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# Developments in GNSS-Reflectometry from the SGR-ReSI in orbit on TechDemoSat-1


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## ABSTRACT

The SGR-ReSI (Space GNSS Receiver – Remote Sensing Instrument) is remote sensing payload compatible with small satellites. GNSS Reflectometry makes use of reflected GNSS signals as if radar transmissions, and as a result, only the GNSS receiver is required onboard the satellite to implement a bi-static radar system. The SGR-ReSI can log unprocessed data from the RF downconverter for later processing, but most significantly can process the reflections on-board into Delay Doppler Maps (DDMs). The first flight of the ReSI is on the UK TechDemoSat-1 (TDS-1) satellite, launched in July 2014. The DDMs are downloaded, extracted and processed to synchronise with the satellite's GPS position and other metadata. Surrey's partner, the National Oceanographic Centre provided algorithms that recover the ocean roughness and wind speed (Level 2 data) from the DDMs.


## INTRODUCTION

The GPS Reflectometry experiment on the UK-DMC satellite mission, launched in 2003, proved the feasibility of using GNSS reflections for measuring the sea state and other geophysical observables through a partnership between SSTL and National Oceanography Centre (NOC).[1,2,3] Subsequently a new instrument was developed called the SGR-ReSI (Space GNSS Receiver Remote Sensing Instrument) to gather more spaceborne reflectometry data and demonstrate the potential for a sea state service. The first opportunity arose for the flight on a satellite called TechDemoSat-1 (TDS-1) initiated in 2010, and with the launch taking place in July 2014.

In parallel, a US mission called CYGNSS was selected by NASA that plans to measure hurricanes with reflected GNSS signals collected using an updated revision of the SGR-ReSI, (also referred to as Delay Doppler Mapping Instrument) as payload on each of 8 satellites. This project is led by University of Michigan and prime contractors are South West Research Institute, and satellites are due for launch in 2016-17.[4]

This paper gives an overview of the TDS-1 SGR-ReSI experiment and recent developments. A more detailed review can be found in ref[5].

## SGR-RESI ON TDS-1

TechDemoSat-1 (TDS-1) is a satellite providing an early flight for UK space technology with a view to promoting future use. TDS-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 gyros, magnetometers and torque rods.

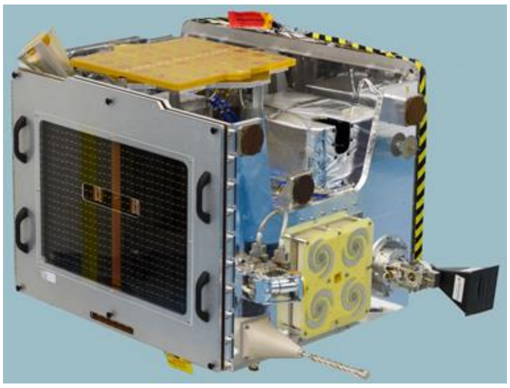

**Figure 1: TechDemoSat-1 (TDS-1) prior to launch**

The SGR-ReSI is one of the eight UK payloads hosted on TechDemoSat-1 (others including an altimeter, radiation, charge and atmospheric measuring instruments, and deorbit sail) alongside a number of new SSTL platform technology demonstrations. As a result of the multiple payloads, none are allowed to be operated continuously, but are allocated specific days on an 8 day operating cycle.

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 some of the SGR-Axio's planned extra capabilities – such as multi-constellation and multi-frequency operation. The SGR-ReSI is shown in Figure 2.

**Figure 2: The SGR-ReSI on TDS-1**

The instrument is principally designed for GNSS-R, using the ground-reflected GNSS signals to remotely sense the Earth's surface. Reflected GPS L1 signals are processed into Delay Doppler Maps (DDMs), as shown in Figure 3, either on-board using the co-processor, or alternatively on the ground if the raw data is downloaded.

