Analysis of GNSS Signals using the Robert C. Byrd Green Bank Telescope

Marco Pini[1], Dennis M. Akos[2]

[1]Politecnico di Torino, Electronics Department
C.so Duca degli Abruzzi n.24, 12138, Torino, Italy
Phone: +392276436, e-mail: marco.pini@polito.
[2]University of Colorado, Aerospace Engineering Sciences
429 UCB, Boulder, CO 80309-0429
Phone: +303 7352987, e-mail: dma@colorado.edu

Abstract. Recent experiments have shown that a valuable way to monitor the quality of the signal broadcast by Global Navigation Satellite System (GNSS) satellites is to use a high gain antenna. Signal monitoring experiments are important to check the health of the electronic devices on board of the satellite just after the launch, but also to characterize the signal quality over time. In fact, for high performance applications such as Global Positioning Systems (GPS)-based aircraft navigation and landing systems, even small errors due to signal distortions must be considered in the error budget.

This paper describes the experiment performed in Green Bank, West Virginia (U.S.A.), where a 110 meter high gain antenna has been used to track several GNSS satellites. After the description of the system set up, the paper will present interesting results obtained in post processing through a toolset, specifically developed for this type of analysis.

1 Introduction

Using traditional antennas and receiving hardware, the received power of the GPS signal is below the thermal noise floor. This implies that the received signal broadcast by the satellites is masked by the noise; thus the chips of the Coarse Acquisition (C/A) and Precision (encrypted) P(Y) codes are not discernable. The signal processing relies on the gain obtained from the spread spectrum nature of the signal structure. In fact, the receiver is able to demodulate the navigation data and recover the precise time of transmission by correlating the incoming signal with a local version of the known spreading code transmitted by satellites [1]. GPS satellites operate at an altitude of over 20,000 Km and the transmitted power is not sufficient to observe their complete signal structure directly using conventional demodulation methods.

An alternate approach is to use a high gain antenna to receive the signal transmitted by the satellites and perform measurements directly on the signal at the Radio Frequency (RF) output. The high gain antenna provides a positive Signal-to-Noise Ratio (SNR), such that both the individual chips and the navigation bits can be demodulated without performing the despreading procedure.

This paper presents the analysis on the data sets collected using a high gain antenna. After introducing the motivation of the work, the experimental setup and the data collection approach will be explained. The paper will then focus on the most important results obtained in post processing through an analysis toolset developed for this type of experiment. Such a toolset has been developed on the basis of the previous work carried out by Mitelman [8]. The most significant diagrams will be shown and the differences between the signals broadcast by various satellites will be underlined.

2 Background and Motivation

Using traditional GPS antennas and receiving hardware, the signal at the front end output is masked by noise. The received signal power spectral density is approximately 20 dB below the thermal noise floor and both the navigation data bits and the chips of the spreading code are not discernable. GNSS receivers are based on the "de-spreading" process and assume that the Pseudorandom (PRN) codes are perfect square wave signals. This assumption can not be taken for some high accuracy applications like aircraft navigation, where even small deformations of the signal must be considered to assure the integrity of the positioning procedure. Thus, for the most demanding users of satellite navigation, it is important to characterize the nominal signal structure in order to detect minimal variations resulting from hardware-based errors.

A high gain antenna can improve the Signal-to-Noise Ratio (SNR) at the front end output and drastically increase the signal observability.

As an example, Fig. 1 (a) clearly shows that the signal at the front end output using a commercial GPS antenna looks like noise, but, looking at Fig. 1 (b), one can see that the high gain antenna drastically increases the SNR and the chips of both the C/A and the P(Y) codes become visible.

Recently, high gain antenna measurements have been employed to characterize the signal quality of GPS satellites belonging to different blocks [3] [4]. This type of investigation started on the early 90's when an anomalous behaviour was observed on Satellite Vehicle Number (SVN) 19. After several investigations, it was found out that the problem was due to a misalignment between the Coarse Acquisition (C/A) and the Precision (encrypted) (P(Y)) codes [5].

