



## Cross-platform evaluation for Software Defined Radio GNSS receiver

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### Abstract

Nowadays, Global Navigation Satellite Systems (GNSS) and complementary positioning technologies are expanding, offering new resources to the localization process. Software Defined Radio (SDR) is emerging as an alternative to developing flexible and multi-technology solutions in a dynamic environment. This work describes the main operational signals in GNSS systems that can be used in a multi-constellation, multi-frequency receiver. Also, it proposes the reception of GNSS signals using a modular architecture based on SDR. The SDR GNSS receiver is confronted with two platforms operating as Front-Ends: ADALM-PLUTO and Ettus USRP X310 - UBX160. The results, corresponding to the capture of GPS signals in the L1 band, show the impact of the platform's performances in the satellite acquisition signal process.

### 1 Introduction

The most widely used and widespread navigation system is the Global Navigation Satellite System (GNSS), thanks to its worldwide coverage and free provision of absolute positioning solutions. With the increasing adoption and availability of GNSS signals, frequencies, and services, user technologies have evolved and spread across many devices and applications. The fact that GNSS technology is one of the most scalable and frequently used implies the design of solutions that offer modularity and flexibility. Therefore, the goal of the present work includes a modular approach for the localization process, starting from a GPS receiver. Software Defined Radio (SDR) is an excellent solution in developing systems that integrate different technologies. Our SDR GNSS receiver scheme incorporates a first Front-End stage and then the digital processing chain. The Front-End performs three fundamental functions: filtering, downconversion of the analog signal, and digital conversion. SDR platforms can implement two different receiving topologies: heterodyne or homodyne. A heterodyne receiver has multiple downconversion stages where amplification and filtering are applied, increasing complexity and costs and eliminating the image band. In addition, the use of a direct baseband conversion in GNSS systems can verify aliasing when performing Doppler compensation or detection.

This work includes the evaluation of two different SDR

platforms in the satellite identification process. ADALM-PLUTO and Ettus USRP with UBX-160 daughterboard, implement direct downconversion in the L1 frequency band. The use of the USRP platform is widely spread in SDR GNSS receivers [1, 2] and the good accuracy levels in the local oscillator (LO) guarantee the correct satellite identification. In the case of the ADALM-PLUTO platform, it is little used as Front-End because the LO accuracy levels exceed the expected threshold of the Doppler effect. Recently, some works have focused on error correction using a previous calibration process. In [3] a calibration process using the bladeRF 2.0 platform as the transmitter is proposed. Although the works consulted do not make an extended analysis on the limitations of SDR platforms in GNSS environment, it is important to highlight the open-source solution proposed in [4]. The GNSS-SDR project is based on the architecture proposed by Fernandes-Prades et.al that includes the generic use of a Front-End and a software receiver inside a Linux or MacOS environment. The receiver is highly configurable, but at the same time has many Software dependencies (including GNU Radio). Another limitation of GNSS-SDR is that it does not allow interaction with other localization techniques. In addition, it is difficult to modify all the configuration aspects of the acquisition process. The calibration functionalities for frequency corrections are limited and not functional.

This paper describes the main operational signals in GNSS systems that can be used in a multi-constellation, multi-frequency receiver. Our receiver includes a scalable modular architecture that uses, as Front-Ends, SDR platforms. The GNSS receiver scheme is evaluated for the specific case of GPS signals in L1 band. Subsequently, the performance of two SDR platforms is analyzed from the point of view of signal identification capability, local oscillator accuracy, and carrier frequency detection ability. The acquisition is performed in a controlled environment, simultaneously and using a scheme where the antenna is shared from a power divider.

### 2 GNSS signals characteristics

GPS was the first to provide global coverage and currently has 31 satellites in orbit. It offers four "open" or "civil" type signals distributed in the L1, L2 and L5 bands: L1-C/A, L1C, L2C and L5C. The GPS uses the CDMA technique to send different signals on the same radio frequency,

and the modulation method used is Binary Phase Shift Keying (BPSK). The Pseudorandom Noise Code (PRN) is an unique Gold code, of 1 millisecond in length at a chipping rate of 1.023 Mbps. Although the coding frequency is the same, the modulation used determines a minimum receive bandwidth of 2.046 MHz for L1-C/A and 4.092 MHz for L1C. The L5C signal was designed for users requiring Safety of Life (SoL) applications. There are two signal components: the in-phase component (L5I) with data and ranging code, both modulated via BPSK onto the carrier; and the quadrature component (L5Q), with no data but also having a ranging code BPSK modulated onto the carrier.