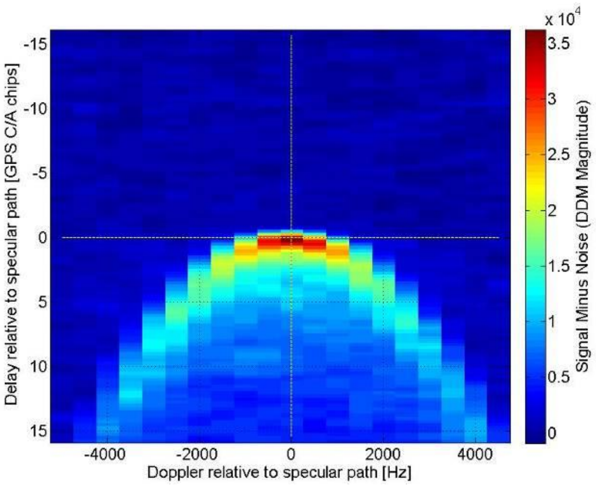


**Figure 3: An example Delay Doppler Map from TDS-1**

A left hand circularly polarised dual frequency L1/L2 fixed phased array antenna (gain 13.3 dBiC with approx. 30° half-power pattern at L1) 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 occupy the space facing facet with more typical RHCP and hemispherical patterns. These antennas are intended to provide navigation function for the satellite, with the potential for attitude determination. Figure 4 shows the high gain nadir antenna and Figure 5 the zenith antenna, both of which are dual frequency.

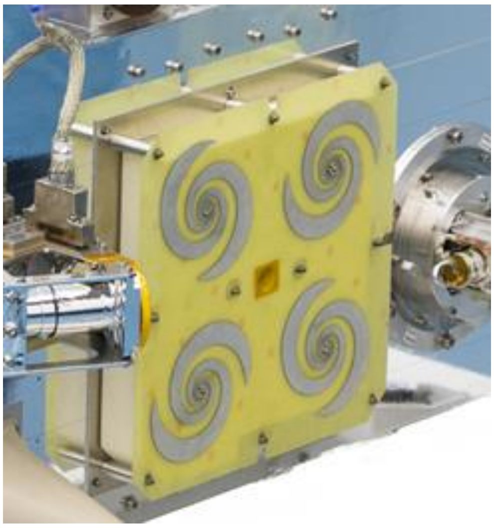

**Figure 4: TDS-1 Nadir GNSS Antenna**

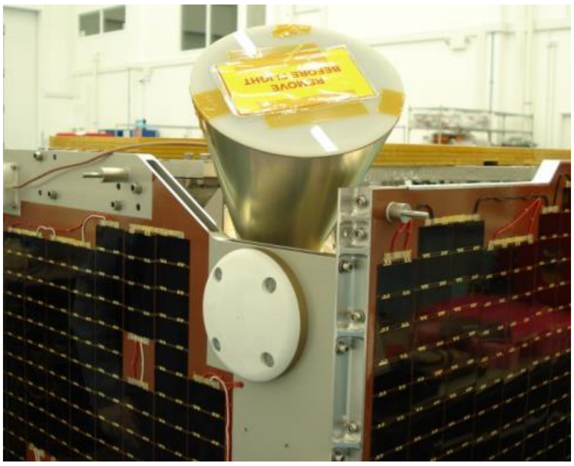

**Figure 5: TDS-1 Zenith GNSS Antenna**

## LAUNCH AND FIRST OPERATIONS

The Soyuz-2 launcher was successfully launched on 8th July 2014 and it deployed its main payload 825 km altitude, then after manoeuvres, the Fregat upper stage deployed all 8 secondary payloads in a lower orbit, including TDS-1. TDS-1 commenced life with LTAN (Local Time of Ascending Node) of 09:00, but is drifting to 12:00 over its three year life.

The SGR-ReSI instrument was powered up 8 days after launch to initially test its positioning capability, and the orbit fitting demonstrated a self-consistency of around 2.5 meters. Following payload commissioning, in Spetember, the SGR-ReSI was operated in reflectometry mode for the first time (Figure 6). These operations resulted in the capture of an SGR Binary Packet Protocol (SBPP) log containing the packet-based telemetry generated by the SGR-ReSI, and two raw data logs, each 1 minute in duration containing sampled IF GPS L1 data from Antenna 1 and Antenna 2.

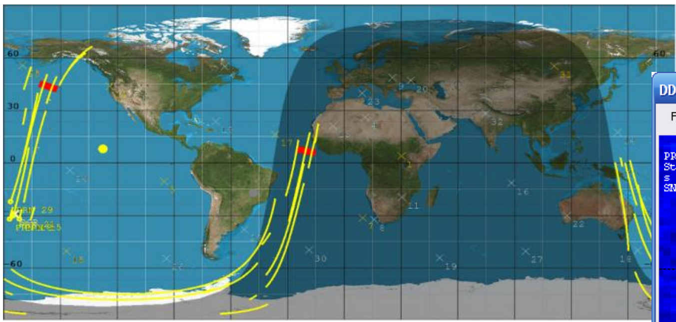

**Figure 6: Map of DDM collections (yellow tracks) and Raw Data Captures (red blocks), Sept 2014**

The generation of Delay Doppler Maps in these first hours of operations represented about 4 times the quantity (by time period) of Delay Doppler Maps generated in the entire lifetime of the UK-DMC experiment.

