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Multi-Frequency GNSS-R Receiver using BladeRF SDR and Single-Board Computer

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Abstract

The Global Navigation Satellite System (GNSS) continuously transmits Radio Frequency (RF) signals in three different frequency bands, namely, L1 (1575.42 MHz), L2 (1227.6 MHz) and L5 (1176.45 MHz). The multipath signals from the GNSS constellation have become a valuable source of information as they can successfully be utilised to analyze the Earth's geophysical characteristics. The multi-GNSS constellations and multi-frequency band signals provide more observations, information, and ground tracks than a single constellation. In order to utilise multi-frequency signals for GNSS-Reflectometry (GNSS-R) applications, a Software-Defined Radio (SDR) receiver is proposed in this paper. The hardware and software development for simultaneously receiving and processing the NavIC-L5 and GPS-L1 signals is also explained. The analysis of results shows the feasibility of the proposed hardware for performing the multi-frequency GNSS-R analysis.

1 Introduction

The advancement and development in various Global and Regional Navigation Satellite Systems (GNSS, RNSS) have not only improved the Navigation, Positioning and Timing services but have given rise to the development of other potential applications of GNSS signals. The use of Earth's reflected multipath GNSS signals is a relatively new technique to perform remote sensing applications. This technique is termed as GNSS-Reflectometry (GNSS-R) [1]. GNSS-R is based on the principle of bi-static radar, where the transmitter and receiver antennas are located on different platforms. A dedicated Left Hand Circularly Polarised (LHCP) receiving antenna is required for the GNSS-R technique, as the direct Right Hand Circular Polarised (RHCP) GNSS signal changes into LHCP after getting reflected from the Earth's surface. Therefore, the antenna to be used for real-time GNSS-R applications should have strong rejection for RHCP signals and high sensitivity for LHCP signals. The GNSS-R technique can provide estimates of sea-level height [2], snow depth [3], soil moisture [4], vegetation height [5] and sea state [6] by analysing the characteristics of the multi-path Earth reflected signals. The above-mentioned applications of GNSS-R provide essential climate variables that can successfully be used by the scientific community and incorporated with other remote sensing techniques to develop more accurate and precise climate models.

Until now, the various space-borne and air-borne [7] GNSS-R missions, including the UK's TechDemoSat-1 (TDS-1) [8] and NASA's Cyclone Global Navigation Satellite System (CYGNSS) [9], use a dedicated single frequency GNSS signals for the reflectometry analysis. However, with the development of different GNSS constellations, the use of multi-frequency and multi-constellation GNSS signals can be explored for GNSS-R analysis. The GNSS-R studies carried out till now are majorly centred on the use of GPS and GLONASS [10] and Beidou signals, whereas the studies on the use of NavIC constellation for reflectometry analysis are very few and still under development [11]. In this paper, a low-cost and compact multi-frequency GNSS-R receiver is proposed using a BladeRF Software Defined Radio (SDR) receiver and a single board processing unit. The receiver unit proposed has a small dimension of 19x16x3 cm and a low power consumption. Hence, it can be mounted on a platform near the ground, an Unmanned Aerial Vehicle (UAV), or a LEO satellite (if radiation hardened), depending on the area of interest and user application. The proposed software-defined receiver has the capability of receiving and processing the NavIC-L5 and GPS-L1 signals simultaneously. As the availability of GNSS transmitting satellites has increased, therefore the use of multi-frequency GNSS signals for reflectometry analysis can provide an increased number of observations for a particular surface of interest [12]. The revisit time and coverage of the GNSS-R will also improve significantly with the use of multi-frequency GNSS signals [13].

The remaining paper is structured as follows: the theoretical and software development of multi-frequency GNSS signal processing is explained in section 2. The hardware details of the GNSS-R receiver are provided in detail in section 3, followed by the multi-frequency GNSS signal simulation results in section 4. Section 5 concludes the paper with a discussion of possible future directions.

2 Methodology

In GNSS-Reflectometry (GNSS-R), the Earth's surface-reflected GNSS signals are received in a bi-static radar configuration and used as a source of information to study the geophysical properties of the underlying Earth's surface. Before performing the GNSS-R analysis, satellite signal acquisition is an essential step to determine the visibility of a satellite from the observer's point of view. Satellite signal acquisition is a 2-dimensional search process in the Doppler frequency shift and PRN code phase domain. The traditional satellite acquisition algorithms include Serial Search (SS) Acquisition, Parallel Frequency Space Search (PFSS) Acquisition and Parallel Code Phase Search (PCPS) Acquisition [14]. In the PCPS algorithm, the acquisition is performed in parallel, and it significantly speeds up the acquisition process [15]. The PCPS algorithm for satellite signal acquisition is outlined in the following block diagram in Fig.1.