Galileo satellites transmit permanently three independent Code Division Multiple Access signals, named E1, E5 and E6. E1 supports the OS, CS, SoL and PRS services. It contains three navigation signal components in the L1 band and two components, E1-B and E1-C, are open access signals with unencrypted ranging codes accessible to all users. The MBOC modulation is used for the E1-B and E1-C signals, which is implemented by CBOC. The E5 signal is subdivided into signals denoted E5a and E5b. The composite signal E5 can be processed as a single large-bandwidth signal or as two different signals. In the receiver implementation the impact of bandwidth is very important, an approach that includes both components (E5a + E5b) requires more than 50 MHz, while a separate treatment implies a bandwidth of 20.46 MHz for each of the components.

The Beidou System, in phase III, provides global coverage for navigation through 35 satellites which support open services SPS (Standard Accuracy Signal Service). Also in this case, and with the objective of non-interfering frequency band allocation, MBOC and AltBOC spreading modulation are used for the B1C and B2 signal respectively. This has a direct impact on the minimum bandwidth necessary to receive the signals coming from the BeiDou constellation. The bandwidth required for the B1C signal, centred at 1.57542 GHz, is 32.736 MHz and for the B2 signal, centred at 1.17645/1.20714 GHz, is 20.46 MHz.

In contrast to the other constellations, each Glonass satellite broadcasts at a particular frequency within the band. This frequency determines the frequency channel number of the satellite and allows receivers to identify the satellites (with the Frequency-division multiple access technique). The CDMA Open Service Navigation Signal in L3 frequency band is called L3OC and consists of two BPSK(10) components: data and pilot. These components are in phase quadrature with each other and L3OCd is delayed 90°.

### 3 SDR GNSS receiver

We define the SDR GNSS receiver as an SDR-based system consisting of three main blocks: Front-End, Core, and Position solutions. The Front-End, consist in an antenna and an SDR device that implements the down-conversion process directly in base-band in two components: in-phase and quadrature. Subsequently, both components are digital-converted, filtered and sent to the core of the software receiver.

The core is composed of the GNSS signal acquisition and tracking block and can be performed in parallel. The acquisition process is implemented to identify the available satellites and a first estimation of the frequency and phase of the carrier [5, 6]. After verification of positive acquisitions, the tracking block follows the evolution of the signal. When the detected signals are correctly tracked, it moves on to the demodulation of the navigation information and the measurement process which results in the calculation of the position. Finally, the results of the complete process are encoded in the compatible formats: RINEX, NMEA or KLM. Below, the GNSS SDR receiver scheme is applied from the implementation in GPS environment. However, the GNSS receiver scheme can interact with other localization techniques, i.e. it can be extended to hybrid localization. The location and navigation data provided by other technologies can be added directly into the "measurements" block or at a subsequent stage, from the receiver output file.

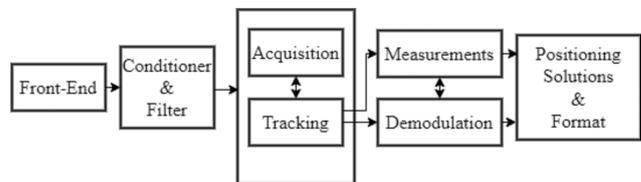


Figure 1. GNSS SDR receiver block diagram.

#### 3.1 SDR GPS receiver

For the implementation of the first stage of the GPS SDR receiver we use two different devices: USRP X310 and ADALM-PLUTO. Both devices have a Zero-IF or direct downconversion architecture, which decomposes the signal in phase and quadrature. Subsequently, both components are digitized and sent to the receiver core. Considering that the C/A code is present in the quadrature component after downconversion process, equation 1 represents the superposition of all the components captured by the antenna in L1 band.

$$S_{L1} = \sum_{k=1}^N PCA_k(t)N(t) \sin [2\pi (f_{L1} + f_{D_k}) + \varphi_{ik}] + n(t) \quad (1)$$

$K$ ,  $N$ ,  $P$ ,  $CA_k(t)$ ,  $N(t)$ ,  $f_{D_k}$  and  $\varphi_{ik}$  represent the received satellite sequence number, the total received satellite number, the  $k$ -th satellite power, the C/A code, the received ephemeris data  $k$ -th satellite, the  $k$ -th Doppler frequency and the initial frequency phase, respectively. The  $n(t)$  component represent the noise. To simplify, the multipath components and other phenomena are modeled in the noise representation.

