NOVEL MEASUREMENT SYSTEM FOR GNSS SIGNAL ANALYSIS WITH HIGH-GAIN ANTENNAS

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ABSTRACT

This paper describes a novel measurement system for recording baseband I/Q samples of GNSS signals with a very high bandwidth of up to 600 MHz and over a very long time of 8 hours or more. The recording device is a data grabber based on a high-performance digitiser. Together with a high-gain antenna it allows very detailed GNSS signal analysis for both polarisations (RHCP and LHCP).

The challenges of using a data grabber instead of a signal analyser are addressed. Test results using a simple sine wave and navigation signals from a Galileo and GPS satellite are presented and compared with results obtained using a signal analyser.

1. INTRODUCTION

Global Navigation Satellite Systems (GNSS) have become a central infrastructure of our modern world in recent years. They are used in many critical applications, and our dependence on accurate and readily available navigation signals is expected to increase in the coming years, for example for autonomous transport. It is therefore essential to monitor the quality of navigation signals and provide warnings in the event of significant degradation in positioning accuracy. There are numerous sensor stations scattered around the globe that support real-time GNSS performance monitoring and/or can be used for performance analysis. However, sensor stations usually provide only post-correlation data generated by navigation receivers. And as it was already shown in [1, 2], the performance analysis is valid for the GNSS receiver used, but may be different for other receiver types. In addition, post-correlation results do not allow detailed failure or interference analysis and typically there is no full calibration of the receiver data. Even if an anomaly can be detected using post correlation data, root-cause analysis is often not possible.

It is therefore important to study in detail the quality of the signals emitted by the GNSS satellites. As these signals arrive at Earth with a power density well below the noise level, such studies can ideally be performed using high gain antennas. High antenna gain allows the signal structure to be lifted above the noise floor, eliminating the need for correlation to see the full spectrum of the signals emitted by GNSS satellites. Such measurements are virtually multipath free, whereas the measurements at sensor stations with normal geodetic antennas are affected by multipath. Additionally, the high directive beam pattern reduces the possible impact of interfering signals from outside of the antenna main lobe. Detailed signal analysis using baseband I/Q sampling allows measurement of the signal in space at chip and waveform level and characterisation of both analogue and digital signal distortion [3, 4].

DLR has a long tradition in detailed GNSS signal analysis using high-gain antennas. The first measurements were performed in 2005/06 and 2008 for the first two Galileo satellites Giove-A and Giove-B, respectively [5, 6]. Since then numerous measurements have been performed as part of the IOT for newly launched Galileo satellites and studies on further GNSS constellations. Several anomalous satellite behaviours have been detected and analysed, e.g. [7, 8, 9].

2. DLR'S PREVIOUS MEASUREMENT SYSTEM

The high-gain antenna used is a 30 m diameter Cassegrain reflector antenna [10]. Figure 1 shows a photo of the antenna, which is located in Weilheim, Germany, about 40 km from the DLR site in Oberpfaffenhofen.

Figure 1 DLR's 30 m high-gain antenna in Weilheim/Bavaria

This antenna has a gain of approximately 50 dBi at L-band and its feed has outputs for both polarisations: right-handed circular polarization (RHCP) and left-handed

circular polarization (LHCP). It is calibrated to support absolute power level measurements.
A signal analyser with a bandwidth of up to 160 MHz bandwidth and a recording time of up to 2 s was used as the recording instrument. The dynamic range of this instrument is better than 105 dBc for 16-bit operation.

3. REQUIREMENTS FOR EXTENDED MEASUREMENT SYSTEM

Signal analysers are the standard recording instruments for GNSS signal analysis. They have many advantages such as high dynamic range, high flexibility in terms of measurement parameters such as centre frequency, resolution bandwidth, and they offer live signal viewing features which are very useful during signal measurements. However, they are very limited in recording time, which is only up to a few seconds.

For many types of analysis, such as infrequent events, it is advantageous to have recording times which are much longer than a few seconds. Ideally, the signal should be recorded for the entire time that a satellite passes over the station, which can be up to 10 hours.

In addition, signal analysers have a single RF input and can only record one polarisation at a time. In certain cases, it is advantageous to record synchronously both co- and cross-polarisations (RHCP and LHCP), so a recorder with two synchronised input channels would be required.

To maintain the phase relationship between different bands (signals), the entire GNSS spectrum from ~1150 MHz to ~1650 MHz must be recorded simultaneously. The fully synchronous capturing of multiple bands and signal over full satellite pass provide the opportunity to perform analyses like code-code-coherency or code-carrier-coherency with the raw samples instead of using GNSS receivers.