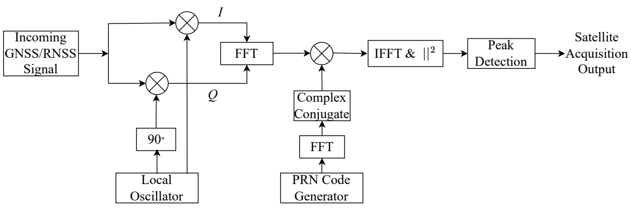


Figure 1. Block diagram of satellite signal acquisition algorithm

Typically, 1 ms of data length is selected for performing the satellite signal acquisition, whereas for the weak satellite signal acquisition, it is necessary to perform coherent or non-coherent integration to improve the detection output [16]. After performing the satellite acquisition to detect the available satellites, Delay Doppler Map (DDM) generation is the next step for performing GNSS-R analysis. The DDM is a 2D characterisation of the power distribution of the Earth-reflected GNSS signal around the specular point. The analytical representation of power distribution in a DDM is defined as [17]:

$$|P(\tau,f)|^2 = \frac{P_t G_t T_i^2 \lambda^2}{(4\pi)^3} \iint_A \frac{G_r(\vec{\rho})\sigma^{\circ}_{pq}}{R_{ts}(\vec{\rho})R_{rs}(\vec{\rho})} \chi^2(\vec{\rho};\delta\tau,\delta f)d\vec{\rho} \quad (1)$$

where the integration time is represented as T_i, P_t is the GNSS/RNSS transmitted signal power, with the transmitted signal wavelength denoted as λ, G_r and G_t are the receiver and transmitter antenna gain respectively, R_{rs} is the distance between the receiver and the specular point and R_{ts} is the distance from the transmitter to the specular point, σ°_{pq} denotes the bistatic-radar coefficient for a given polarisation pq, and $\chi^2(\vec{\rho};\delta\tau,\delta f)$ represents the Woodward Ambiguity Function. The received power calculated using (1) is further used for GNSS-R analysis to retrieve the geophysical properties of the reflecting surface. Additionally, using the GNSS signals from different constellations will provide more number of observations for a particular observation surface and, hence, will improve the accuracy of the GNSS-R analysis[15, 12].

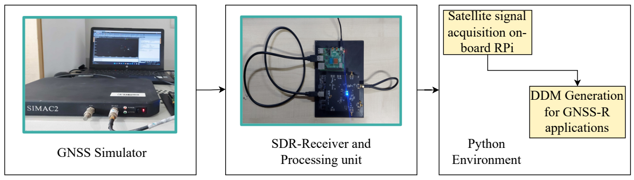


Figure 2. Multi-frequency GNSS simulator hardware and workflow

Now, in order to perform the multi-frequency GNSS-R analysis, it is essential to develop hardware and a software algorithm capable of receiving and processing the multi-frequency GNSS signals. The workflow and the hardware devices involved are shown in Fig.2. The hardware includes the GNSS simulator and receiver unit and a software processing block to process the GNSS signal. The multi-frequency GNSS signals are simulated using the Accord's SIMAC2 GNSS simulator. It has the capability to generate the multipath NavIC-L5 and GPS-L1 satellite signals. The BladeRF Software Defined Radio (SDR) Receiver is tuned to receive both the GPS-L1 and NavIC-L5 satellite signals. The BladeRF is interfaced via commands from the onboard processing unit, i.e. RaspberryPi. The script followed for receiving the multi-frequency GNSS signal is summarized and explained in Algorithm 1. The script is implemented in Raspberry Pi, and it collects both the NavIC-L5 and GPS-L1 signals simultaneously in a single run. The collected binary data files are read and further processed for satellite signal acquisition and DDM generation using the Python script.

Algorithm 1 Multi-frequency GNSS signal receiving script

STEP1: Receiving the NavIC-L5 signals

- set frequency rx 1176.45M
- set samplerate rx 16M
- set bandwidth rx 5M
- rx config file=NavICL5.bin format=bin n=1M
- rx start;
- rx
- rx wait
- rx

STEP2: Receiving the GPS-L1 signals

- change the rx frequency to 1575.42M
- change the filename to GPSL1.bin
- repeat the steps given in STEP1

OUTPUT: NavIC and GPS I/Q data (NavICL5.bin, GPSL1.bin)

3 Hardware SDR-Receiver Setup

The hardware setup for multi-frequency GNSS-R receiver development comprises a BladeRF SDR receiver and a single-board processing unit. The Nuand BladeRF x115 is used as a GNSS signal receiver unit. It can tune to a frequency range of 300 MHz to 3.8 GHz and, hence, is suitable for all the GNSS frequency bands (L1 (1575.42 MHz), L2 (1227.6 MHz) and L5 (1176.45 MHz)). The BladeRF SDR is used as a digital front-end device to receive the GNSS RF signals and downconvert the received GNSS signal to the baseband signal. The BladeRF digitized RF signal can be stored as a .csv or .bin file, which includes the In-phase and Quadrature phase (I/Q) GNSS signal. The BladeRF x115 is paired with a Nuand XB-300 amplifier. Nuand XB-300 amplifier is a Low-Noise Amplifier (LNA) with a typical gain of 21 dB at 2.0 GHz and a bandwidth ranging from 500 MHz to 5 GHz.