The raw data files were processed using a software GPS receiver, which showed that several reflected signals were present and of a good quality. The DDM file contained Delay Doppler Maps ready processed on-board. Figure 7 shows the position of the four reflections tracked by the SGR-ReSI with a corresponding screen capture of the DDMs taken from the DDM playback tool. Each DDM has 20 pixels in y-axis (Doppler) and 128 pixels in the y-axis (delay).

## DATA STRUCTURE, COLLECTION AND ASSESSMENT

Although Delay Doppler Maps are processed on-board the TDS-1 SGR-ReSI in orbit, a significant amount of processing is still required on the ground. A ground processing system has been designed to generate the higher level products from the satellite data. Data levels (Level 0-2) are used, where Level 0 is raw sampled data (only accessible when specifically scheduled to be downloaded), Level 1a comprises Delay Doppler Maps, Level 1b comprises corrected and synchronized DDMs, and Level 2 contains derived geophysical parameters, in particular wind speed. These products are accompanied by copious metadata that includes all parameters needed by users for using or reprocessing the data.

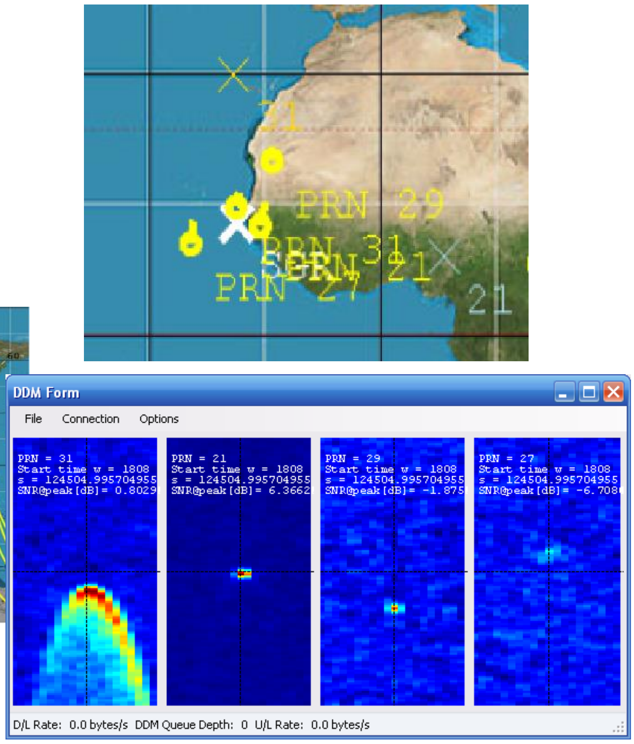


**Figure 7: SGR-ReSI position (white cross) and reflections (yellow circles) b) DDMs generated showing reflections from both ocean and land**

TDS-1 experiment has certain limitations, not least sharing of the platform and hence intermittent operation for 2 days out of 8. The attitude determination of TDS-1 grows in error when the satellite enters eclipse and loses sun sensors, and this has an impact on the wind retrieval accuracy. The radiometric calibration of the signals is important – either reflected measurements can be referenced to the received noise (where signal to noise ratio cancels system gain), or an absolute signal level can be determined, using switched loads within the Low Noise Amplifiers to provide the reference noise. The RF front-ends can be operated in automatic gain control mode (AGC) or in fixed gain mode; measuring switched load reference noise is only effective when the gain is fixed.

Figure 8 shows an example of 20 hours of data collected over the globe in October 2014. A decimated summary sequence of the DDMs in one track is also shown. This illustrates how the signal becomes stronger as it passes through the maximum of the SGR-ReSI nadir antenna gain, before weakening again.