In the recent years, a new generation of recording devices – data grabbers based on high-speed digitisers – has reached a level of performance that allows them to meet the above requirements and to be used as GNSS signal recording devices over a period of several hours.

Data grabbers use a similar architecture to digital oscilloscopes, called baseband sampling, where the entire signal is sampled. In this architecture, the signal is only amplified or attenuated in the analogue domain to the required level and filtered with a low pass filter to avoid false or alias products in the processed results. Frequency conversion, downsampling and further filtering are performed in the digital domain and require significant processing power.

In contrast, signal analysers use bandpass sampling, where the signal is downconverted and band-limited before being digitised. Sampling is then performed at the intermediate frequency (IF), significantly reducing the sampling rate required by the digitiser.

4. DATA GRABBER

DLR has extended its GNSS signal recording system with a powerful data grabber capable of synchronously recording of I/Q samples for both polarisations of navigation signals in the 1100 MHz to 1700 MHz frequency range at a sampling rate of up to 5 GS/s. The data grabber is based on a Spectrum M5i.3357-x16 dual channel high speed digitiser [11]. The digitiser provides 10 GS/s on one channel or 5.0 GS/s on two channels and offers a bandwidth of 3 GHz. The ADC used has a resolution of 12 bit and a memory of 8 Giga-samples (16 Gbytes).

A special 8-bit mode is provided to reduce the amount of stored data by half compared to the 12-bit mode. Figure **2** shows a block diagram that shows the working principle of the data grabber.

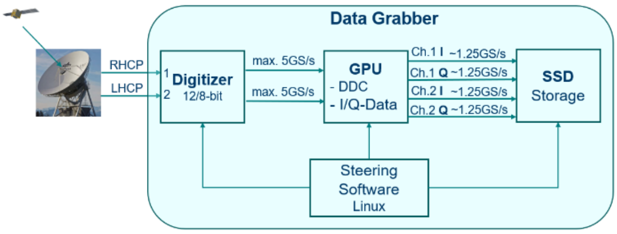

Figure 2. Block diagram of the data grabber

Signals for both polarisations (RHCP and LHCP) from tracked GNSS satellites are first filtered with a low-pass or band-pass filter to suppress the unwanted frequency bands and then amplified to match the full signal range of the digitiser. The digitiser has two input channels which are synchronised and it is possible to fine tune the both channels with a step of 3 ps. The incoming signals are then digitised at up to 5 GS/s covering all frequencies from 0 to 2.5 GHz according to the Nyquist sampling criterion.
The sampled signal is transferred directly to a powerful GPU where all the signal processing takes part. The transfer to the GPU can be done at 12-bit or 8-bit depth.

As mentioned in the previous section, the data grabber uses a direct sampling architecture. The incoming signal is converted to a lower frequency signal with a lower sampling rate. This is done by multiplying the incoming signal with a complex sine wave at an intermediate frequency (IF). Figure 3 shows the down-conversion process for a GNSS band between 1100 MHz and 1700 MHz.

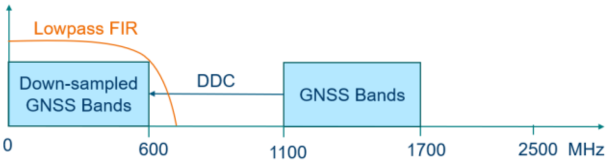

Figure 3. Down conversion of the GNSS signals

In this case, the IF used for the DDC is set to 1100 MHz. Multiplying the input signal by the complex sinusoid at the IF produces images centred at the sum and difference frequencies. The sum frequency is then suppressed using a low-pass filter (e.g. FIR). The whole process results in a complex baseband (I/Q) representation of the original signal. As the highest frequency is now 600 MHz, the sampling frequency can now be reduced to as low as 1200 MHz, according to the Nyquist theorem. The reduction of sampling frequency is done by simply decimating the results obtained with the original sample rate and the decimation factor must be a natural number. In the example above, a maximal decimation factor of 4 can be used, reducing the original sampling rate of 5 GS/s to 1.25 GS/s.
The digital down-conversion described above is performed in parallel for both channels.

The down-sampled signals are then stored in four files written in parallel to a fast storage SSD. Each file contains only one component (I or Q) of only one channel. The files contain only digitised signal samples in Int8 or Int16 format without any header or timestamp. The file size can be set to as low as 1 GB for easy processing. When recording on both channels, only 8-bit depth (Int8) data can be stored on the SSD in real time. For one channel, the full 12 bits provided by the digitiser can be stored in Int16 format.

