

Remote Sensing Using GPS Signals – The SGR-ReSI Instrument

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ABSTRACT

Global Navigation Satellite Systems (GNSS), which include both the GPS and Europe's fledgling Galileo systems, radiate signals at the Earth from orbit. Beyond the every day application of navigation, these signals can also contain information that is valuable to scientists interested in studying the Earth from space.

Information about the Earth's atmosphere and Ionosphere can be derived using a technique known as GNSS Radio Occultation (GNSS-RO), whereby signals that pass through the Earth atmosphere are received by a small satellite orbiting in a Low Earth Orbit (roughly 400-800km) and then looking at the distortions on those signals. GNSS Reflectometry (GNSS-R) is a relatively new application and this technique seeks to derive information about the Earth by looking at GNSS signals that have been reflected off the Earth's surface and subsequently received by a satellite in low Earth orbit. In the process of reflecting, these signals are distorted by the reflecting surface and, through the use of inversion models, it is possible to subsequently derive information about that surface from the signals. The driving application for this development is the monitoring of the Earth's oceans and, in particular, information about ocean roughness and wind speeds could be derived. Reflections off land and ice have also been detected and potentially contain a wealth of useful information. The concept has been proved on an experiment flown on the UK-DMC mission, but more data from orbit is required to improve the models that will allow this technique to become a useful tool to scientists.

At its heart, the GNSS-ReSI instrument is a highly versatile, multi-frequency GNSS navigation receiver. With the addition of multiple front-ends, reconfigurable DSP capabilities, a small data recorder and specialised antennas, the GNSS-ReSI enables both Reflectometry and Radio Occultation applications. Building on SSTL's small satellite expertise and using state of the art technology, the instrument aims to provide a highly capable yet relatively compact and affordable way of studying the Earth from orbit.

INTRODUCTION

The small satellite UK-DMC launched in 2003 carried a pioneering experiment able to collect samples containing reflected GNSS signals from the ocean surface. This generated data showing the feasibility of GNSS Reflectometry as a remote sensing technique, with special application to ocean roughness sensing.

The primary limitation of this experiment was the small amount of data that could be collected – only 20 seconds each time. The data was sufficient to demonstrate after post-processing a relationship between reflections and sea state.

SSTL is developing a follow-on instrument that is intended to take the state of the art beyond that achieved with the UK-DMC experiment by permitting the collection of higher quality sampled data and near continuous on-board processed data. SSTL has been working with partners NOCS, University of Bath, Surrey Space Centre and Polar Imaging Limited, under sponsorship of the UK Centre for Earth Observation Instrumentation with the intention of developing a flexible instrument that can not only log sampled data for post-processing on the ground, but provide on-board processing and compression to support GNSS reflectometry over the ocean and other GNSS remote sensing applications.

SCIENCE AND OPERATIONAL NEEDS

A number of orbiting missions have made use of GNSS Radio Occultation (GNSS-RO), i.e. using GNSS signals for the recovery of tropospheric temperature, pressure and humidity, (for example COSMIC/Formosat and the GRAS instrument on Eumetsat) as well as Total Electron Content and scintillation in the ionosphere. This science case is therefore well-developed, although further research into targeted areas is possible, and the exploitation using new GNSS signals requires more work. Less mature is the exploitation of GNSS signals reflected off the Earth’s surface (GNSS-R). Two approaches can be taken - GNSS-R for altimetry, e.g. for ocean height measurement, requires recovery of dual frequency phase measurements off the Earth’s surface and needs a physically large high gain antenna. GNSS-R for scatterometry uses the non-coherently integrated reflected power to recover to recover Geophysical information about the dielectric and roughness properties of the surface, with applications to ocean, ice and land remote sensing, as pioneered by the UK-DMC GPS-Reflectometry experiment in 2003 [GLE05], [GLE06]. Oceanography is the primary beneficiary of the measurements, but there are a number of other promising applications for the SGR-ReSI. Much of the potential is linked to the higher sampling over other instrumentation afforded by such a low size, power & cost GNSS-based sensor that could be hosted on multiple satellites in the future. Based on results to date, the applications with the highest relevance to scientific and operational needs are listed below.