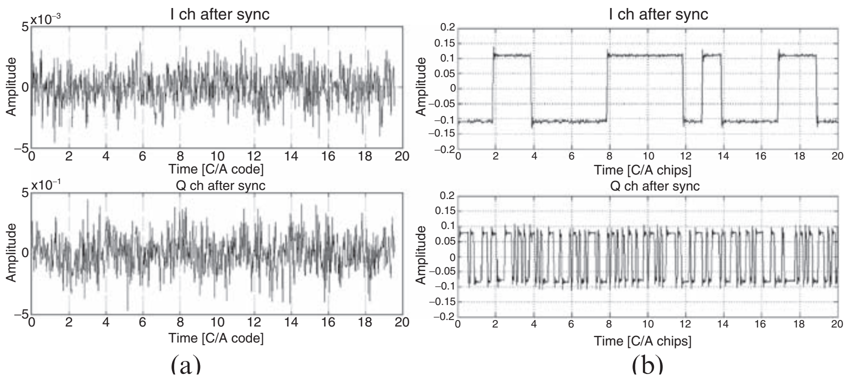

Fig. 1. Inphase and quadrature signal at the front end output (a) using a commercial GPS antenna and (b) a high gain antenna.

It was only possible to fully understand the problem source using a high gain parabolic antenna. In fact, such an antenna guaranteed that the signal power rose above the thermal noise floor. Today, the signal analysis with high gain antennas is widely used by scientists. For example, the first Galileo satellite (GIOVE-A) has been closely monitored just after the launch by radio telescopes in Redu (Belgium), Chilbolton (UK) and Weilhein (Germany) as it is described in [6].

3 System Set Up Description

Figure 2 shows the block diagram of the system used to collect data during the experiment performed on the 24th of July 2005 in Green Bank, West Virginia (USA).

In this particular case, the Robert C. Byrd radio telescope was used. It is the world's largest fully steerable radio telescope equipped with a 110 meter dish diameter antenna (see Fig. 3). The GBT antenna has a gain of approximately 70dB in the L-band and guarantees the received GPS signal power rises above the noise floor. The surface of the telescope can be adjusted and the overall structure is a wheel-and-track design that allows the telescope to view the entire sky above 5 degrees elevation [7].

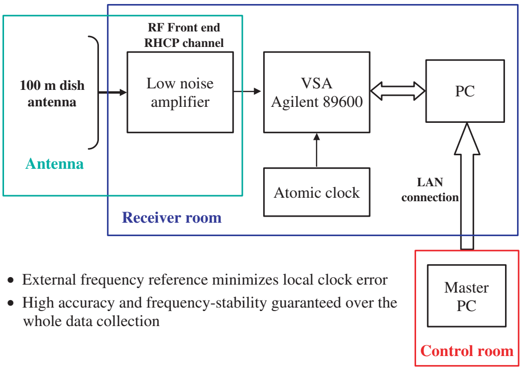

Fig. 2. Block diagram of the system used to collect data.

Fig. 3. Robert C. Byrd radio telescope, Green Bank, West Virginia USA.

The received signal was amplified, filtered and finally sent to a Agilent 89600 Vector Signal Analyzer (VSA) which was used to downconvert the signal to a lower intermediate frequency and then to a digital format. The raw samples of the signal were stored into a disk for post processing analysis. The VSA was slaved to a 10 MHz rubidium clock, which guaranteed high accuracy and frequency stability over the whole duration of the data collection.

The VSA was installed inside the receiving room at the top of the telescopes and was controlled from a remote centre, through a Local Area Network (LAN) connection. It is important to underline that all the instruments installed in the receiving room were previously tested in the lab, in order to avoid breakdowns during the experiment.

The experiment lasted about 12 hours and thanks to a good data collection schedule, 24 satellites were observed.