In the example above, four streams of 8-bit data are created at 1.25 GS/s, resulting in 5 GB/s of storage. A recording time of 8 hours results in 144 TB of data produced. The purchased data grabber has a storage capacity of 240 TB, allowing over 13 hours of data to be stored.

5. DATA REDUCTION STRATEGIES

Recording I/Q samples of GNSS signals for both polarisations over a long period of time results in a very large amount of data, as described above.

Reducing the recorded bandwidth to 500 MHz (1150-1650 MHz) results in 115 TB for a recording time of 8 hours. A further reduction in the amount of stored data can be achieved by not storing the entire frequency spectrum with GNSS bands at once, but by down-converting and down-sampling only the frequency bands of interest, e.g. E1, E5 and E6 for Galileo or L1, L2, and L5 for GPS. In the case of GPS, storing only three bands of 50 MHz each would result in only 35 TB of data for an 8-hour recording period. The phase relationships between the bands would still be preserved. The down-conversion process is shown in Figure 4, where bands L2 and L5 are processed together.

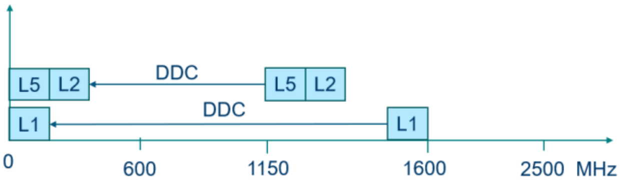

Figure 4. Down conversion of GPS signals

For Galileo the resulting storage requirement for E1 (60 MHz), E5 (100 MHz), and E6 (60 MHz) would be approximately 60 TB for 8 hours.
It is also possible to process the three bands separately. In this case the down-conversion must be performed 6 times for both polarisations, resulting in 6 DDCs processes running in parallel.
The data grabber uses the Nvidia Quadro RTX A6000 48 GB GPU. This high-end GPU has enough processing power to support 6 DDCs in parallel. It also allows the use of digital filters with a very high number of coefficients, resulting in very steep filter characteristics and very good suppression of higher frequencies.

6. NUMERICAL RESULTS

To characterise the properties of the data grabber and compare its performance with that of a signal analyser, a series of measurements were made using a simple sine wave and navigation signals from a 5 m high gain antenna.

A simple sine wave (continuous wave) was generated by a signal generator at a frequency of 1300 MHz. The following data grabber settings were used:

- 8-bit mode
- Sampling rate 4 GS/s
- Downshift frequency 1200 MHz
- Decimation factor 3
- FIR filter bandwidth 600 MHz

Figure 5 shows the spectrum calculated by FFT from recorded I/Q samples for the data grabber and a signal analyser for different levels of the input signal. After down-conversion, the frequency of the sine wave has been shifted to 100 MHz in the case of the data grabber. As might be expected, the noise floor and the spurious are lower for the signal analyser than for the data grabber. This is due to the higher dynamic range of the signal analyser (16 bit) compared to the data grabber (8 bit). But even for the data grabber, the SNR is ≈ 48 dB, a value that makes it suitable for signal analysis with the 30 m antenna without significant loss of accuracy. The input power of -3 dBm set on the output of the used signal generator was slightly too high for the digitiser, so that a spurious at 1500 MHz appeared, which is almost not visible for lower input signal levels. Reducing the maximal power level by a factor of four has no significant effect on the quality of the results.

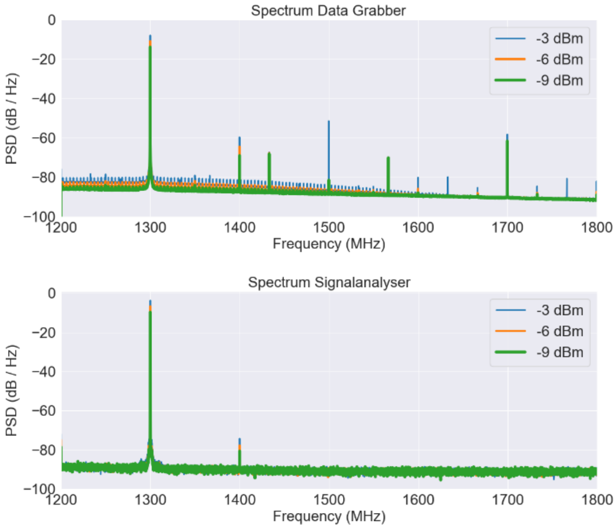

Figure 5. Spectrum computed from recorded I/Q data from the data grabber (above) and a signal analyser (below) for different input power levels.