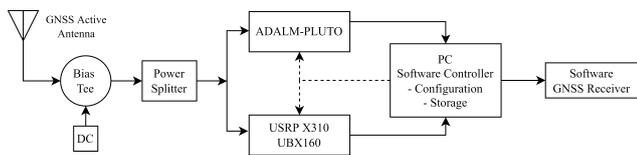
The method used in the acquisition process is Parallel Code Phase Search Acquisition. The idea is to perform a correlation with the incoming signal and a local PRN in frequency domain. The in-phase and quadrature digital components coming from the front-end are multiplied by a locally generated carrier. The result corresponds to the C/A component when compensating for the Doppler effect suffered by

the signal and other errors introduced in the downconversion process. In order to sweep the frequency range, 41 iterations with 250 KHz steps are performed. Each carrier multiplication process is converted in the frequency domain using the Fast Fourier Transform and multiplied by the conjugate of the local PRN code. This multiplication process in the frequency domain corresponds to the circular cross-correlation operation in the time domain. The result of the multiplication is transformed into the time domain by an inverse Fourier transform. The absolute value of the output of the inverse Fourier transform represents the correlation between the input and the PRN code.

## 4 Results

In our SDR-platform experiment, we propose to use the same RF reception chain formed by an active GPS antenna, a Bias Tee, and a power divider. Subsequently, the SDR platforms receive the configuration and the command of reception through software from a computer that controls the storage of the samples. We capture blocks of 1667 ms at 10 MSps in order to maintain temporal continuity in the acquisition (footnotes: Adalm-Pluto limits). The results correspond to three captures performed at different time instants in a low-interference indoor environment of the campus of the University of Aquila, Italy.

The DAM1575A23.3V antenna was used to capture the

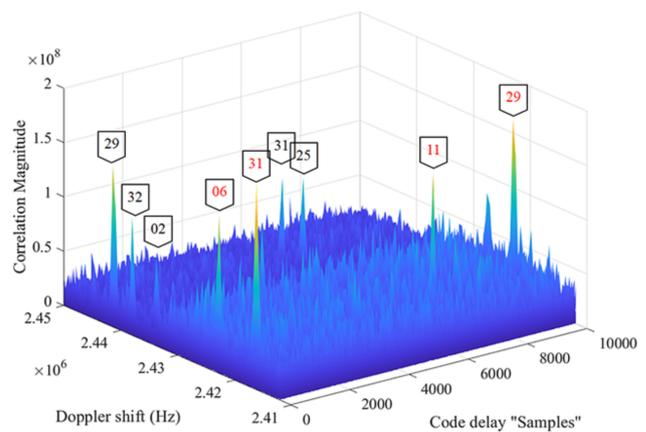


**Figure 2.** Multi-platform experimentation scheme.

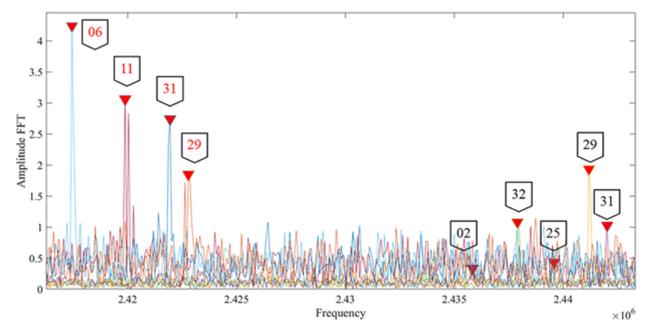
1.57542 GHz L1 GPS signal. This antenna has a voltage standing wave ratio (VSWR) of 1.5:1, bandwidth of  $\pm 5$  MHz, and 50 ohm of impedance. The antenna include a LNA/Filter with 28 dB of gain and 7dB attenuation of over 20 MHz around the center frequency (GPS L1). As noted in the block diagram of Figure 2, the antenna is fed by the Bias Tee TW154 Regulated 0.5 to 3GHz, 3.3V. The resistive Power Divider SMA 50 Ohm (Huber&Suhner) was used for the signal split: one component goes to the ADALM-PLUTO platform and the other to the USRP X310 with UXB160 daughterboard. For the SDR platforms' configuration process, we use a personal computer connected to both devices. The start of the acquisition is performed simultaneously, and the samples are stored in the PC. The samples from each device are converted to complex, defining the real part as the in-phase components and the complex part as the quadrature components. The sample blocks are passed to the GPS receiver software for processing and analysis.

The Ettus Research USRP X310 is a high-performance, scalable software defined radio (SDR) platform for designing and deploying next generation wireless communications systems. The hardware architecture combines two

extended-bandwidth daughterboard slots covering DC – 6 GHz with up to 120 MHz of baseband bandwidth [ettus]. For this experiment, Ettus UBX-160 RF front-end daughterboards have been chosen for their characteristics in the receiver path. For frequencies in the 0.5 - 6 GHz range, Ettus UBX-160 performs the direct downconversion process. This feature allows a parity evaluation of the acquisition process, as the ADALM-PLUTO platform also features a zero-IF architecture. Certainly, other elements distinguish them in the GNSS field. A crucial aspect is the stability and accuracy of the local oscillator. The level of accuracy (without calibration) presented by the Ettus platform (2.5 ppm) exceeds ten times the value of the ADALM-PLUTO (25 ppm). In a first test, with a range of 10 KHz



