Software receiver design for GNSS-R using multiple GNSS satellites as transmitters

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Abstract: A novel global navigation satellite system-reflectometry (GNSS-R) software receiver and its preliminary experimental results are presented in this study. The antenna systems, the multi-channel radio-frequency front end, and the digital signal processing unit of this receiver are described in detail. With this developed software receiver, the signals in the Global Positioning System L1 band (GPS L1), BeiDou-2 B1, Global Navigation Satellite System L1, and Galileo E1 bands can be tracked and used as the transmissions of GNSS-R to obtain more information about the scattering properties of ground objects. The preliminary experimental results show that various GNSS signals can be successfully acquired and tracked by this receiver. Furthermore, when it was applied to the soil moisture estimation with the ground-based GNSS-R technique, a relative measure error of 5.79 and 1.39% can be obtained with GPS L1 and BeiDou-2 B1 signals, respectively, by comparing the retrieval results with the measuring results provided by a moisture metre.

1 Introduction

Multi-path signals, which include these signals scattered by the earth’s surface, are known as one of the significant sources causing the accuracy degradation in the global navigation satellite system (GNSS) and are usually eliminated to improve the positioning accuracy [1]. On the contrary, Martin-Neira [2] pointed out that the GNSS multi-path signals can be applied to the ocean altimetry in 1993 and subsequently proposed the concept of passive reflectometry and interferometry system [3]. Auber and Bibaut [4] further demonstrated that the Global Positioning System (GPS) signals reflected by the ocean surface can be successfully received during their airborne experiments in 1994. In recent years, a large number of ground-based, airborne, and space-borne global navigation satellite system-reflectometry (GNSS-R) experiments have been conducted by a series of research groups to evaluate the potential of applying the GNSS-R technique to remote sensing of sea state, soil moisture, sea ice, dry snow, oil slick, above-ground biomass, and so on [5].

As one of the critical components in the GNSS-R technique, the receiver has been attracting a lot of attentions from researchers in this field. Up to now, numerous specialised GNSS-R receivers have been developed for observation such as the GPS open-loop differential real-time receiver [6], the P(Y) and C/A ReflectOmeter [7], and the 3Cat-2 payload [8]. Most of the aforementioned receivers were designed to exploit the signal from only one GNSS constellation at a single band, such as the GPS L1 signal [9]. Compared to these receivers having a single signal source, a GNSS-R receiver, in which the multi-band signals from multiple GNSS constellations are adopted as transmissions, can have more applications. For example, it can be used to perform an inter-comparison of GNSS-R scattering properties as a function of autocorrelation properties of different available GNSS signals and to investigate the performance of different scientific applications as the function of central frequency, receiver bandwidth, signal polarisation, access technique, chipping rate, coherent and incoherent integration times, and satellite elevation angle [10]. However, this kind of GNSS-R receiver and its remote sensing applications have rarely been reported yet. Furthermore, as pointed out by Carreno-Luengo et al. [10], a further development of the GNSS-R technique is still constrained by the lack of experimental datasets in which the signals from multiple GNSS constellations at multi-band and dual-polarisation (right- and left-hand circular polarisation) are employed to detect the ocean, the land, and the cryosphere.

In view of the aforementioned problems, a novel software GNSS-R receiver, in which the signals in GPS L1, BeiDou-2 B1, Global Navigation Satellite System L1 (GLONASS L1), and Galileo E1 bands can be used as transmissions, has been developed to acquire experimental datasets with the ground-based GNSS-R technique. In this paper, we first provide an introduction to the characteristics of various available GNSS signals as well as the configuration of the developed receiver, which includes antenna systems, a multi-channel radio-frequency front end, and a digital signal processing unit. Next, the inner testing results of this receiver are given to demonstrate the effectiveness of processing algorithms. This is followed by the ground-based GNSS-R experimental results for soil moisture estimation. Towards the end, a conclusion of our work is briefly described.

