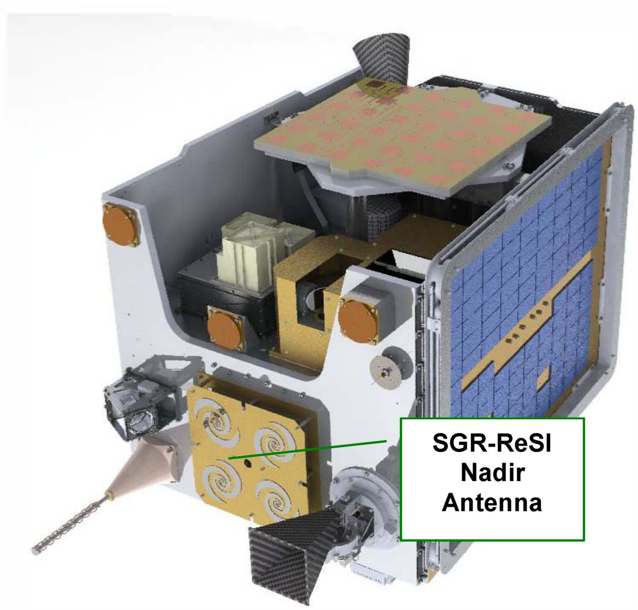

Fig. 8 TechDemoSat-1 Model (approx. 0.7 m cube, 160 kg)

The payloads hosted on TechDemoSat-1 include

- Maritime Suite - Sea State Payload from SSTL comprising SGR-ReSI and experimental altimeter.
- Space Environment Suite – radiation and charging instruments provided by Surrey Space Centre, MSSL, Langton Star Centre and RAL
- Platform Technology – Cranfield, SSL, SciSys
- Air and Land Monitoring – Oxford /RAL.

The main two purposes of the SGR-ReSI on TechDemoSat-1 are to demonstrate its core GPS capability, and to demonstrate the technology and science required for GPS Reflectometry through the operation and collection of data over the ocean. Secondary aims include demonstration of new single and multi-frequency signals (e.g. Galileo, Glonass, GPS L2C), low cost precise orbit determination, radio-occultation demonstration, reflectometry over ice, snow and land, attitude determination and GNSS interference detection.

Although the SGR-ReSI can, in principle, support up to 4 dual frequency antennas, a reduced subset is being flown on TechDemoSat-1 to support its planned applications. A left hand circularly polarised dual frequency L1/L2 fixed phased array antenna (gain 13 dBiC) sits on the earth facing facet for GNSS reflectometry. It is the opposite polarisation to conventional GNSS antennas and provides the higher gain required to receive the weak signals from GNSS reflections. A dual-frequency L1/L2 antenna and two additional L1 antennas will occupy the space facing facet with more typical RHCP and hemispherical patterns. These antennas are intended to provide navigation function for the satellite and also support monitoring of radio occultation events with both the L1 and L2 signals. The provision of three antennas on the space facing facet with suitable baselines between them also enables the SGR-ReSI to support GNSS based attitude determination as previously demonstrated by SSTL on the UoSAT-12 and TopSat satellites.

A new low noise amplifier has been designed that supports both L1 and L2 frequencies, is equipped with a temperature sensor, and a switched load to provide a known noise level when enabled for calibration purposes. One each will be used on the nadir and zenith dual frequency antennas respectively. The two L1-only zenith antennas will use the heritage integrated L1 LNAs used with previous single frequency GNSS receivers.

At the time of writing, TechDemoSat-1 is scheduled for a launch in Q2 2013 on board a Russian launcher, and the final near-polar orbit has an approximately 680 km altitude. The plans for operation of the payload require coordination with all the other 7 payloads on the satellite, but a scheme of cycling through 8 days has been defined that permits full operation of the ReSI 1 or 2 days per 8 day cycle. Special operations on other occasions will be possible, subject to agreement with the other payload operators.