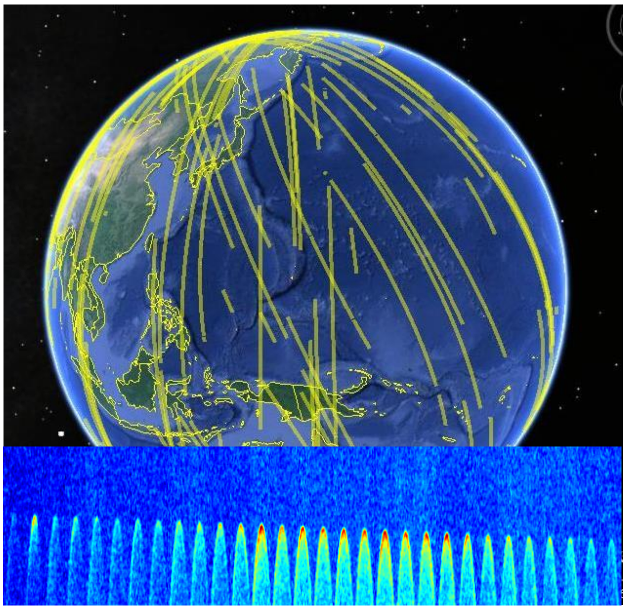

**Figure 8: Example TDS-1 DDM Data collection–global coverage and summary of one DDM track**

The rate of data gathering increased as operations were refined, and a large volume of data has been collected. From the period of Sept 2014 to April 2015, a total of 5,740,000 valid Delay Doppler Maps were collected, and in one 48 hours period alone, 630,000 DDMs can be gathered, when acquiring almost 4 DDMs per second.

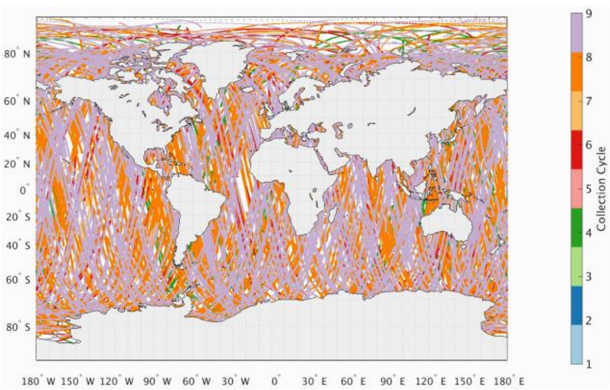


**Figure 9: TDS-1 GNSS-R ocean geographical distribution and coverage from Sept 2014 to Feb 2015.**

### *Data Characteristics*

The peak SNR observables of a large quantity of the Level 1 data were computed and categorised into three regions: ocean, land and polar, where 55º latitude was used as the threshold to separate ice-free ocean from polar regions (see Figure 10). In this example, only data from the Antarctic region is shown to represent polar regions.

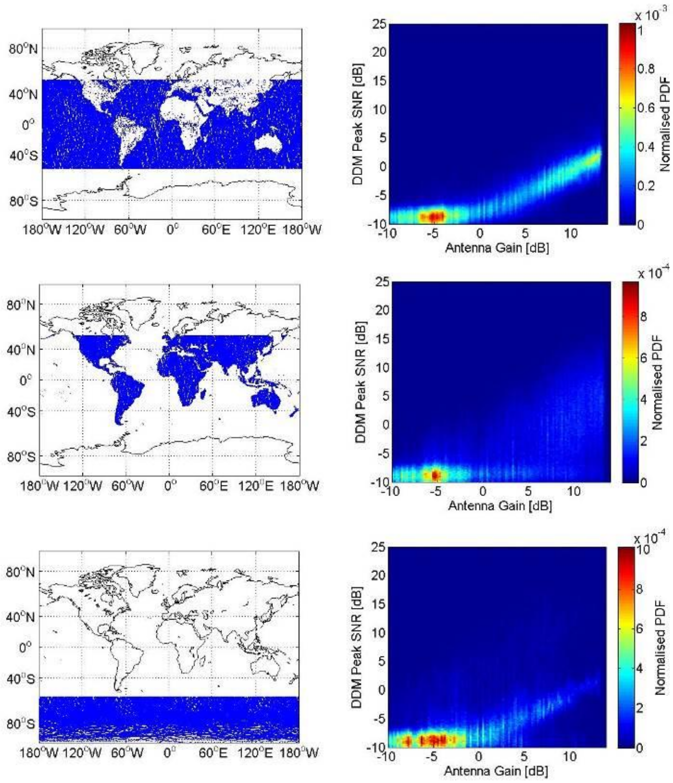


**Figure 10: Signal to Noise ratio and antenna gain histogram for specular points a) Over oceanic regions, b) over land, c) over polar regions**

These plots show the different characteristics of the signal over different surfaces. Over ocean, the spread is relatively limited, and this contains information about the roughness of the sea, and hence the wind. It can be seen that the spread is still visible away from the peak antenna gain of 13 dBi, perhaps down to 5 dBi before hitting the noise floor. The spread over land is far less well contained with very strong and very weak signals present, while the measurement over the poles contains a mixture of ice and water reflections, though fewer measurements are available at nadir due to the hole in the GPS constellation over the poles.