2 Description of the developed receiver

2.1 Characteristics of GNSS signals

Taking into account the service type, the signals of GNSS satellites presently available are listed in Table 1. It can be seen from Table 1 that GPS L1 (C/A) signal has the same central frequency and chip rate as the Galileo E1(C) signal. Moreover, the central frequency of the BeiDou-2 B1(I) signal is lower than those of the GPS L1(C/A) and Galileo E1(C) signals, but its chip rate is twice larger. The central frequency of the GLONASS L1(C/A) signal, however, is not constant owing to the utilisation of the frequency division multiple access technique. The aforementioned differences in the

| Table 1 Presently available signals of GNSS satellites. |
|-----------------------------------------------------|
| GNSS signals | Central frequency, MHz | Chip rate, Mcps |
|-----------------|----------------------|-----------------|
| GPS L1(C/A)     | 1575.42              | 1.023           |
| BeiDou-2 B1(I)  | 1561.098             | 2.046           |
| GLONASS L1(C/A) | 1598.0625-1609.3125  | 0.511           |
| Galileo E1(C)   | 1575.42              | 1.023           |
oscillator uses a field-programmable gate array (FPGA) or a digital signal processing. Nevertheless, the receiver presented in this paper was GNSS-R because of its poor performance in real-time signal results in real time such as a delay-Doppler map (DDM). Its categories, i.e. the hardware and software receivers. The former processes the sampling data in an off-line mode and obtains the DDM using some specialised software systems such as the DDM disc array can also be used for recording the data in an off-line processing mode. In addition, a specialised USB chip CY7C68013 employed to implement the function of the USB bus.

2.2 Software receiver design

To date, GNSS-R receivers can be mainly divided into two categories, i.e. the hardware and software receivers. The former uses a field-programmable gate array (FPGA) or a digital signal processor to process the sampling data, and outputs the processing results in real time such as a delay-Doppler map (DDM). Its advantages include high efficiency, small amount of output data, and good real-time performance in signal processing. However, its cost is little high, and the software upgrade capability is poor. The latter processes the sampling data in an off-line mode and obtains the DDM using some specialised software systems such as the MATLAB. Its merits include simple configuration, high flexibility, and easy to upgrade. However, the amount of its output data is very large. Furthermore, this receiver is not suitable for the space-borne GNSS-R because of its poor performance in real-time signal processing. Nevertheless, the receiver presented in this paper was designed as a software receiver because it can be well suitable for the development of new algorithms and for the functional verification. Fig. 1 shows a block diagram of the developed receiver. One can see that this software receiver mainly consists of antenna systems, a multi-channel radio-frequency front end, and a digital signal processing unit. Some system specifications of this software receiver are listed in Table 2.

2.2.1 Antenna systems: With regard to the proposed software receiver, five receiving channels were used for the direct signal synchronisation and the reflected signal reception. As a result, five antennas were needed, where one antenna looked at the sky and other antennas pointed to the ground target area.

In practice, an omnidirectional right-hand circularly polarised (RHCP) antenna with a gain of 3 dB was used for receiving the direct signal from all of these GNSS satellites ~10° above the horizon. Moreover, a four-element patch antenna array with a gain of 14 dB was employed for receiving the reflected signal from ground objects due to its simplicity and small size. The operating frequency of this left-hand circularly polarised (LHCP) antenna array ranged from 1.52 to 1.66 GHz, well covering the carrier frequency of these GNSS signals given in Table 1. In addition, the 3 dB beam-width of this antenna array was ~30° to minimise the direct signal. Following each antenna element, a low-noise preamplifier with a gain of 27 dB, a low insertion loss band-pass filter, and a second stage amplifier with a gain of 15 dB were integrated to obtain a low noise figure for the developed receiver, to compensate the propagation loss for cables used to connect antenna systems to receiving channels, and to suppress the strong interference from adjacent satellites.

