GRSPI, a Prototype for an Optimal Orbiting GNSS Science Instrument

T. K. Meehan, S. Esterhuizen, G. W. Franklin, S. Lowe, T.N. Munson, D. E. Robison, J. Y. Tien, L. E. Young
Jet Propulsion Laboratory, California Institute of Technology
Pasadena, CA, USA
Thomas.K.Meehan@jpl.nasa.gov

***Abstract*— Science-based instruments which use radio signals from Global Navigation Satellite Systems (GNSS) have been successfully deployed on several NASA missions. Applications range from Precise Orbit Determination (POD), limb sounding and formation flying. Remotely sensing the Earth's surface using reflected GNSS signals as a bi-static radar source (GNSS-R) is one of the most challenging applications of radiometric instrumentation. As part of NASA's Instrument Incubator Program, our group at JPL is building a prototype instrument, GRSPI (GNSS, Remote-Sensing, POD Instrument), to address a variety of GNSS science needs. Observing GNSS reflections is one focus of the design and development effort but technology for additional science needs will also be developed. GRSPI will process upcoming additions to the GPS signal structure which will improve accuracy for POD as well as limb sounding. This paper outlines the GRSPI design as it would apply to a next generation science instrument giving specific attention to observing science quality GNSS-R signals from low Earth orbit.**

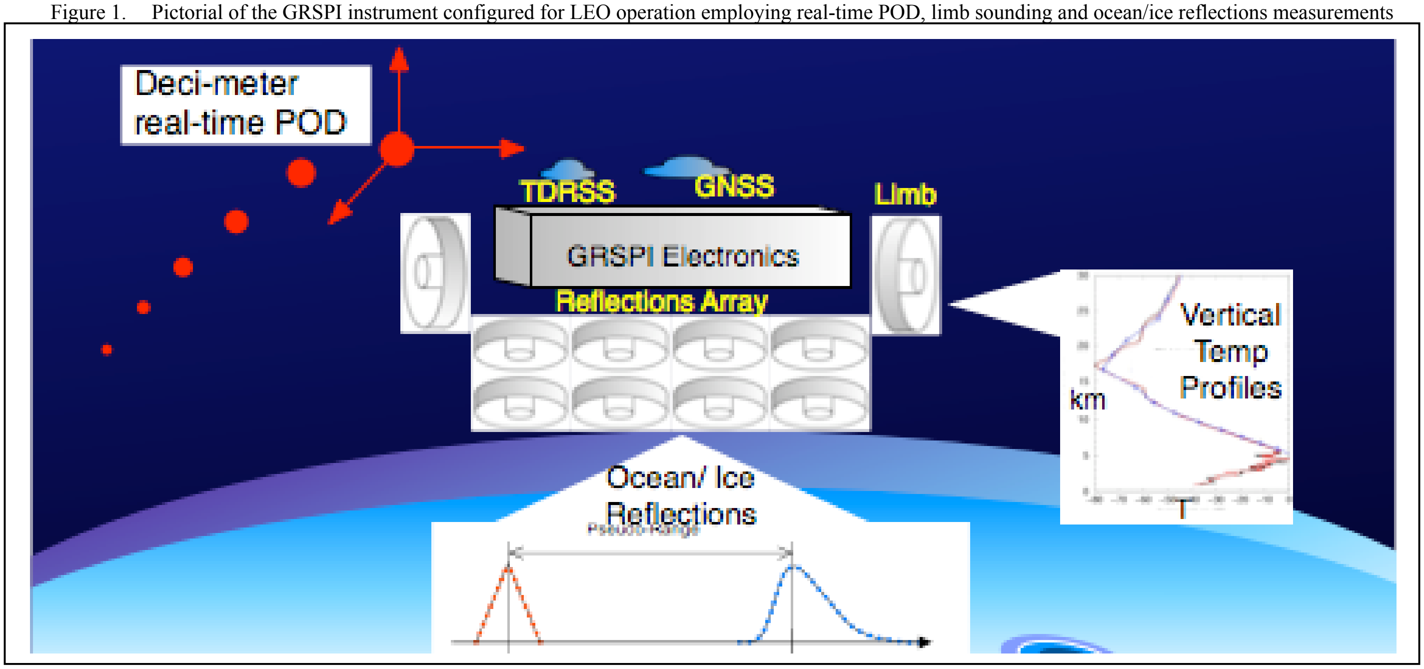
Keywords; GNSS-R, GRSPI, Global Positioning System, BlackJack GPS, Galileo, Bi-static radarIntroduction