4 Post Processing Results

Monitoring of the GNSS Signal Quality Via a High Gain Antenna

With a 70 dB gain antenna the structure of the signals transmitted by GNSS satellites is well visible at the front end output. As an example, Fig. 4 shows a zoomed view of the C/A and the P(Y) code, once the unknown phase offset between the incoming carrier and the local oscillator has been recovered in post processing with a Phase Lock Loop (PLL).

The signal is no longer masked with noise and it is possible to use appropriate diagrams (e.g.: IQ diagrams, eye patterns) usually used in the communication field, to better analyze the signal structure.

The block diagram depicted in Fig. 5 summarizes the main features of the software toolset developed to support the GNSS signal quality analysis performed using high gain antennas.

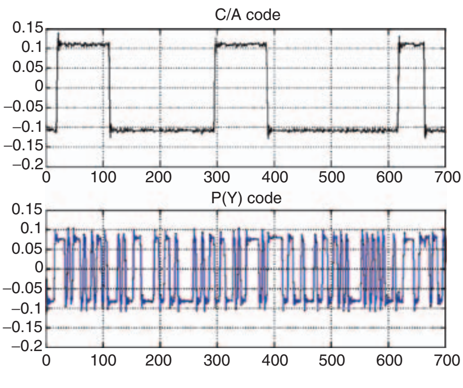

Fig. 4. Inphase (C/A code) and quadrature (P(Y) code) signals broadcast on L1 by satellite SVN 24 (a), IQ diagram (b).

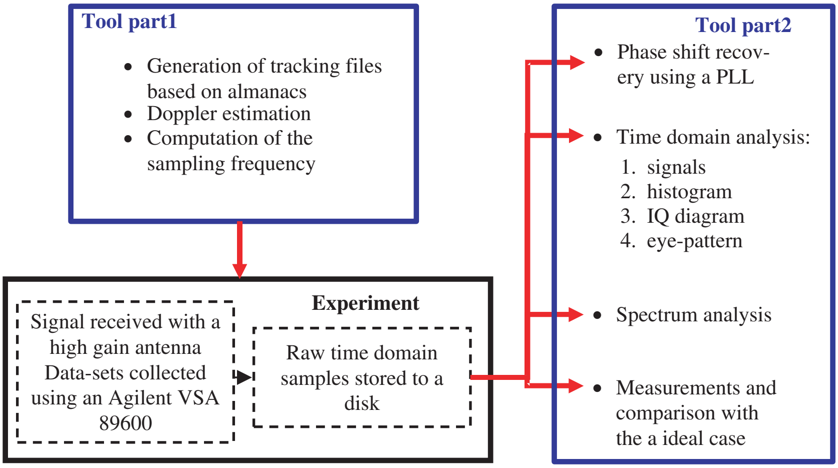

Fig. 5. Structure of the software toolset used in the quality monitoring of GNSS signals.

Such a software toolset is composed by two parts:

- **Tool part 1** generates the tracking files used during the experiment to aim the antenna at the satellite under test. Furthermore, it is useful to predict the Doppler effect on the incoming signal and compute the desired sampling rate. Note that if the dithered sampling frequency [8] [9] is implemented, the computation of the sampling rate require an accurate estimation of the code rate, which is affected by Doppler and changes as the satellite moves.
- **Tool part 2** is used to analyze the collected data sets in post processing. This part of the tool automatically generates important plots of interest (i.e.: IQ diagrams, histograms, eye patterns. . .). These plots are compared to the theoretical ones and used to quantify possible distortions or anomalies on the signal structure.

As an example of the plots that can be obtained with the developed toolset, Fig. 6 compares the IQ diagrams of the signal broadcast by Satellite Vehicle (SV) 24 and SV 59. The IQ diagrams show the Quadrature signal versus the Inphase signal and reveals additional details that are not readily apparent from the time domain data [4].

While the first IQ diagram does not show particular anomalies, the IQ diagram in Fig. 6 (b) does not match the ideal one (grey) when only the C/A code change signs. For this satellite it was found out that the ratio between the amplitudes of the C/A and the P(Y) codes is approximately 1dB lower than 3dB, which is the expected value.