2.2.2 Multi-channel radio-frequency front end: As shown in Fig. 1, five super-heterodyne receiving channels were included in the radio-frequency front end. In practical operation, one receiving channel was usually connected to an RHCP antenna to receive the direct signal, and other receiving channels were connected to four LHCP array elements to receive the reflected signal. Actual received signals can be arbitrarily chosen by the operator. For example, each receiving channel can be adjusted to receive the signal in GPS L1, BeiDou-2 B1, GLONASS L1, and Galileo E1 bands, respectively, and to perform an inter-comparison of GNSS-R scattering properties as a function of autocorrelation properties of different available GNSS signals. It is worth mentioning here that five receiving channels had the same hardware architecture.

Each receiving channel in the developed receiver was divided into three parts, i.e. the radio frequency (RF) part, the intermediate frequency (IF) part, and the baseband part with a bandwidth of 2 MHz. The RF part contained a low-noise preamplifier with a gain of 27 dB and a band-pass filter to amplify the weak echoes and to further suppress the out-of-band signals. Following the RF amplification and filtering, the received signal was shifted to an IF of 140 MHz by mixing with the first local-oscillator (LO) frequency. The IF part was composed of a 140 MHz band-pass filter, four cascaded IF amplifiers with a total gain of 100 dB, and a 10 dB attenuator used to avoid the last amplifier from being saturated and to improve the impedance matching between these components. Although the signal bandwidth was different between GPS L1 (or Galileo E1), BeiDou-2 B1, and GLONASS L1 bands, only one band-pass filter with a passband of 6 MHz was used for the attenuation of image frequency and noise. Subsequent to the amplification and filtering in the IF stage, the IF signal was output to a specialised quadrature demodulator to generate the in-phase (I) and quadrature (Q) output signals. Here, the IF signal was mixed with two LO signals that were 90° apart in the phase. After a low-pass filter, I/Q signals were transferred to an analogue-to-digital converter (ADC) for digital signal processing. To maintain the coherence between five receiving channels, all the LO signals were phase locked with a common reference clock source of 10 MHz. Furthermore, a multi-channel direct digital synthesiser along with a phase-locked loop (PLL) were used to generate the LO signals due to its fine frequency resolution and good capability of frequency agility.

2.2.3 Digital signal processing unit: Subsequent to the analogue demodulation, I/Q signals were digitised by a 2-bit multi-channel ADC, where the sampling clock was 50 MHz. Following the ADC, digitised I/Q data were filtered by several finite impulse response digital filters in an FPGA chip, and then were transferred to a host computer via the universal serial bus (USB) bus. To avoid the packet dropout in data transmission, a 512-Gb disk array controlled by the FPGA was employed for the data caching. This disc array can also be used for recording the data in an off-line processing mode. In addition, a specialised USB chip CY7C68013 belonging to the family of the FX2 USB 2.0 transceiver was employed to implement the function of the USB bus.
After receiving the sampling data via the USB bus, the signal processing in the host computer mainly included two parts, i.e. the acquiring and tracking of the direct signal and the computation of DDM. Regarding the acquiring and tracking of the direct signal, local pseudorandom codes were first generated. Then, these pseudorandom codes were circularly correlated with the received direct signal in the frequency domain to search the maximum correlation value for all the possible pseudorandom noise sequences. Once the maximum correlation value was found, its phase value and Doppler shift were estimated using a conventional PLL. The extracted Doppler shift removed the frequency variation from pseudorandom codes in the received direct signal. Locally generated pseudorandom codes were then delay synchronised to the Doppler-eliminated direct signal. Moreover, a conventional delay locked loop was used for delay tracking. When the direct signal was tracked steadily, the navigation message was decoded by a phase transition detector. This is due to the fact that if adjacent navigation bits have a different polarity, the resulting phase transition is 180° or −180°. On the contrary, if the polarity is the same, there is no phase change. In terms of the navigation acquisition, pseudorandom codes in the local pseudorandom codes to form the local reference signal. Furthermore, the local reference signal was correlated with the reflected signal received by an LHCP antenna array. To achieve a finer propagation delay between the ground object and the receiver, one chip duration was oversampled by 16 times with an interpolation method. Similar to the direct signal acquisition, pseudorandom codes in the local reference signal was circularly correlated with the received echoes to search the maximum correlation peak. Before estimating the propagation delay and Doppler shift from the maximum correlation peak, a coherent integration with a period of 1 ms and a non-coherent integration with a number of 1,000 were performed in turn to improve the signal-to-noise ratio. Finally, a DDM was depicted in terms of the extracted propagation delay and Doppler shift.