I. Introduction

The radio signals transmitted by the Global Position System (GPS) satellites, have emerged as a powerful and relatively low cost approach for wide ranging science related measurements. New GNSS signals from GPS and the nascent Galileo satellite navigation system will greatly strengthen science opportunities for a new generation of GNSS instrumentation. NASA has a long heritage of applying the latest GPS instrumentation where highest accuracy or unique capabilities are required. Using the BlackJack GPS receiver, developed at JPL for NASA, science quality GPS measurements have become an important tool for altimetry missions like JASON, Synthetic Aperture Radar (SAR) positioning for the Shuttle Radar Topography Mission (SRTM) and relative positioning and time-tagging of the tandem GRACE spacecraft. In some cases, like the CHAMP, SAC-C and COSMIC missions, the GPS signal is the science observable, with the instrument making precise phase delay measurements of the signal as it is refracted by the Earth's ionosphere and atmosphere. Another direct GNSS science measurement can be made from an aircraft or low-Earth orbit (LEO) platform when both the incident and reflected "GNSS-R" signals are observed.

Measurements of GNSS-R from low-Earth orbit (LEO) can have multiple scientific uses with surface altimetry the most often cited. Altimetry via GNSS-R is described in a number of sources [1],[2],[3],[4] with theoretical description and experimental evidence of the expected resolution and accuracy. The key observable is the reception-time difference between the direct and reflected signals, as illustrated in Fig. 2. These measurements, along with knowledge of the precise locations of the receiver and transmitters, allow a calculation of the ocean or

Figure 1. Pictorial of the GRSPI instrument configured for LEO operation employing real-time POD, limb sounding and ocean/ice reflections measurements



ice heights at each of the specular reflection points. From a LEO platform, signals received from GNSS-R transmitters (GPS & Galileo satellites) are much weaker than those from traditional nadir pointing altimeters. A high-gain antenna can compensate for this but the increased directivity reduces the total number of sources and the benefit of observing many sources simultaneously.

The power of the GNSS-R technique lies in the large number (~10) of simultaneous measurements, one for each GNSS satellite in view, compared to a radar altimeter. Each new GNSS signal represents a potential new, independent height measurement. Each measurement's altimetric accuracy is expected to be less than that of a state-of-the-art traditional altimeter, but it is the synoptic set of measurements over several thousand kilometers of ocean that differentiates this concept. In other words, compared to radar altimeters, the present GNSS concept trades altimetric accuracy for greater spatial and temporal resolution. The three parameters, altimetric accuracy, spatial resolution, and temporal resolution, can be traded optimally for a given application, depending on how the data are processed. This adds an important complementary dimension to measurements from traditional LEO altimeters. That is, the active radiometer makes accurate measurements sparsely sampled in time and space, and the GNSS reflections instrument will sample more densely in time and space.

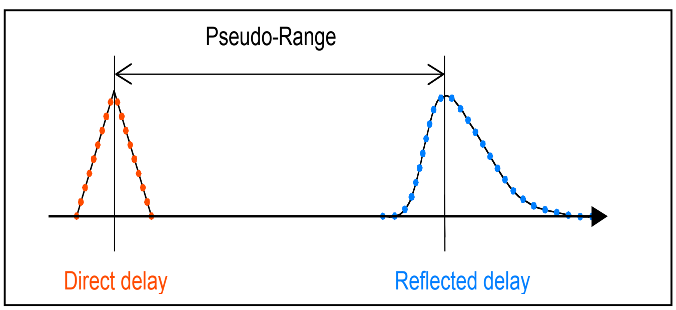


Figure 2. The correlation functions of the direct and reflected signals with a delayed and Doppler shifted copy of the transmitted signal generated inside the receiver.

A. *GRSPI Instrument Features*

- Receive and process multi-frequency GPS and Galileo
- Observe GNSS transiting Earth's ionosphere and atmosphere
- Process multiple reflected signals, simultaneously with high gain for sufficient precision
- Multi-lag processing to fully characterize delay waveforms
- Observe different specular points with high gain to maximize precision
- Autonomous scheduling and operation
- On-board data fitting and compression to reduce spacecraft data bandwidth requirements
- Reconfigurable to optimize processing post-launch

GRSPI combines some recent commercial technology with existing NASA flight GPS technology. The BlackJack GPS receiver [5] provides the essential GNSS navigation direct signal tracking, and timing information. Newer, off-the-shelf technology is employed for the array of RF downconverters and for the digital antenna phasing that handles the high gain beam forming. Experiment scheduling and reflected signal modeling is carried out with software under the Linux operating system (OS).