**Figure 3.** Result of the acquisition using ADALM-PLUTO Platform (black font) and Ettus USRP X310 - UBX160 (red font).



**Figure 4.** Frequency allocation for ADALM-PLUTO Platform (black font) and Ettus USRP X310 - UBX160 (red font) signal acquisition.

in the frequency sweep, we check the failure of the acquisition process with the Adalm-Pluto device. This failure means that the frequency shift exceeds the frequency search range. Extending the frequency range detects the presence of GPS signals in the range of 20 KHz above the center frequency. This problem requires a considerably longer processing time concerning samples captured with the USRP platform. The USRP platform tested positive acquisitions by keeping a 10 KHz sweep around the frequency 1.57542

GHz. The precision values of the local oscillator of the USRP platform indicate a maximum frequency shift near 2 KHz, enough for the case of the receiver at a stationary position on the ground. These results highlight the limitations of using the Adalm-Pluto platform in the GNSS signal acquisition process. The frequency shift indicates the need for a calibration process before the acquisition.

Figure 3 shows the acquisition process results for a block of 1,667 seconds. The USRP platform concentrates the correlation peaks around the center frequency L1, while the Pluto platform experiences a significant shift. In addition, in the carrier detection process through the maxima criterion using the FFT, a low level in the peaks detected with the ADALM-PLUTO platform is verified. For example, the values corresponding to PRN 02 and PRN 25 do not correspond to absolute maximums. These low values of FFT render the correct detection of the carrier frequency impossible. In the case of the USRP platform, all detected satellites are global maximums, indicating a higher value in the Carrier-to-Noise ratio. The signals are captured in time

**Table 1.** Result of GPS signal acquisition using GnsLogger application, ADALM-PLUTO and Ettus USRP X310 - UBX160.

Acquisition Instrument	PRN 02	PRN 06	PRN 11	PRN 12	PRN 16
PRNGnsLogger App	x x x	x x o	o o x	x x x	o o o
Ettus USRP X310 - UBX160	o x x	x o o	x x x	o x x	o o x
ADALM-PLUTO	x o x	o o o	o x o	o o o	o o o
Acquisition Instrument	PRN 22	PRN 25	PRN 29	PRN 31	PRN32
PRNGnsLogger App	x o o	o x o	x x x	x x x	x x o
Ettus USRP X310 - UBX160	o x x	o o o	x x x	x o o	o x x
ADALM-PLUTO	o x o	x o o	x x x	x o o	x o o

blocks of 1.667 seconds and processed in off-line mode. The experiment was repeated three times at a uniform time distance of 10 minutes. In each block the acquisition is performed with the two platforms. In order to verify the positive acquisitions of our receiver, it is compared with the GnsLogger v3.0.3.1 application. The measurements made are described in Table 1. All the satellites detected, with each tool, during the three-time captures are recorded. The symbol  $x$  indicates a positive acquisition and  $o$  a negative one. In addition, in the case of red color indication, the value of the carrier frequency was not correctly determined due to the low level of the Carrier-to-Noise Ratio. Thus, the ADALM-PUTO platform acquisitions for the PRN 02 and 25 satellites can be considered incomplete. The comparative analysis is focused on the two SDR devices, the GnsLogger application is used to contrast the satellite presence. The mobile device used was the Xiaomi Redmi note 9 Pro smartphone model m2003j6b2g. The GnsLogger application uses Augmented-GNSS, i.e., it combines location information provided by the network serving the mobile device on which it is installed. However, the performance of the pure GNSS receiver, using the USRP device as front-end, presents a number of hits similar to that experienced by the application. When the ADALM-Pluto device is used, the number of hits decreases by almost half to the Ettus device.

## 5 Conclusion

This article provides a summary of updated GNSS signal characteristics. Identifying new open-civil satellite services reinforces the thesis of using the multi-constellation approach in the localization process. The new operational services indicate a uniformity in the medium access schemes (Glonass L3OC-CDMA).

The proposal of a GNSS SDR receiver, although not new, includes interaction with other localization techniques and presents a flexible modular structure. This scheme generalized the proposal [4], which contemplates specific functions for Front-End and Receiver Software. The acquisition of real GPS signals demonstrated the limitations of the SDR platforms in the GNSS domain. A fundamental aspect is identified in the accuracy of the local oscillator. The case of the Ettus USRP X310 -UBX160 platform presents a low-frequency shift that does not affect the GPS identification process. However, the ADALM-PLUTO SDR platform has an accuracy incompatible with the frequency search range implemented by GNSS receivers. Moreover, from the Carrier-to-Noise ratio point of view, some limitations directly impact the correct identification of the carrier.

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