Overview of the Delay Doppler Mapping Instrument (DDMI) for the Cyclone Global Navigation Satellite Systems Mission (CYGNSS)

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***Abstract*—The CYGNSS satellite constellation consists of eight satellites equipped with GNSS bi-static radar receivers which map the ocean surface scattered signal power in the vicinity of the specular reflection point using time domain and Doppler frequency filters. The satellites orbit in the same plane at an altitude of 500 km and at a orbit inclination of 35 degrees. CYGNSS will act as a GNSS bi-static scatterometer capable of sensing sea level winds in tropical cyclones, including in high precipitation conditions. An overview of the GNSS remote sensing concept is included in this paper.**

Subsequently, an overview of the Delay Doppler Mapping Instrument (DDMI) carried by all of the CYGNSS observatories will be presented. The DDMI uses GPS forward scattered signals of opportunity to produce delay Doppler maps (DDMs) of the scattered signal delay and frequency spreading over the surface. This paper will conclude with results from preliminary laboratory testing of the CYGNSS instrument engineering models.

***Index Terms*—Calibration, Scatterometry, GNSS, GPS, Reflectometry, Bistatic Radar, Instruments, CYGNSS**

I. Introduction

Remote sensing using GNSS reflected signals is in many ways a logical extension of traditional radar remote sensing. However, there are a number of important differences that need to be considered before the environmental measurements obtainable using GNSS signals are deemed useful. The most important difference between GNSS and traditional remote sensing applications is that GNSS signals must be received and processed using a bistatic configuration. The transmitter and the receiver are not co-located, resulting in the transmitted GNSS signal reflecting or scattering in a forward direction, as opposed to the more conventional backscattered signals used in traditional remote sensing applications. An illustration of the bistatic configuration, with the receiver on a low Earth orbiting satellite is shown in Figure 1.

II. History

Using Earth-reflected GNSS signals as a means of sensing the ocean surface was proposed as far back as 1988 by [1]. Some time later the concept was put forward as an alternative technique for ocean altimetry in [2]. In 1998, the same principle was demonstrated as a useful tool to sense ocean surface roughness in [3]. Significantly, the first space based detection of an ocean reflected GPS signal was achieved in [4]. Notably, it was shown that wind speed estimation in tropical cyclones was also possible, as demonstrated in [5]. The feasibility of this technique for global ocean, land and ice sensing at spacecraft altitudes was demonstrated in [6], with a validation of ocean wind sensing published in [8] and [9]. Finally, the technology is rapidly gaining in momentum as demonstrated by the launch of TechDemoSat (which carries a GNSS-R instrument) [12] and with the selection by NASA of the Cyclone GNSS (CYGNSS) mission in 2010 [13]. An overview of GNSS remote sensing and its applications can be found in [14] or [15].

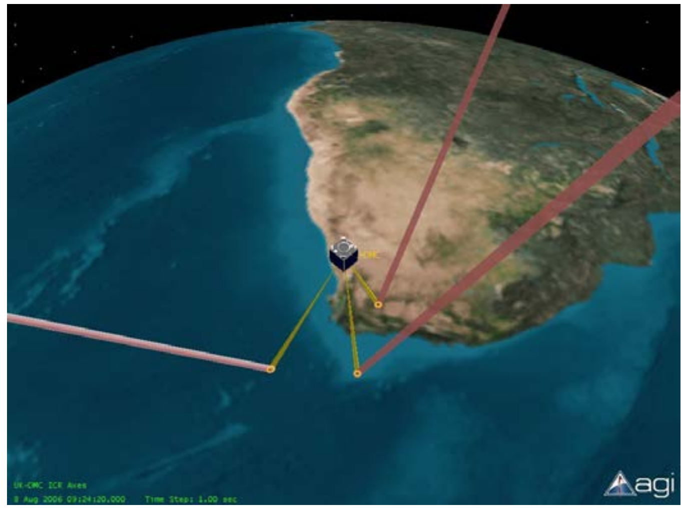

Fig. 1. Illustration of the GNSS reflections remote sensing concept. A single satellite, properly configured, is capable of receiving forward scattered GNSS signals from multiple GNSS satellites, including reflections off the ocean, land and ice surfaces. Figure taken from [14] with permission.