II. GRSPI System Architecture

A. *Major Components*

GRSPI is comprised of 5 main components:

- Antenna Array
- RF Downconverter Array
- Reconfigurable Digital Processor
- GNSS Real-time Receiver
- Science Processor

B. *Antenna Array*

With a LEO configuration, a nadir facing antenna will receive GNSS-R signals from specular points off the Earth's surface. Because a high antenna gain is needed to deliver acceptable precision and because the bi-static geometry yields a continuously changing angle between nadir and the reflection source, an antenna with steerable gain is needed. GRSPI is designed to accommodate 16 to 64 antenna elements which can be phased and combined to produce high-gain over a wide angle (~120 degrees). Each element is a 2 1/2 turn helix in a cavity (helibowl). This provides about 8-10 dB of gain over the receive frequency range for GPS & Galileo of 1150-1600 Mhz.

Various applications require high-gain signals. Using arrays of antenna elements with fixed phase shifts is one way to obtain high-gain observations. Using phased arrays to steer a single beam is also common, but the simultaneous steering of several high-gain beams is not. One approach consists of switching elements into or out of an array, resulting in a finite number of quantized beam directions. A connection matrix then assigns each desired beam with a given quantized direction. The approach here [6],[7] shown in Fig. 3, uses highly accurate digital mixers, the same as those used to perform basic receiver functions, to phase each array element and continuously steer multiple beams, thereby avoiding beam-direction quantization effects.

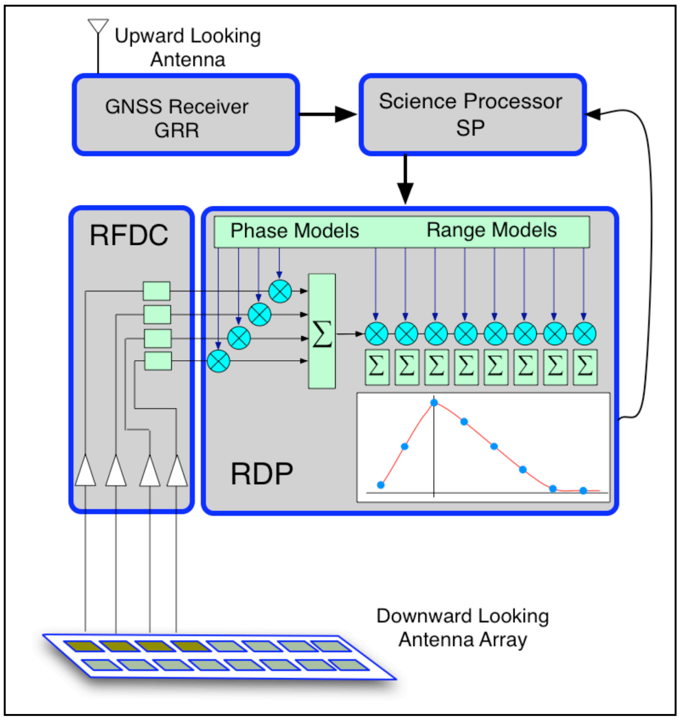


Figure 3. GRSPI concept configured for GNSS-R application. The GNSS receiver passes real-time data to the Science Processor which applies models for antenna beam steering, Doppler, and range delay. A subset of the number of antennas and correlator channels is shown here for simplicity.

Because the instrument itself controls the steering, no additional hardware unit, hardware interfaces, or additional communications lines are required. This approach is relatively inexpensive, highly accurate, avoids beam pointing quantization effects, and keeps the required RF hardware simple.

This phasing is performed in digital logic following a frequency down-conversion and digitizing step. Thus, an electronically scanned array antenna (ESA) provides the gain required to extract radiometric information from weak GNSS surface reflection signals. GRSPI will test an array of 16 elements arranged in a 2x8 pattern. Fig. 4 shows the resulting simulation of this arrangement for select scan angles. This will yield over 20 dB peak gain at the L1 frequency of 1575 MHz.