After performing numerous measurements with simple sine waves and various settings the data grabber was connected to a 5 m high-gain parabolic antenna located on the roof of the Institute of Communications and Navigation in Oberpfaffenhofen. This antenna provides a gain of approximately 31-33 dBi at L-band.

Figure 6 shows the spectrum of the GPS satellite G03 which was calculated from the I/Q samples recorded by the data grabber with a FIR filter bandwidth of 600 MHz. The signal from the antenna was filtered using a multiband GNSS diplexer prior to connection to the data grabber. The data grabber was used in 8-bit mode with a sampling rate of 4 GS/s and a decimation factor of 3. This resulted in a reduced sampling frequency of 1.33 GS/s. The spectrum of all GPS bands is clearly visible. The peaks which are visible on the right-hand side of the L2 band are most probably caused by amateur radios which are allowed to use this frequency spectrum.

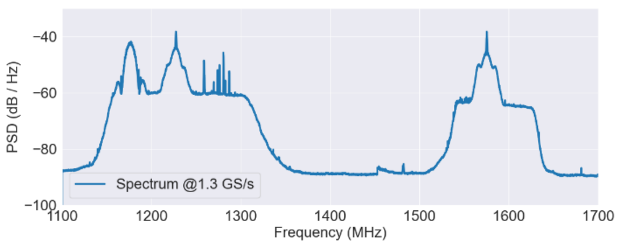

Figure 6. Spectrum of GPS G03 satellite computed from recorded I/Q data from the data grabber.

As the signal analyser used (see Sec. 2) could not store I/Q samples with such a large bandwidth, separate measurements were made for each GPS band.

Figure 7 shows the comparison for the L1 band, where different signal levels were measured with the data grabber. There is very good agreement between the results obtained using the signal analyser and the data grabber. In addition, it can be seen, that even attenuation of the signal from the optimum attenuation level (8 dB) to 13 dB has no negative effect on the quality of the results obtained.

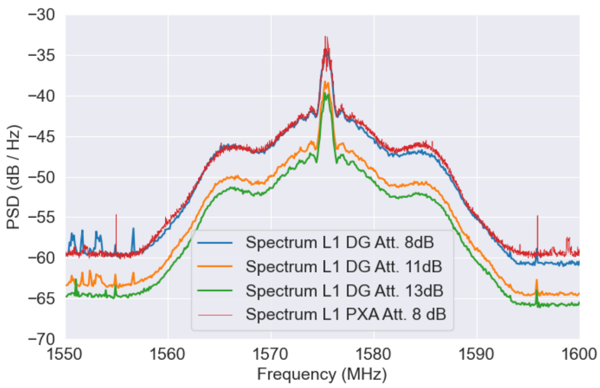

Figure 7. Comparison of L1 spectrum of GPS G03 satellite computed from recorded I/Q data from the data grabber and the signal analyser PXA.

Figure 8 shows the E1 spectrum of the Galileo E08 satellite, computed using I/Q samples recorded by the data grabber in 8-bit mode. Again, the full signal structure is very well visible.

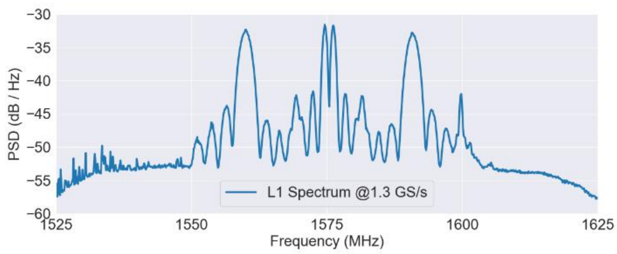

Figure 8. E1 spectrum of Galileo E08 satellite computed from recorded I/Q data from the data grabber.

The additional peak at 1600 MHz is due to a signal transmitted by a GLONASS satellite which was flying nearby during the measurements and was visible through the antenna main beam or a side lobe.

7. CONCLUSIONS

Data grabbers are an ideal complement to signal analysers for monitoring GNSS signal quality. They provide solid performance in terms of amplitude accuracy and dynamics, and offer unique features such as very high bandwidth and continuous data acquisition over hours. They are more challenging to use than signal analysers because they require more careful signal preparation (amplification, filtering) and the right settings to avoid aliasing and exploit the full dynamics available.

Without the need for live view capability, extremely high dynamics and full flexibility in analyser settings such as centre frequency or sample rate, data grabbers are likely to replace signal analysers in various/future applications.

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