| | |
|--|---|
| Ocean Roughness (directional mean square slope variance, <i>dmss</i>) | understanding ocean/atmosphere exchange of heat and gases, especially CO ₂ : Operational measurements of <i>dmss</i> useful for weather forecasting, dangerous sea states and storm surge predictions: Supporting role for other operational missions & measurements that require ocean roughness. |
| Reflectometry Ice edge and freeboard | Measurement of ice edge and (dual frequency) measure of ice free-board valuable to Climate Change and Global Water and Energy Cycles. Potential for supporting improved forecasting, tactical ice support and operational ice services in polar regions based on higher temporal revisit [UNW08]. |
| Radio-Occultation: Troposphere | The refractive index of the atmosphere is measured from the bending of the GNSS signals, and meteorological institutes assimilate this to extract information on humidity in the lower atmosphere. New GNSS satellites and signals will allow a higher measurement density to improve weather forecasting. |
| Radio-Occultation: Ionosphere | Ionosphere knowledge has always been important for GPS/GNSS and military communications, but is becoming increasingly important for Earth Observation, for example, JPL Global Ionospheric Model is used for correcting altimetry measurements, but there is a shortage of ionospheric measurements and incomplete knowledge about effects such as scintillation. |

The major gap in the science of ocean reflectometry is the lack of data. UK-DMC only generated about 40 useable data collection sets. These showed the potential for remote sensing, but cannot be used to develop any statistical empirical refinement of the models. It is therefore essential that a priority is placed on more extensive data collection in orbit.

| Measurement | Science Needs Addressed |
|-------------------------------|--|
| Reflectometry for Directional | Higher sampling and longer time-series of <i>dmss</i> valuable for |

One year of instrument operation would permit much data to be gathered – this may be achieved on a demonstration satellite. However, the move towards an operational data source would require a longer duration, suggesting a three year plus mission lifetime. The spatial and temporal characteristics of the ocean vary considerably depending on latitude; a study [SMO04] found the mean duration and length of stationarity at the Equatorial Atlantic was 7 hours duration and 189 km square and in the North Sea was 3 hours 63 km length. One satellite cannot meet these requirements, so ultimately of a constellation of satellites is required. Accuracy requirements are wind speed to better than 2 m/s, however GNSS Reflectometry arguably does not measure wind speed directly, unless the sea is well developed. Instead, the measurements taken by GNSS reflectometry are more closely directional mean square slope, a parameter increasingly used in wave modelling.

THE UK-DMC GPS-REFLECTOMETRY PROOF OF CONCEPT

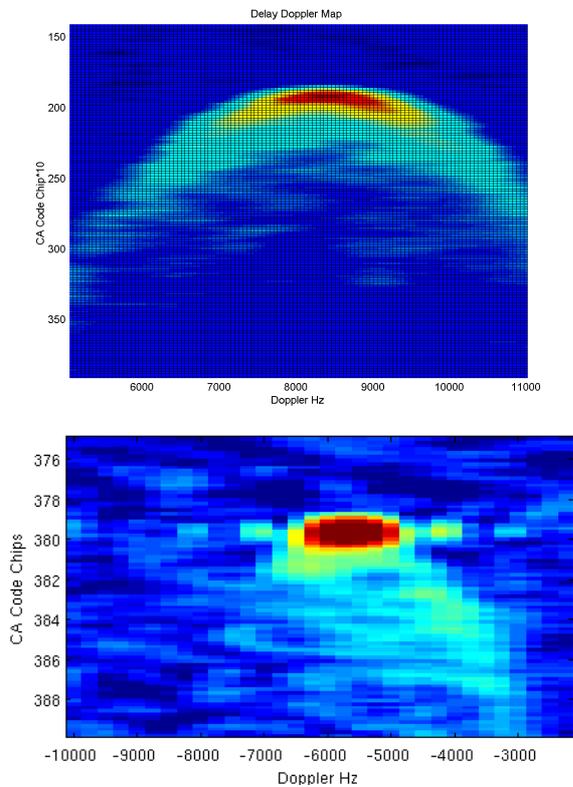


Figure I: Example Delay-Doppler Maps from UK-DMC GPS-R Experiment; a) Ocean reflection, b) sea ice / water reflection

The potential for GNSS Reflectometry was demonstrated on the UK-DMC mission by SSTL and the University of Surrey with support from the BNSC NEWTON programme in 2003 [UNW03]. A 12 dBi nadir downward pointing antenna had a 3 dB field of view of approximately 20 degrees by 80 degrees, 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 using software receiver techniques (see Figure I) to allow analysis of signal returns off ocean, land and ice.