3 Experimental results

3.1 Inner testing results

Since the Galileo navigation system is still under construction and the software developed for acquiring and tracking of GLONASS L1 signals is on-going, the signals in GPS L1 and BeiDou-2 B1 bands were exploited in our experiments.

It can be seen from Fig. 2 that eight GPS satellites (PRN 3, 4, 16, 22, 26, 29, 31, 32) and five BeiDou satellites (PRN 1, 3, 6, 7, 9) can be successfully acquired and tracked with the developed software receiver, demonstrating the effective operation of hardware and signal processing software.

3.2 Soil moisture estimation

Several ground-based GNSS-R experiments were conducted to estimate the soil moisture with the developed software receiver on 20 February 2018. Furthermore, the method described in [11] was used to retrieve the soil moisture. During these experiments, a moisture metre was employed for measurement at the same time. Table 3 shows a comparison of soil moisture estimation by using the GNSS-R with BeiDou and GPS satellites, and a moisture metre, respectively.

One can see from Table 3 that the values of soil moisture are a little high. This is due to the fact that these experiments were conducted after a heavy rainfall. Furthermore, a significant fluctuation can be found in the soil moisture estimation by using not only the GNSS-R technique but also the moisture metre. This may be because the observation area is covered by vegetation. In addition, compared to the soil moisture measured by the moisture metre, one can find that the relative measure error is 5.79% when GPS L1 signals were used as the transmissions of GNSS-R, and this error changes to be 1.39% when BeiDou B1 signals were adopted. The reason for this phenomenon is that the BeiDou satellite used in these observations was a geostationary earth orbit satellite. Therefore, when the pointing direction of the receiving antenna is determined, the system observation configuration is fixed consequently, and a series of stable measurements can be performed to achieve a better accuracy.

Table 3  Comparison of soil moisture estimation by using the GNSS-R with BeiDou B1 and GPS L1 signals, and the moisture metre, respectively.

| Measuring numbers | GNSS-R with BeiDou B1 signal (%) | GNSS-R with GPS L1 signal (%) | Moisture metre (%) |
|-------------------|---------------------------------|------------------------------|--------------------|
| 1                 | 29.35                           | 32.75                        | 28.74              |
| 2                 | 29.35                           | 35.75                        | 26.65              |
| 3                 | 30.75                           | 35.85                        | 30.14              |
| 4                 | 30.25                           | 35.00                        | 24.71              |
| 5                 | 29.80                           | 32.15                        | 32.29              |
| mean value        | 29.90                           | 34.30                        | 28.51              |

Subsequently, the propagation delay, the Doppler shift, and the phase value were added into the locally generated pseudorandom codes to form the local reference signal. Furthermore, the local reference signal was correlated with the reflected signal received by an LHCP antenna array. To achieve a finer propagation delay between the ground object and the receiver, one chip duration was oversampled by 16 times with an interpolation method. Similar to the direct signal acquisition, pseudorandom codes in the local reference signal was circularly correlated with the received echoes to search the maximum correlation peak. Before estimating the propagation delay and Doppler shift from the maximum correlation peak, a coherent integration with a period of 1 ms and a non-coherent integration with a number of 1,000 were performed in turn to improve the signal-to-noise ratio. Finally, a DDM was depicted in terms of the extracted propagation delay and Doppler shift.