III. Description of the CYGNSS Delay Doppler Mapping Instrument

The instrument for the CYGNSS missions is the Delay Doppler Mapping Instrument (DDMI) (also known as the SGR-ReSI [12]). The instrument contains both a traditional GPS navigation receiver integrated with a reflections processor and is capable of producing delay Doppler maps of up to 4 surface reflections in real time. The instrument uses a frequency domain FFT based technique known as a ”Zoom” transform correlator (ZTC) described in detail in [17]. The full instrument consists of,

1) A Delay Mapping Receiver (DMR), including three RF front ends (two for reflected signals and one for processing navigation signals), and the digital processing unit.
2) Three low noise amplifiers (LNAs) for each of the three RF inputs.

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3) One right hand circularly polarized zenith facing navigation antenna.
4) Two left hand circularly polarized nadir facing science antennas.

The DMR is responsible for sampling, down converting and processing the RF signals from all all three antennas. It uses the navigation signals to determine the position and velocity of the receiving satellite as well as for several tracked GPS satellites used in the navigation solution. It uses this information to target reflection points on the surface and steers its reflection co-processor units to the correct delay and Doppler center to generate real time DDMs of up to 4 reflections in parallel. The LNAs are the same for all three channels and have been designed for low noise figure performance by the inclusion of a cavity filter. The zenith navigation antenna is a RHCP antenna of modest gain (approximately 5 dB), covering most of the zenith direction of the satellite. The two nadir antennas are LHCP and of approximately 14 dB gain, with patterns directed (by mechanically tilting) towards the cross track direction of the satellite motion.

IV. The GNSS-R Measurement: The Delay Doppler Map

The basic measurement in GNSS remote sensing applications is the delay Doppler Map (DDM). This consists of mapping the spread in the signal in both time delay and frequency over the ocean surface. And example of how a forward scattered GPS signal spreads over the surface, as observed from an Earth orbiting satellite is shown in Figure 2. During the signal processing by the DMR the power detected across the surface is binned across dimensions of delay and Doppler, with the strongest signals present at the center specular reflection point. At points farther away from the specular point the amount of power detectable at the receiver decreases as a function of the geometry and the sea state. The rougher the ocean the more power detected at delay bins farther from specular, while calm seas exhibit a smaller glistening zone from which scattered power can be observed. It has been shown that the shape of the DDM over the ocean can be predicted using a theoretical model [16].

An example of a simulated delay Doppler map as generated by the CYGNSS end to end simulator (E2ES) is shown in Figure 3. An extensive set of simulated CYGMSS DDMs have been generated for pre-launch algorithm validation, details on the E2ES can be found in [7]. The delay axis is shown in the vertical and the Doppler axis in the horizontal. The predicted DDMs generated by the E2ES have been demonstrated to be in good agreement with the space based reflections received from the UK-DMC satellite. The glistening zone of a DDM can cover up to hundreds of kilometres square. However, the most useful portion is the area near the specular reflection point, within about 25 km square of the center. In this region the power fluctuations of the peak are directly related to the surface wind speed [8].