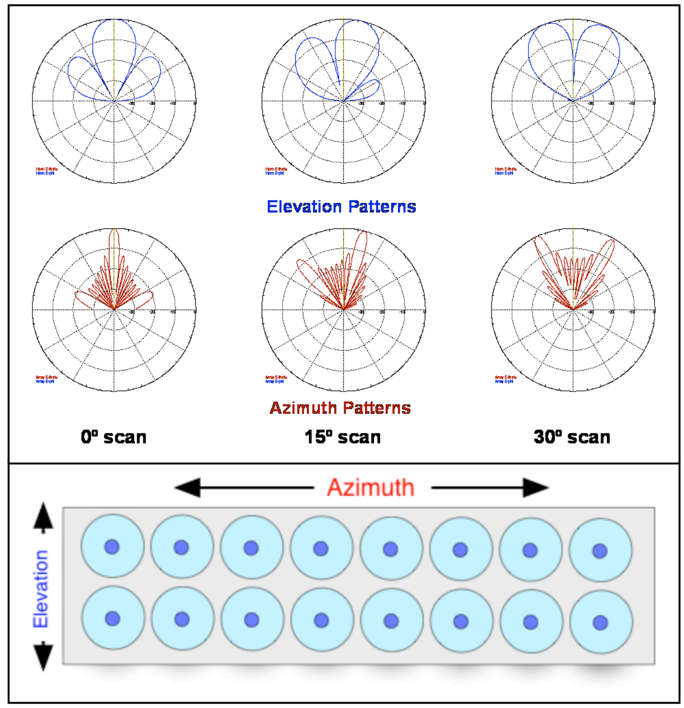


Figure 4. Simulation of antenna gain patterns for 2x8 helibowl array for the L1 frequency (1575 MHz). Peak gain exceeds 20dB.

C. *RF Down Converter Array (RFDC)*

Each wide band RF signal is filtered with a low-loss 500 MHz band-pass filter centered at 1400 Mhz. After amplification, the signals are separated into L1,L2 and L5(E5) channels and routed to a single-stage mixer and low-pass filter chip. Each I,Q output is filtered with a 7-pole Butterworth low-pass filter with 10 MHz bandwidth, and sampled at the Nyquist rate of 20.456 Mhz. Either 1 or 1.5 bit sampling can be used . Initial GRSPI testing will be accomplished with 1-bit sampling.

To process 16 antennas worth of GNSS-R data, 16 RFDC chips are required for each of the frequencies considered. The GRSPI development will test a 48 RFDC system so antenna phasing at all three frequencies can be tested. However, the GRSPI RF architecture is designed to accommodate up to 192 RFDC chips, enabling a total 64 antenna elements.

The three mixing frequencies are multiples of the same reference oscillator signal. This 10.228 reference is multiplied by 110, 120 and 154 for the L5(E5), L2 and L1 respectively, RFDC chips. This same 10.228 reference (x2) provides the sampling signal for the 96 1-bit data streams. RF and digital processing signals are synchronized to the same timing reference.

D. Reconfigurable Digital Processor (RDP)

The GRSPI prototype will process 96 1-bit data streams simultaneously clocked into FPGA logic. All RFDC data is sampled on the same 20.456Mhz clock edge effectively giving each sample a consistent time tag. These data are shunted off the FPGA into a RAM buffer sufficiently large to store several seconds of observations. Furthermore, because the data are the digitized "raw" signals from each antenna element, they contain all reflected signals in view of each antenna element. This allows great flexibility in the processing since the FPGA logic can operate much faster (4x) than the sampling clock rate. The digital logic can be configured to sequence through different GNSS satellites, or different frequencies, different antenna elements and so on.

The first stage of digital processing digitally counter-rotates the signal to remove the residual carrier and to generate multiple antenna beams. A 3-level phase model digitally multiplies the incoming signal for each of the 16 antenna elements. Phase offsets between each antenna are modeled based on the incident angle (relative to the array coordinate frame) and a calibration table derived from the fixed antenna element geometry and relative RF electronics delay offsets. This set of 16 multiplication operations is duplicated for each of the desired beam directions.

E. GNSS Real-time Receiver (GRR)

In the GRSPI instrument, GNSS-R processing is performed "off-line", one to several seconds behind real-time. This allows models for reflected signals to be generated based on real-time navigation and tracking from the direct GNSS signals. The GRR operates from the 10.228 Mhz reference and provides continuous timing to the RDP and real-time GNSS navigation to the Science Processor.

F. Science Processor (SP)

The SP controls the digital signal processing of the RDP. It receives real-time navigation and timing data from the GRR and uses this to schedule reflection observations. The SP uses a Linux based computer to provide a convenient and familiar programming environment for controlling GRSPI. For each observation sequence , the SP sets up the observation start/stop time, writes signal processing models to the RDP and reads back the correlation products. The command/data interface between the SP and RDP is via a Universal Serial Bus (USB 2.0). This interface can handle up to 480 megabits per second.