A substantial ongoing effort into the modelling 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 [GLE05], [GLE06] and the retrieval of directional roughness information [CLA09], [CLA09b]. 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. [JALE08]. The UK-DMC experiment demonstrated the feasibility for many remote sensing applications but not enough space-based data is available to date to allow robust assessment of the geophysical retrieval accuracy of GNSS-R.

SGR-RESI REQUIREMENTS AND DESIGN

Prioritised requirements were developed based on experience from the UK-DMC experiment and inputs from partners in the study to help steer the functional design of the instrument. SSTL has long experience in developing GNSS receivers for spacecraft for navigation using commercial technology, and so the technology push from this approach also helped in the design of the architecture of the SGR-ReSI. Table 1 shows the main characteristics of the SGR-ReSI as compared to the experiment used in the UK-DMC experiment, and Figure II shows the block diagram of the SGR-ReSI model.

Table 1 SGR-ReSI advances over UK-DMC Experiment

| | UK-DMC GPS Experiment | SGR-ReSI Core |
|----------------------------------|----------------------------|---|
| Signals | GPS L1 | 1) GPS & Galileo L1 2) Either GPS L2C or L5 & E5ab |
| Sampling Rate | 5.7 MHz, 1 bit (effective) | 16+ MHz, 2 bits (with Q option) |
| Storage | 20 sec (128MB) | 60 seconds (1 GB) |
| Measure of Power Received | SNR only | AGC monitoring & on-board source investigation |
| Direct Tracking | C/A only (commercial IC) | Reprogrammable to other signals |
| Reflected Tracking | Not practical | Reprogrammable in SRAM FPGA |
| Contin. output | No | Yes – Delay Doppler outputs |

daughter boards with a reasonably generic interface scheme, allowing the adaptation of new front-ends without requirement of a motherboard redesign, and other front-ends are also being considered for the future.

The development of the SGR-ReSI involved the adoption of new FPGA (Field Programmable Gate Architecture) technologies that are at the forefront of space technology, but offer processing power and flexibility that allows the remote sensing capability envisaged for the SGR-ReSI. The Actel ProASIC3E is a non-volatile Flash-based FPGA that consumes little power. It contains the processor and 24 channels of SSTL-developed correlators, plus other peripherals, such as UART, CAN-bus, and SPI. Two soft-core VHDL-based processors have been investigated for implementation – the Cortex-M1 (an FPGA-optimised reduced version of the ARM processor) and the LEON3 SPARC processor. The RTEMS operating system has been selected to allow control over multitasking application software, portability between different processors, and compatibility with other developments at SSTL.

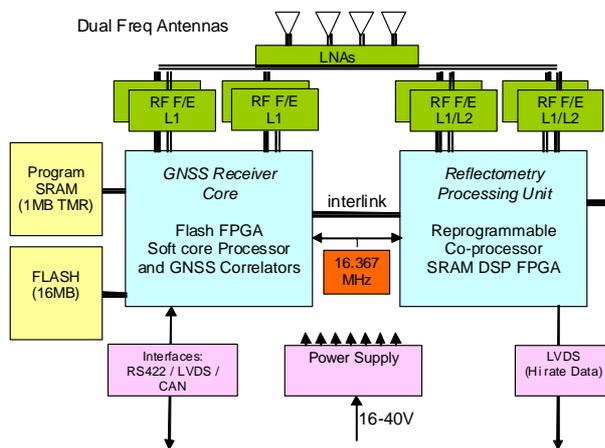


Figure II GNSS Reflectometry Instrument Configuration

To allow for a wide range of possible applications, the prototype SGR-ReSI supports up to 8 separate RF inputs, enabling up to 4 dual frequency antennas. Two varieties of COTS-based RF front-ends have been incorporated, one of which is L1 optimised (MAX2769) while the other is re-configurable to any of the GNSS bands (MAX2112). The RF front-ends are housed on