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SSTL is a partner in a project called WaveSentry [9] that is looking to use wave information from multiple sources including buoys and ferries to generate a commercial wave notification service. Another partner, National Oceanographic Centre, is providing the algorithms for inversion, and these will be validated using the measurements from TechDemoSat-1.

6. THE SGR-RESI ON CYGNSS

The requirements on the SGR-ReSI for CYGNSS are different from TechDemoSat-1 as there is more of a focus on the autonomous operational mode for hurricane sensing. Priorities include signal to noise ratio and signal coverage optimization, and there is less of a need for multi-frequency signal reception.

The CYGNSS satellites are placed in a lower altitude orbit than UK-DMC and TechDemoSat-1 (500 km instead of 680 km) achieving an increase in the signal to noise ratio. A wider coverage on the Earth's surface is achieved by using two nadir pointing antennas on two separate angled facets on the CYGNSS satellites. Nominally, the same antenna design is used as on UK-DMC (just under 12 dBiC), although there may be scope and space for an updated design optimized for CYGNSS. The resultant combined antenna pattern is broad enough that it is calculated that on average four or more specular reflections will be visible within the antenna beamwidth simultaneously. Consequently, the SGR-ReSI must be able to track and process reflections from at least four GPS reflections.

One GPS L1 front-end is allocated to each antenna, so three front-ends are to be supported. Each antenna has an associated low noise amplifier (LNA) to provide amplification of the weak GPS signals immediately after the antenna adding as little noise as possible. These L1 LNAs also carry a switched load for calibration purposes.

CYGNSS plans to use the SGR-ReSI primarily in an autonomous manner generating DDMs at a low data rate continuously, and this will provide a source of measurements for the ocean roughness across the oceans. When a particular location of interest is identified, for example as a CYGNSS satellite passes over a developing storm, the SGR-ReSI may be operated in raw data mode, where 60 seconds of raw sampled data is accumulated. This allows the scientists to fully analyze and re-analyze the acquired data using different processing schemes to ensure that the nominal DDM mode of operation is not losing important geophysical data. Hundreds of Megabytes of data will be generated in this situation, however, which could take a long time to download from such a small satellite platform. An intermediate lower data alternative is to generate DDMs with a higher resolution and lower integration time. If alternative processing schemes are identified, the SGR-ReSI has the ability to accept new Virtex-4 processing images to be stored in its non-volatile Flash memory.

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7. CONCLUSIONS AND FUTURE

This paper has introduced the SGR-ReSI and its capabilities in GPS Reflectometry. TechDemoSat-1 will offer the first demonstration of this instrument and many of its applications, and will be a valuable pre-cursor and validation of the concept in the preparation for the CYGNSS mission.

As the CYGNSS constellation is optimized for the cyclone germination zones near the equator, it has a coverage that is limited globally by the selected inclination of 35°. A future mission that covers the higher inclinations is likely to make a valuable contribution towards weather knowledge at higher latitudes. The coverage achieved is also limited by the number of satellite reflections used within the SGR-ReSI. Future work is being planned to upgrade the DDM processing to make use of more of the available GNSS signal reflections, such as from Glonass, Galileo and Compass. This change would reduce the number of sensing satellites required to achieve an effective coverage of the globe and would also increase the cost effectiveness of GNSS Reflectometry as it moves towards becoming an operational Earth Observation tool.

RELATED PAPERS

This paper is part of a coordinated series of papers being presented at the 2013 IEEE Aerospace Conference in Big Sky, MT. The full series includes:

- CYGNSS Mission overview, science objectives, and requirement allocation [Session 2.05-2532; Dr. Chris Ruf]
- CYGNSS Mission implementation with specific emphasis on the microsat [Session: 2.05; Randy Rose]
- CYNGSS Science instrument [This Paper, Session: 6.02-2410; Martin Unwin]
- CYGNSS Mission operations [Session: 12.02-2559; Debi Rose]

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Biographies

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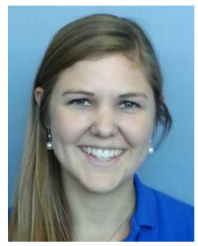

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