The IQ diagram is also extremely useful to check the synchronization between the C/A and the P(Y) codes. In fact, when both C/A and P(Y) codes change sign at the same time, a transition occurs along one of the diagonals of the diagram [4]. Ideally, the diagonals pass through the origin, but looking at real diagrams, it is evident that this is not the case. SV 59 shows an asymmetry across the origin, while for SV 24 the chip transitions are more symmetrical. It was interesting to verify that all the satellites of Block IIR present the distortion observed on SV 59, while no satellite of

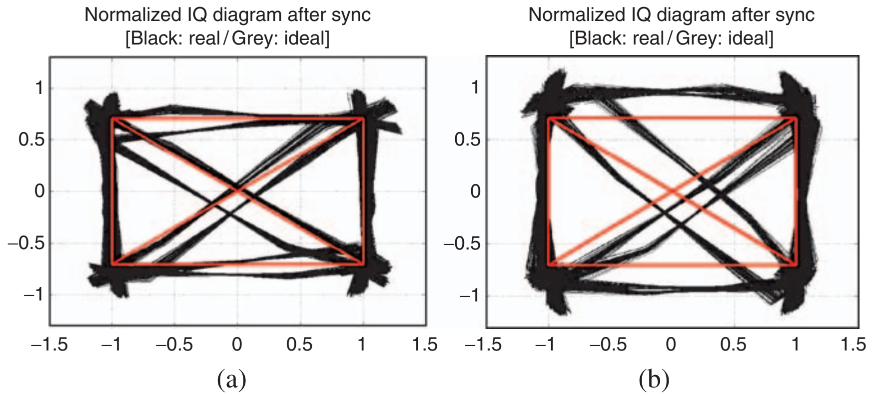

Fig. 6. Normalized IQ diagrams of the signal broadcast on L1 (a) by SV 24 and (b) by SV 59, compared to the theoretical IQ diagrams (grey).

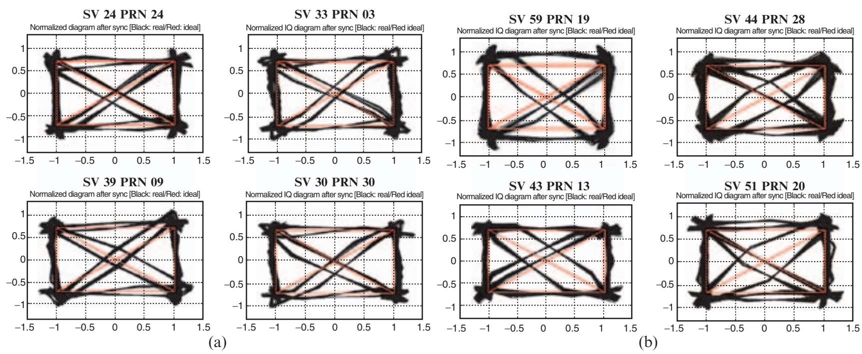

Fig. 7. IQ diagrams of the signal broadcast on L1 by several satellites belonging to (a) Block IIA and (b) Block IIR.

Block IIA has this unusual asymmetry on the IQ diagram of the L1 signal. Figure 7 compares the IQ diagram of 8 different satellites. Four of them (SV 24, SV 33, SV 39, SV 30) belong to the Block IIA and are gathered together in Fig. 7 (a), while those of Block IIR (SV 59, SV 44, SV 43 and SV 51) are shown in Fig. 7 (b).

For all the satellites of Fig. 7 (b) the distortion across the origin is quite evident and is due to a not perfect synchronization between the C/A and the P(Y) codes, which can be quantified with an average delay as it has been shown in [4].

Monitoring of the GNSS Signals Using Innovative Signal Processing Techniques

The described analysis can be further improved using a particular sampling rate, called dithered sampling frequency. Such a sampling frequency follows the same approach adopted for repetitive signals in sampling oscilloscopes and has been proposed for use in GNSS by Mitelman [8].