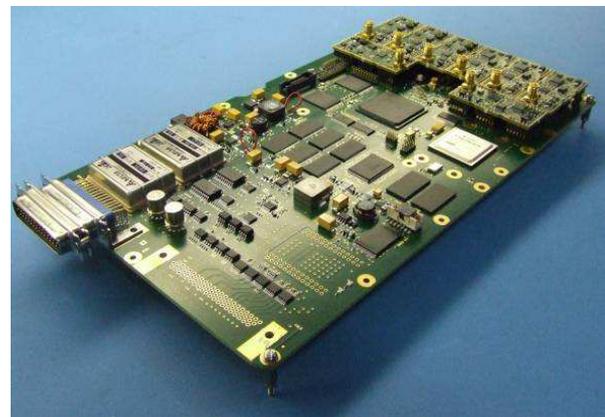


Figure III SGR-ReSI prototype with 8 Front-Ends

While the first FPGA contains the core functions of a GNSS receiver, a second FPGA is available as a co-processor. This is a Xilinx Virtex 4 FPGA that is SRAM based, allowing the upload of new co-processing algorithms even while in orbit. It enables special processing algorithms for reflected or occulted signals, allowing the equivalent of hundreds of correlators to map the distorted signals. To allow the storage of both sampled and processed data, a bank of DDR2 memory with a capacity of 1 GByte is used.

The instrument supports multiple interfaces (CAN, RS422, Spacewire, USB) so it could be accommodated by a variety of different satellite missions. The unit is around 1 kg in mass, consumes less than 10 watts, and fits within half of an SSTL standard satellite micro-tray (approx 300x 160 x 30 mm).

COTS & RADIATION

To maintain low cost and flexible approach, SSTL has often used COTS parts in its spacecraft design. This has advantages and disadvantages. A larger choice of technology is readily available at commercial lead times and costs, with professional development tools. If components are selected from higher volume production lines, there is an increased assurance of the component reliability. COTS components, however, carry the risk of susceptibility to orbital radiation effects and are subject to manufacturing process and die change without warning.

Measures are taken to mitigate the risk of radiation effects, including a latch-up switch, and memory protection through triple modular redundancy. Some parts have been characterised under radiation and documented results have been used to help select components. SSTL and SSC have recently undertaken total ionising dose tests on the SGR-ReSI RF front-ends and Low Noise Amplifiers with promising results, to be published elsewhere.

ANTENNA DEVELOPMENT

SSTL’s Space GPS Receivers have used active L1 patch antennas with hemispherical beam patterns for the navigation function of the receivers. For the 2003 UK-DMC experiment, a higher gain L1 antenna nadir antenna (approx 12 dBi gain) was used, supplied by European Antennas Ltd, with an external LNA (low noise amplifier).

The SGR-ReSI poses a number of new challenges in antenna design. To exploit the new civil GNSS signals and frequencies that are becoming available, the GNSS antenna needs either multiple resonances or a very wide bandwidth. A spaceborne antenna needs to be small and lightweight, with materials suitable for the space and thermal environment.

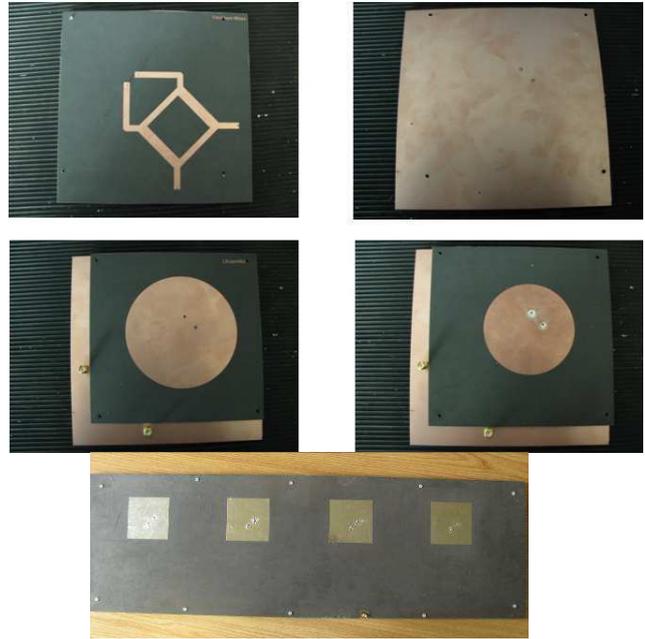


Figure IV a) Dual Frequency GNSS Antenna Prototype, b) High Gain Antenna Array

Surrey Space Centre has been designing prototype antennas for the SGR-ReSI (Figure IV), initially with requirements are for L1 and L2C antennas [MAQ10]. The zenith pointing antenna requires a hemispherical pattern, while the nadir antenna is specified with a more directional beam with a 12 dBi gain at boresight. A GNSS-RO antenna would need to be mounted on the side facet of the satellite, and have directionality towards the horizon.