![Fig. 2 Acquiring and tracking results of (a) GPS satellites and (b) BeiDou satellites](http://creativecommons.org/licenses/by/3.0/)
4 Conclusion

A novel software GNSS-R receiver, in which the signals in GPS L1, BeiDou-2 B1, GLONASS L1, and Galileo E1 bands can be adopted as transmissions, was presented. In terms of the experimental results, one can find that the GPS and BeiDou satellites can be successfully acquired and tracked with the developed software receiver, demonstrating the effectiveness of hardware and signal processing software. In addition, ground-based GNSS-R experimental results for soil moisture estimation demonstrate that the developed software receiver can be used to obtain experimental datasets with the ground-based GNSS-R technique in which the signals from multiple GNSS constellations were employed to detect the land. In future work, this developed receiver will be used to perform GNSS-R experiments in which the GLONASS L1 and Galileo E1 signals are used as transmissions. Furthermore, a variety of experiments will be conducted to obtain the experimental datasets in which the signals from multiple GNSS constellations at multi-band and dual-polarisation (right- and left-hand circular polarisation) are employed to detect the ocean, the land, and the cryosphere.

5 Acknowledgments

This work was supported in part by the National Natural Science Foundation of China under grant no. 41504007, in part by the Natural Science Foundation of Hubei Province under grant no. 2016CFB3383, and in part by the Open Research Fund of State Key Laboratory of Information Engineering in Surveying, Mapping and Remote Sensing under grant no. 16P01. The authors would also like to thank the financial supports from China Scholarship Council (no. 201706275026) and Hubei Chenguang Talented Youth Development Foundation.

6 References

[1] Fu, Z., Hornbostlilfe, A., Hammesfahr, J., et al.: ‘Suppression of multipath and jamming signals by digital beamforming for GPS/Galileo applications’, GPS Solut., 2003, 6, (4), pp. 257–264
[2] Martin-Neira, M.: ‘A passive reflectometry and interferometry system (PARIS): application to ocean altimetry’, ESA J., 1993, 17, (4), pp. 331–355
[3] Martin-Neira, M., Caparrini, M., Font-Roselllo, J., et al.: ‘The PARIS concept: an experimental demonstration of sea surface altimetry using GPS reflected signals’, IEEE Trans. Geosci. Remote Sens., 2001, 39, (1), pp. 142–150
[4] Aubert, J.C., Bibaut, A.: ‘Characterization of multipath on land and sea at GPS frequencies’. Proc. Inst. Navigation ION GPS-94 Conf.: Part 2, Paris, France, September 1994, pp. 1155–1171
[5] Jin, S.G., Zhang, Q.Y., Qian, X.D.: ‘New progress and application prospects of global navigation satellite system reflectometry (GNSS + R)’, Acta Geod. et Cartographica Sin., 2017, 46, (10), pp. 1389–1398
[6] Nogues-Correig, O., Gali, E.C., Campderros, J.S., et al.: ‘A GPS-reflections receiver that computes Doppler/delay maps in real time’, IEEE Trans. Geosci. Remote Sens., 2007, 45, (1), pp. 156–174
[7] Carreno-Luengo, H., Camps, A., Ramos-Perez, L., et al.: ‘Experimental evaluation of GNSS-reflectometry altimetric precision using the P(Y) and C/A signals’, IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens., 2014, 7, (5), pp. 1491–1500
[8] Olive, R., Amezaga, A., Carreno-Luengo, H., et al.: ‘Implementation of a GNSS-R payload based on software-defined radio for the 3Cat-2 mission’, IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens., 2016, 9, (10), pp. 4824–4833
[9] Lowe, S.T., Kroger, P., Franklin, G., et al.: ‘A delay-Doppler-mapping receiver system for GPS-reflection remote sensing’, IEEE Trans. Geosci. Remote Sens., 2002, 40, (5), pp. 1150–1163
[10] Carreno-Luengo, H., Camps, A., Via, P., et al.: ‘3Cat-2 – An experimental nanosatellite for GNSS-R earth observation: mission concept and analysis’, IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens., 2016, 9, (10), pp. 4540–4551
[11] Yan, S.H., Gong, J.Y., Zhang, X.X., et al.: ‘Ground based GNSS-R observations for soil moisture’, Chinese J. Geophys., 2011, 54, (11), pp. 2735–2744