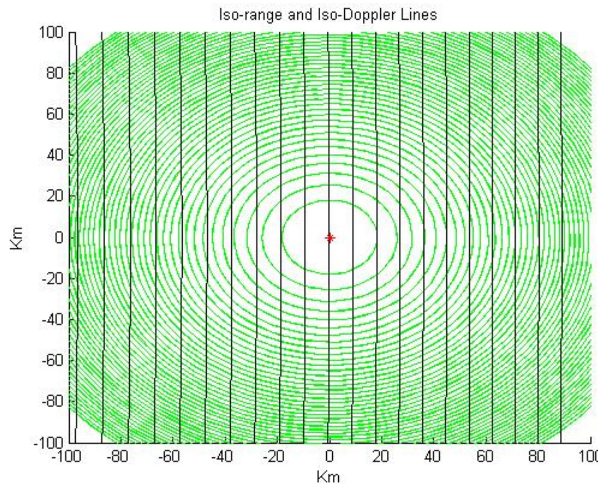

Fig. 2. Example of delay and Doppler spreading over the surface. Lines of constant delay are shown as ellipses while lines of constant Doppler are shown as parabolas (resembling vertical lines in the figure due to the space craft geometry).

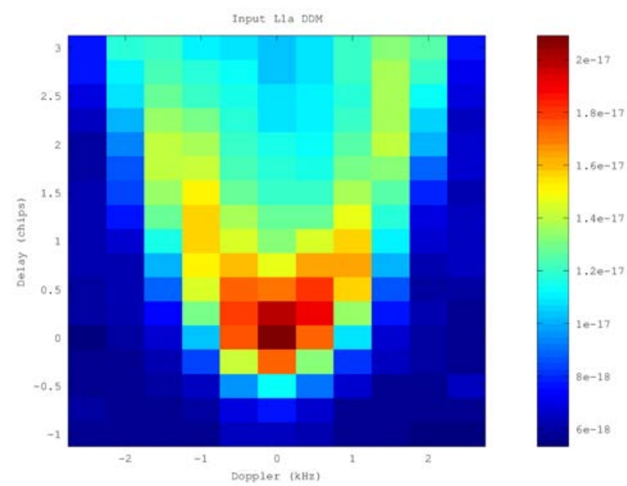

Fig. 3. Simulated Level 1A delay Doppler Map showing signal power in Watts spreading over the surface in both delay and Doppler.

V. CYGNSS DDM Calibration and Wind Speed Estimation

The DDMs processed on board the CYGNSS DDMI are compressed and sent to the ground for calibration. The processed DDM in counts is first geolocated and converted to units of Watts. This is known as the L1a DDM and contains the uncorrected power spreading over the surface in delay and Doppler. Subsequently, the L1a DDM is converted to a calibrated DDM of forward scattered σ^0, including corrections for the transmitter power and antenna gain, path losses, the receiver antenna gain and all non-ocean factors effecting the received power. Details of teh CYGNSS L1 calibration algorithm can be found in [10].

The CYGNSS level 2 products are then generated using the

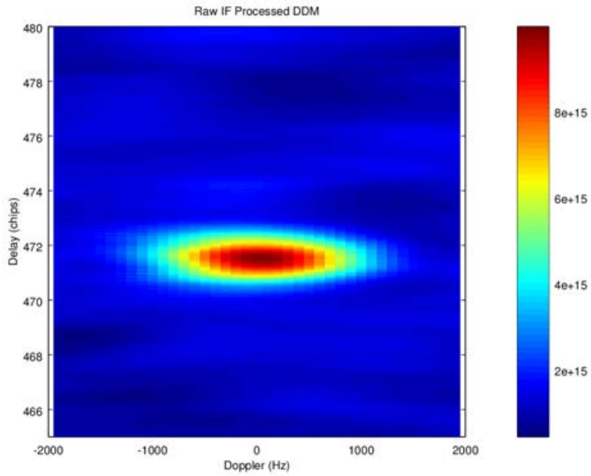

Fig. 4. Delay Doppler map of a direct signal processed in the raw IF data generated by the instrument. DDM is shown in units of uncalibrated counts.