### *Ocean Wind Speed and Validation*

NOC developed two wind speed inversion algorithms. The "Fast-Delivery Inversion" algorithm (FDI) and the more complex "Bistatic Radar Equation" algorithm (BRE). The FDI is most appropriate for rapid generation of wind speed from DDMs. Both are based upon the peak reflection Signal to Noise measurement, but FDI is more empirically based.

The NOC-FDI Level 2 algorithm was implemented in the MERRByS ground processing system[6] to routinely produce and distribute Level 2 wind speed products to potential end-users. Following successful validation by NOC of the output of the operational ground processor against MetOp ASCAT measurements (see Figure 11), Level 2 wind products (Version 1.11) are available on MERRByS for the full period Sept 2014-February 2015. The general performance of the FDI algorithm achieves a bias around 0.2 m/s and a root-mean-square error (RMSE) just below 4 m/s, though further improvements to the performance are anticipated as calibration measures are implemented.

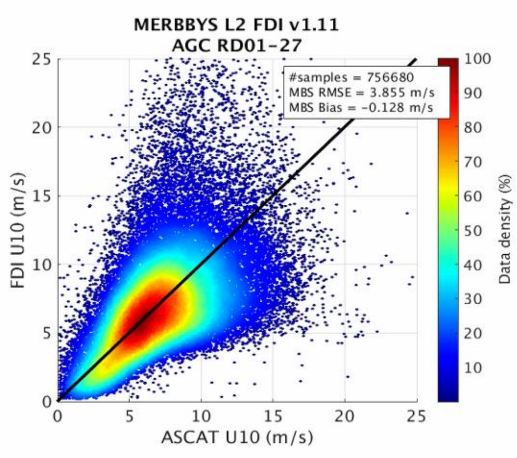


**Figure 11: Validation of the Level 2 FDI wind speed products (Version 1.11) available on MERRByS.**

## COLLECTIONS OVER LAND AND ICE

Two examples of collections of reflections over land are given in Figure 12 from the Amazon basin and North Africa. Rainforests such as in the Amazon are good absorbers of electromagnetic radiation, primarily in the visible spectrum but also at lower frequencies. Mirror-calm surfaces, such as rivers and lakes are likely to give very strong reflections. The contrasts over Africa are perhaps more surprising, as there is less in the way of rain forests and rivers, yet there are strong variations in reflection strength with a clear geophysical imprint visible. Variations may be due to soil moisture, vegetation, surface roughness and surface salinity.

With regular measurements being taken over polar regions, TDS-1 provides a clear opportunity to develop the cryospheric applications of GNSS-R. For the first time, a large dataset of spaceborne GNSS-R data is available for validation of ice monitoring algorithms. Figure 13 illustrates potential application for ice sensing. Four simultaneous reflections confirm the presence of ice in the Northwest passage near Greenland. An algorithm has been developed that automatically detects ice edges to contribute towards ice extent knowledge.

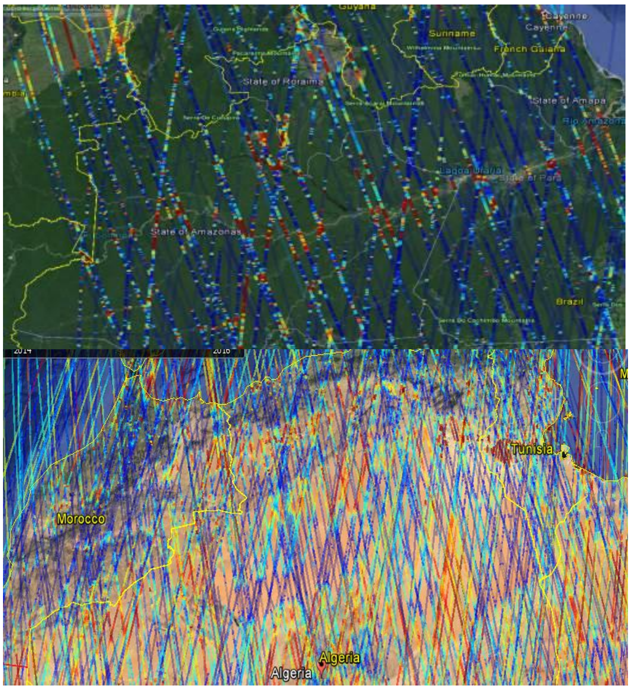


**Figure 12: Reflected SNR over a) the Amazon Basin b) North Africa. Blue tracks indicates weak reflections, red indicates strong reflections**