III. OPERATION

GRSPI is designed to be an autonomous science instrument requiring no special initialization sequence or detailed observation scheduling. This approach is modeled after that of the BlackJack GPS space receiver which schedules atmospheric limb soundings based on a set of simple geometric parameters and storage data bandwidth. Some assumptions for in-orbit operation are that the platform (spacecraft) is 3-axis stabilized and the orientation is known to the Science Processor. When turned "ON" it is also assumed GRSPI stays ON for an extended period of time so a continuous orbit profile can be used for scheduling observations.

Once the GNSS receiver has successfully produced a navigation solution, the RDP is time-synchronized to the GNSS (effectively UTC). This synchronization is maintained to within one reference clock cycle (~50 ns) by the FPGA logic in the RDP. When a reflection observation is scheduled, the SP must perform the following tasks:

- Determine the vectors between the antenna array and the reflection points on the Earth.
- Generate phase offset models to direct the array beams along those vectors .
- Trigger the RDP logic to "capture" data from all array antennas for a specified time interval; e.g. 10 seconds.
- Within a few seconds of the beginning of data capture start RDP processing with antenna array, Doppler and range models.
- Offload correlation products every second for further post processing.

The previous processing scenario is just one of many available with the GRSPI architecture. By allowing for some latency for the data products, the user can examine the reflection data while holding the raw digitized bit streams for a subsequent reprocessing step if desired. An added benefit from the "time-shifted" processing approach is the Doppler and range models are likely to be more accurate since extrapolation of the navigation data isn't necessary. The GRSPI instrument in a LEO configuration Fig. 5, can observe hundreds of GNSS reflections per day over a wide orbit swath.

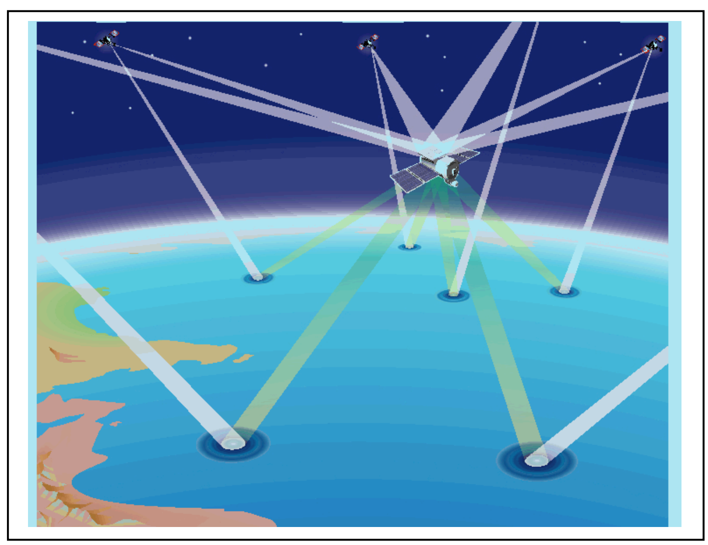


Figure 5. GRSPI in LEO configuration observing GNSS reflections

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IV. MASS, POWER, DIMENSIONS

GRSPI is still under development and has no strict requirements for mass, power or size. However, it can be useful to characterize the main prototype components in their current form. Table 1 gives approximate specifications for the main GRSPI components.

TABLE I.

GRSPI Components (16 element array)	Power (Watts)	Dimension(LxWxH) (cm)
GNSS Real-time Receiver (GRR)	18	20x20x9
RF Down Converter Array (RFDC)	25	50x30x10
Reconfigurable Digital Processor (RDP)	25	30x20x2
Science Processor (SP)	15	20x20x9
16 element Antenna Array	0	200x50x10

V. SUMMARY

An overview of a new instrument, GRSPI, developed at JPL for NASA's Earth Science and Technology Office has been given. The emphasis has been on how this prototype is suited for the particular application to GNSS-R observations. Some key instrument features are a digitally phase-steered antenna array, flexible, reconfigurable signal processing via state-of-the-art FPGA logic and autonomous operation driven by a Linux OS based processor. Using a 16 element array of heli-bowl antennas, a peak gain of over 20 dB can be directed to multiple source points simultaneously. Additionally, GRSPI will have radio occultation capability for weather and climate observations and precise POD processing using real-time corrections via satellite link.

The prototype will demonstrate multi-frequency beam steering with an "up-looking" ground-based test. New GPS signal types (L2C and L5) will be processed along with Galileo L1 and E5 signals. Once testing is completed, the GRSPI design will be ready for upgrading to a flight capable package.

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