Considering repetitive signals (as GNSS signals after a proper Doppler removal stage), this technique allows for a high resolution of the time domain representation through a samples superimposition in post processing.

Moreover, the dithered sampling frequency preserves the synchronization. Thus, the samples of the signal can be averaged over time and the SNR can be further increased in post processing. These advanced signal processing techniques have been adopted in GNSS signal monitoring experiments using conventional receiving hardware/antenna and their effectiveness has been shown in [9].

However, both the dithered sampling strategy and the averaging technique can also be used with high gain antennas. In this case, the noise contribution is further reduced in post processing and the resolution is increased, thus the structure of the PRN code broadcast by the satellite becomes extremely clear. Figure 8 shows a zoomed view of one of the C/A code chips broadcast by SV 24, when both the dithered sampling rate and the averaging technique are applied to the signal received with the Green Bank telescope. In this case, the virtual sampling rate achieved in post processing by the use of the dithered strategy is approximately equal to 460 MHz, whereas the SNR increment due to the averaging technique is equal to 11.46 dB.

The chip shape is well defined and it is even possible to note the ringing effect due to the VSA filtering. In conclusion, it is possible to state that these innovative post processing techniques allows for performing accurate measurements on the time domain signal.

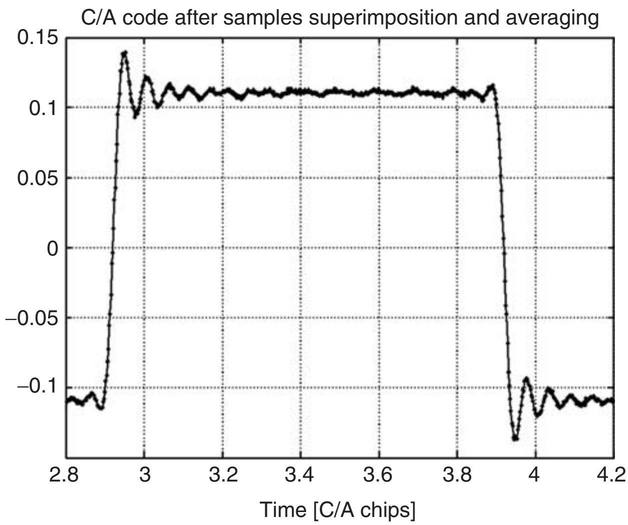

Fig. 8. Zoomed view of a PRN chip, when both the dithered sampling frequency and averaging technique are applied to the signal received with the Green Bank Telescope.

5 Conclusion

This paper has mainly focused on the analysis of GNSS signals. The experiment performed at Green Bank (West Virginia, USA) on the 24th of July 2005, has been described. In the experiment the "Robert C. Byrd" telescope was used to observe the signals broadcasted by GNSS satellites. The high gain antenna drastically increases the SNR and makes the raw code chips directly observable on a vector signal analyzer. This type of investigation is extremely useful to check the quality of the signal broadcast by new satellites as soon as they are in orbit. The same type of investigation has been performed in Europe in January 2006 to quality monitor the first Galileo satellite, called GIOVE-A [6].

The paper has also shown the main features of the software toolset specifically developed to analyze the collected data sets in post processing. It helps to monitor the quality of GNSS signals through appropriate plots and measurements. It has been shown how it is possible to detect differences between satellites as SV 24 (Block IIA) and SV 59 (Block IIR) as well as other possible anomalies.

The paper has also shown that the sampling resolution and the fidelity of the plots can be improved, using the dithered sampling frequency, which achieves high sampling rates preserving synchronization. Furthermore, it has been shown that the noise contribution can be further reduced by averaging several sequences of superimposed samples. It is important to remark that both the dithered sampling strategy and the averaging procedure can be easily applied to noisier signals. This means that the presented experiment can be repeated using smaller directive antennas or a multiple antenna array, reducing the overall cost of the experiment.

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