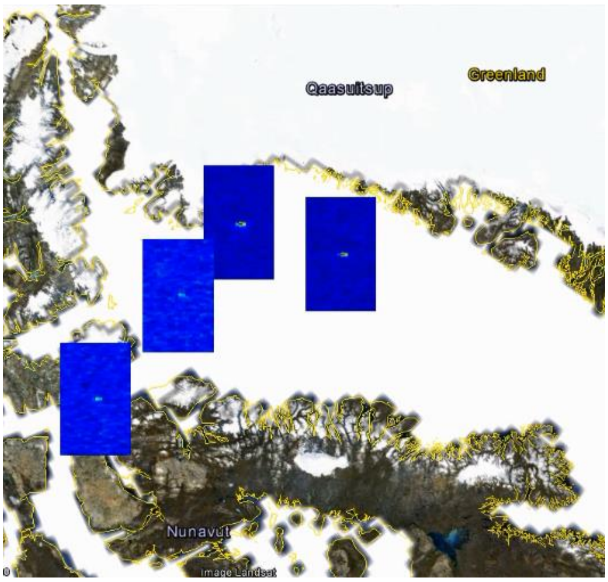


**Figure 13: Delay Doppler Maps collected near Greenland over the Northwest Passage over a sea/ice boundary near Greenland, March 2015**

## ON-GOING ACTIVITIES

### *Data Access*

Much of the data from TechDemoSat-1 GNSS-R experiment has been made available at the MERRByS (Measurement of Earth Reflected Radio-navigation Signals By Satellite) website[6]. The data has been released under a Creative Commons Licence that allows free access for non-commercial use.

A small number of example data sets are provided at Levels 0, 1 and 2 without requiring a log-in. When users have a password, they have access to a large collection of Level 1b and Level 2 data for the TechDemoSat-1 mission.

A map-based interface makes it possible to search for tracks, and view quick look information. A summary of each search is created in KML, such that it can be viewed in Google Earth with the ability to graphically view parameters signal to noise and antenna gain.

From this, users are able to navigate through each track and observe directly the correspondence of the SNR with the geophysical features on the ground.

### *Further Work*

The areas of interest include data collection, instrument calibration activities, processing optimizations, and ongoing validation. Some advanced experimentation is also planned, including dual frequency measurements and Galileo signal tracking.

### *CYGNSS Mission*

Beyond TechDemoSat-1, the SGR-ReSI receiver will be flying (current launch in 4Q-2016) as the primary payload on CYGNSS constellation, funded under NASA's Earth Venture 2 program[4]. This eight nano-satellite constellation is primed by the University of Michigan and being constructed by Southwest Research Institute (SwRI). Its target application is to take wind speed measurements within hurricanes, helping to save lives though improvements to forecasting and monitoring. Many of the results and lessons learnt from TDS-1 will help prepare for the CYGNSS mission. The large quantity of data expected will achieve a new level of coverage compared to TDS-1.

## CONCLUSIONS

This paper has presented an overview of the GNSS-Reflectometry experiment on the UK TechDemoSat-1 (TDS-1) mission. The motivation for the development of the instrument came from an initial experiment on the UK-DMC mission in 2003, and led to an instrument that is able to process measurements on-board into Delay Doppler Maps (DDMs). The satellite was launched in July 2014, and since then data has been gathered both in the form of DDMs and also unprocessed data collections. Preliminary work has been done on inverting the measurements into Level 2 products, specifically wind speed and mean-squared slope over the ocean, with promising results. Reflections recovered over the land surface are also showing a strong geophysical imprint, suggesting potential for hydrological and vegetation related retrieval.

Both ocean and land applications will benefit from further characterisation of the measurements and calibration improvement activities. Clearly a single satellite is inadequate for addressing the temporal resolution required for effective sea state measurement, or even for observing seasonal changes in hydrological cycles over the land. The CYGNSS mission will be the first to make use of the low size weight and power of GNSS Reflectometry instruments, as an enabler for a constellation of eight satellites. Even so, this will only be targeting the globe at inclinations lower than 35°, and the full benefits will only be achievable when there is a larger constellation that is able to cover the higher as well as lower latitudes.

### *Acknowledgments*

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