OPERATIONAL MODES

Two baseline GNSS-R collection modes are being targeted for operations. The first is the sampling of direct and reflected signals directly at Intermediate Frequency, similar to the mode of operation on UK-DMC experiment. The SGR-ReSI, however, can permit either single or dual frequency (L1 and L2C) collection to enable the collection of new scientific data. As part of the instrument testing, the pass-band of both front-ends has been sampled, and then processed with software-based FFTs to recover the pass-band and recover GNSS signals using a software-based receiver (see Figure V and Figure VI.)

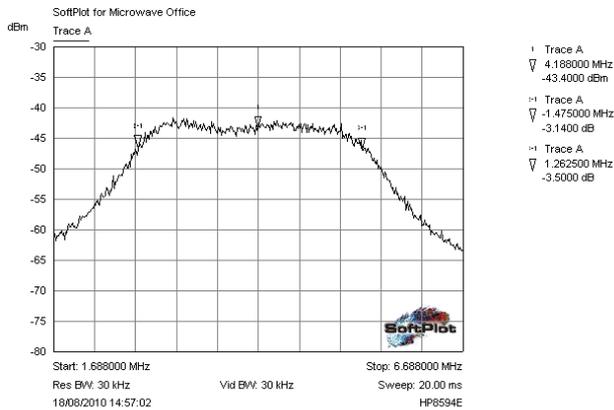


Figure V Pass-band of MAX2769 front-end on SGR-ReSI after sampling and post-processing

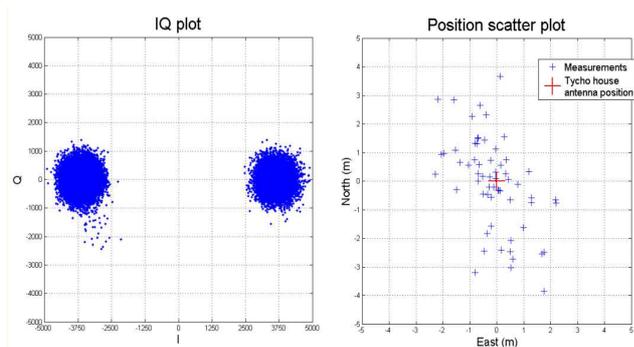


Figure VI Recovery of GNSS signals from sampled data using software receiver

The second mode of operation is the on-board processing of the data into a Delay Doppler Map. In this mode, software predicts with a small uncertainty where the reflection of the GNSS signal is to be found in Delay and Doppler domains. This information is passed to the co-processor as an input to an algorithm that correlates the signal, integrating coherently for 1 millisecond then incoherently for up to 1 second over the range of Delays and Doppler shifts expected. A DDM with the size of 128 x 64 cells, 10 bits deep is generated every second. Figure VII shows an example Delay Doppler Map generated by the SGR-ReSI. The signal was generated using a Spirent simulator with a controllable delay multipath reflection, both shown on the image - unlike DDMs derived from orbital data, there is no significant spread in this DDM.

Due to the flexibility of the instrument, other data collection and reflectometry processing schemes can be supported, one of which is discussed in [JALE10]. There is the potential to optimise algorithms for collecting ice reflections.

In terms of Radio Occultation, SSTL has been working with Shrewsbury School and the University of Bath on a project called POISE to use a GPS receiver in orbit with modified software to monitor scintillations occurring in the ionosphere – this experiment could be implemented on the SGR-ReSI and extended to dual frequency GNSS signals.

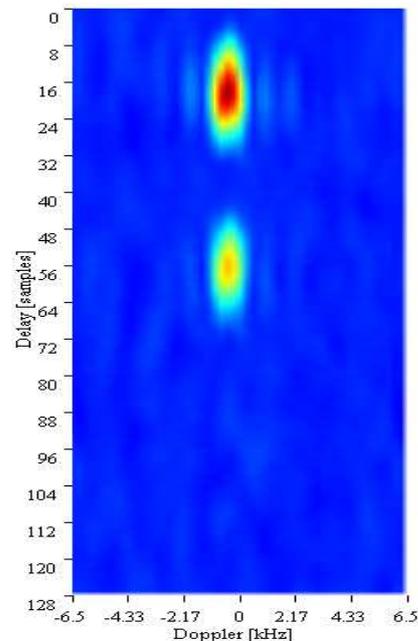


Figure VII Delay Doppler Map (100ms integration) produced in real time within SGR-ReSI. Plot shows direct and multipath signals generated with Spirent simulator