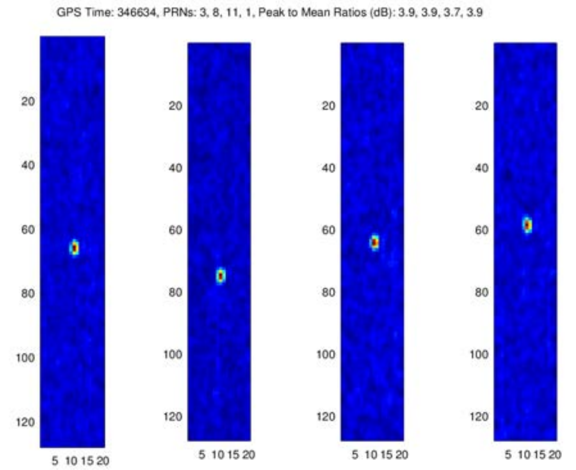

Fig. 5. Example of 4 instrument processed DDMs generated during the 15 minute GSS simulation.

L1b values of σ^0 over a subset of DDM bins corresponding to approximately 25 square kilometers. The wind speed is estimated using a minimum variance technique that includes several DDM observables including the average DDM σ^0 near the specular point and the slope of the rising edge to specular point. Details on the CYGNSS L2 wind retrieval algorithm can be found in [11].

VI. CYGNSS Instrument Pre-Launch Testing Results

The CYGNSS DDMI Engineering Model (EM) has undergone preliminary testing and some of the results are shown below. The CYGNSS DDMI is tested using a GPS Signal Simulator (GSS) which is capable of generating realistic navigation and reflected signals. A simulation scenario has been developed for use in preliminary testing of the DDMI instruments.

The DDMI has two principal science modes: Real-Time DDM generation and Raw IF sampling. The default mode is Real-Time generation of 4 parallel DDMs. However, the instrument is capable of collection high resolution data for shorter periods (1-2 minutes) for detailed ground processing. Figure 4 shows a DDM processed using raw IF data logged from the DDMI.

Subsequently, the DDMI was tested extensively in Real-Time mode, where it produced 4 DDMs in parallel as shown in Figure 5. Each of the four DDMs shown is tracked and processed independently. The DDMs in Figure 5 are shown as they would be downloaded (after on-board compression) in Figure 6, with corresponding delay and Doppler cuts through the peak of the signal. Note that the DDMs being generated by the GSS for DDMI testing are currently only simple ”hot spots” similar to direct signals. The next step is to upgrade the GSS scenario to include realistic DDMs (such as those shown in Figure 3).

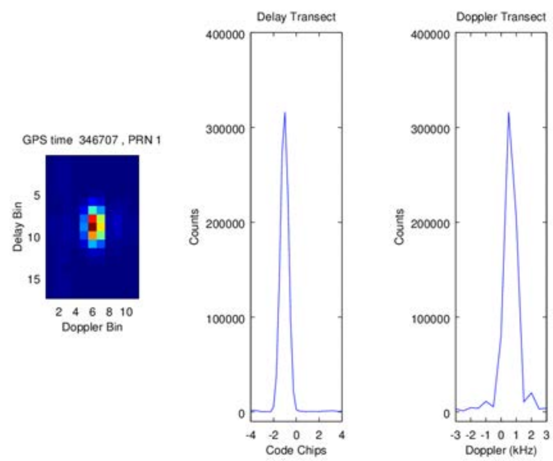

Fig. 6. Example of a single compressed DDM processed by the instrument and the delay and Doppler cuts throught the center.

VII. Conclusion

The CYGNSS GNSS instrument has successfully undergone preliminary testing using Engineering Model (EM) hardware. The DDMI has been integrated into a full spacecraft at Southwest Research Institute and is being testing using a full GPS signal simulator (GSS) developed at the University of Michigan. The simulator is capable of generating realistic navigation and reflection information and the DDMI has successfully completed initial testing demonstrating that it is capably of producing real time DDMs for 4 parallel reflections as well as logging raw IF data for ground processing (As shown in Figure 5, 6 and 4 above). The eight CYGNSS flight satellites and instruments are currently being manufactured and are scheduled for launch in 2016.

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