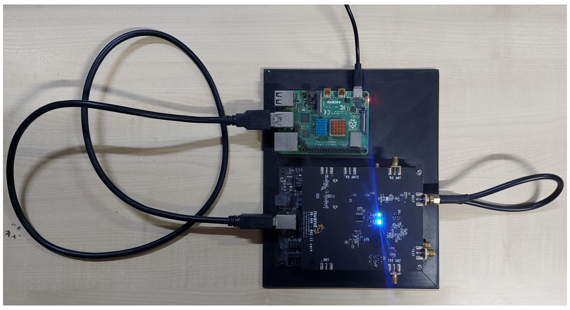
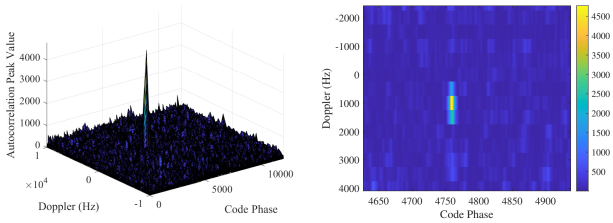


Figure 3. SDR-Receiver and on-board processing unit

The single-board processing unit used in the receiver setup is a Raspberry Pi 4 model B (RPi-4b). The RPi-4B model is used because it has a USB-3.0 port, which supports a faster data transfer rate. The Ubuntu 20.04 is installed on RPi-4B to interface the BladeRF SDR and process the stored GNSS signal. The GNSS signal is processed in a Python environment for satellite signal acquisition and DDM generation. The hardware SDR-Receiver setup is shown in Fig.3. The BladeRF x115 receiver port is connected to the GNSS signal simulator via a sma-to-sma connector to receive the GNSS RF signals. The BladeRF is further connected to RPi-4B using a USB 3.0 SS cable. The RPi-4B is connected to a 5V-DC power supply, and the bladeRF is powered by RPi-4B itself.

4 Results and Discussion

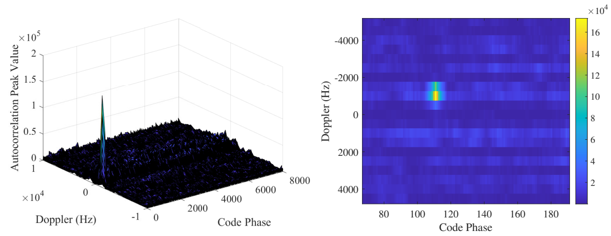
In the following section, the processing of multi-frequency GNSS signal received using the BladeRF is presented. The NavIC-L5 and GPS-L1 multipath satellite signals are collected as mentioned in Algorithm 1. The NavIC-L5 and GPS-L1 signals are collected at a sampling frequency of 12 MHz and a bandwidth of 5 MHz, with the centre frequency of 1176.4 5MHz and 1575.42 MHz, respectively. The received Earth's surface reflected GNSS signals are then processed onboard RPi for satellite signal acquisition and DDM generation. The Python codes are developed for processing the signals onboard RPi as running the MATLAB onboard RPi will be memory-consuming. The satellite signal acquisition and DDM for the NavIC-L5 signal are shown in Fig. 4. The NavIC satellite with PRN-2 is successfully acquired with a clear acquisition peak, as shown in Fig. 4a. The DDM obtained using the NavIC-L5 signals with power distribution around the specular point is shown in Fig. 4b, and this obtained DDM can further be used for GNSS-R analysis.



(a) CAF **(b)** DDM

Figure 4. CAF and DDM for NavIC-L5 signal for PRN-2

Similarly, the satellite signal acquisition and DDM for the GPS-L1 signal received using BladeRF are shown in Fig. 5. The signal acquisition for the GPS satellite with PRN-3 is shown in Fig. 5a, along with the DDM generated for the same satellite signal is shown in Fig. 5b. The multi-



(a) CAF **(b)** DDM

Figure 5. CAF and DDM for GPS-L1 signal for PRN-3

frequency GNSS signal analysed for a particular area of interest can further be used for GNSS-R analysis using the algorithm depending upon the application area. The results presented in Fig. 4 and Fig. 5 show the feasibility of using BladeRF SDR along with RPi to receive and process the multi-frequency GNSS signal simultaneously. The GNSS signals, along with the final DDM results, are sent to a local server as well.

5 Conclusion

This paper presents a hardware and software algorithm to receive and process multi-frequency GNSS signals. BladeRF SDR is used as a receiving unit along with RPi-4B to process the received signal onboard. The proposed hardware has a low power consumption, low cost and compact size. Hence, it can easily be used as a payload onboard a UAV or a LEO satellite for real-time GNSS-R applications. Future work focuses on analysing the utility of multiple observations for a particular area of interest. Also, the availability of different satellite signals for a certain specular point and, hence, the estimation of revisit time will also be analysed using the NavIC-L5 and GPS-L1 signals.

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