TECHDEMOSAT-1 FLIGHT OPPORTUNITY

Surrey Satellite Technology Ltd is in a unique position to offer frequent opportunities for flight experimentation at a low cost and on a rapid schedule. The first GNSS Reflectometry experiment made use of UK-DMC satellite, and SSTL has a number of future DMC and other satellites expected in the next few years.

With the support of TSB and SEEDA, in late 2010, SSTL kicked off the TechDemoSat-1 [PEN10], a satellite to demonstrate UK space technologies in orbit, with a provisional launch date of 2012. The SGR-ReSI is being carried on TechDemoSat-1 as part of the Sea State payload. It will carry four antennas: dual frequency (L1 & L2C) antennas for nadir and zenith, and two more L1 only antennas for zenith.

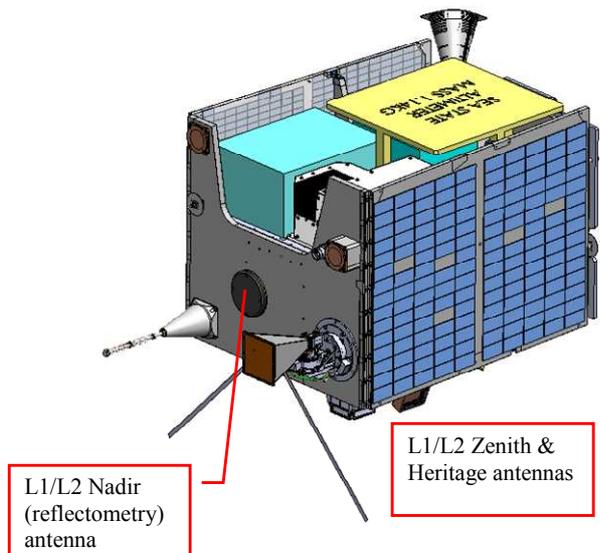


Figure VIII: TechDemoSat-1 CAD model with SGR-ReSI antenna locations

The TechDemoSat-1 project is due for launch in 2012, and the work on the platform and various payloads is almost at the Critical Design Review stage. The SGR-ReSI flight model is due to complete manufacture and testing on time for integration onto the spacecraft in the autumn

Following the demonstration of the SGR-ReSI on TechDemoSat-1, inversion models can be refined, and the oceanography science case can be consolidated. Proposals have been developed that investigate the use of the SGR-ReSI on a constellation for global wind and wave monitoring. SSTL's leadership in spaceborne GPS also introduces some commercial avenues that may turn into opportunities, for example, SSTL has supplied GPS receivers for three different LEO satellite constellations.

SSTL has manufactured some 50 space receivers for different missions, from a product line including the SGR-05U, SGR-07 and the SGR-10 (Figure IX). Aside from the Remote Sensing capability, the GNSS core of the SGR-ReSI will be employed to eventually supersede SSTL's current single frequency GPS receiver product line. Enhanced capabilities will be possible, such as faster acquisition, and the tracking of

Galileo signals. The core of the receiver is contained within one low power FPGA, permitting the configuration of a small receiver, retaining the lower cost associated with COTS-based technology.



Figure IX: A replacement for the SGR-10 Space GPS Receiver will make use of SGR-ReSI core

CONCLUDING REMARKS

The approach adopted for the SGR-ReSI leads to a highly flexible GNSS receiver core that can be configured for remote sensing oceans and atmosphere as required, and gives flexibility for experimentation with novel signal processing techniques that may prove to be necessary with some weak or fading signals. The dual frequency capability also enables the receiver to be configured as a source of ionospheric-free GNSS measurements for precise orbit determination, vital for altimetry and other remote sensing satellites. The receiver uses COTS parts associated with terrestrial GNSS receivers, and will therefore yield a small, low power product at an affordable cost. A flight opportunity on the TechDemoSat-1 has been identified, but the design has flexibility permitting readily deployment on multiple satellites as opportunities arise, to give unprecedented measurement density around the globe.

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