A Multi Antenna Receiver for Galileo SoL Applications

Manuel Cuntz, Holmer Denks, Andriy Konovaltsev, Achim Hornbostel,
Michael Meurer, Arno Schroth
German Aerospace Center (DLR), Institute of Communications and Navigation

ABSTRACT

One of the main features of the Galileo Satellite Navigation System is integrity. To ensure a reliable and robust navigation for Safety of Life applications, like CAT III aircraft landings, new receiver technologies are indispensable. Therefore, the German Aerospace Centre originated the development of a complete safety-of-life Galileo receiver to demonstrate the capabilities of new digital beam-forming and signal-processing algorithms for the detection and mitigation of interference. To take full advantage of those algorithms a carefully designed analogue signal processing is needed. The development addresses several challenging questions in the field of antenna design, frontend development and digital signal processing. The paper will give an insight in the activity and will present latest results.

INTRODUCTION

Future navigation services provided by upcoming global navigation satellite systems like Galileo will require corresponding improvements on the navigation receiving systems. Therefore, the Institute of Communciations and Navigation of the German Aerospace Center originated the development of a GNSS prototyping platform for research on navigation receivers with improved capabilities. The improved capabilities mainly focus at interference and multipath mitigation by utilization of array antenna processing techniques [1], [2].

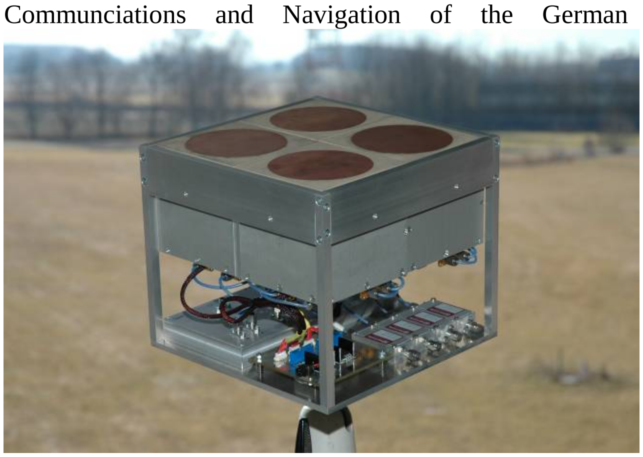

Figure 1: 2x2 Antenna Array

Interference and multipath signals can cause serious performance degradations, which cannot be tolerated for Safety-of-Life (SoL) applications. New digital beamforming and signal-processing algorithms will contribute to overcome this problem by suppressing interference and multipath signals and improving the reception of useful line-of-sight satellite signals and, thus, enable a more accurate and reliable navigation solution [4]-[9]. The aim is to develop a complete SoL receiver demonstration system which includes the whole receiving chain including array antenna, RF front-end, digital signal processing, navigation solution and integrity assessment [9].

This paper presents an overview of the whole platform architecture. In its first realization the platform consists of a two times two array antenna and a subsequent four channel RF front-end for GPS/Galileo L1 signal reception, see Figure 1, which are constructed in a modular way. The received signals are down-converted, digitized and recorded for post processing.
In the first part of the paper the two by two antenna array is discussed. Basic design issues of the front-end concerning interference robustness and low noise are pointed out in the second part. The following part gives a brief overview of the four channel analogue to digital conversion board developed by DLR. Subsequently, the paper introduces the architecture of the FPGA implementation. After that the basic digital receiver design and its implementation in an offline SW-receiver are described. The next chapter provides an overview of the digital beam-forming and direction finding techniques that are used. Finally, early results are presented.

1. ANTENNA ARRAY

To achieve the demanding requirements, a dual frequency receiver concept with a 4 by 4 antenna array was chosen for the main architecture. Through its capability of simultaneously steering multiple independent beams to the satellites by exploiting the digital beamforming concept, this receiver is able to fulfill the high demands on reliability. By detection and suppression of interference it also enhances integrity and availability. The proposed antenna array allows a polarisation selective reception as well as adaptive nulling and sidelobe suppression. Through this, the impact of

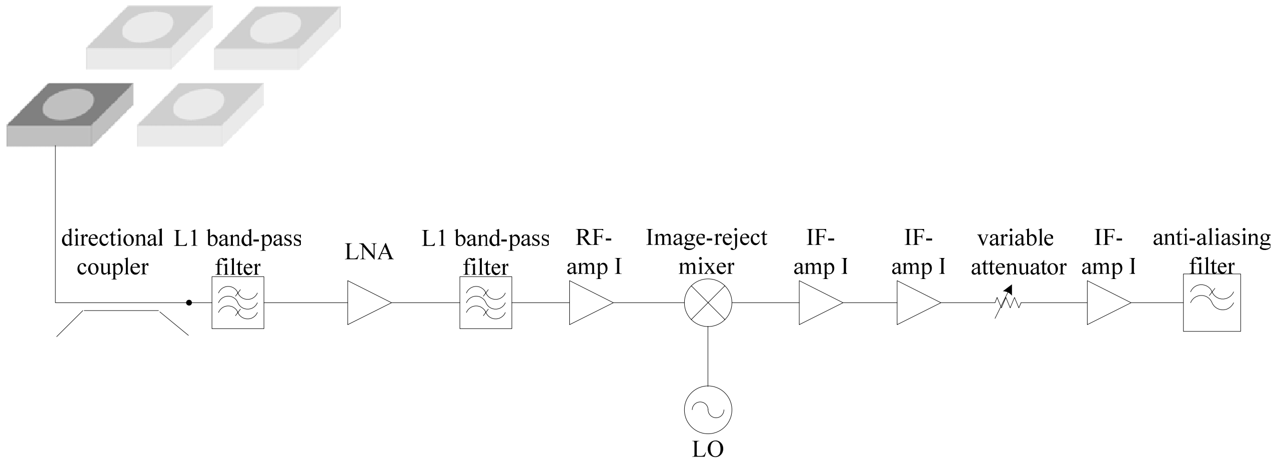

Figure 3: Front End Architecture

intended and unintended interferers as well as of multipath can be dramatically reduced.

The ideal antenna array for GNSS applications should provide a constant gain for any direction subjected to a beam-steering operation and a radiation pattern with perfect right-hand circular polarization (RHCP) in the complete hemisphere and for the whole frequency band from 1164 MHz to 1591 MHz, to cover all Galileo signals. However, in practical terms this scenario becomes much different and physical limitations require the definition of realistic specifications in order to achieve the best possible overall performance for an application-oriented demonstrator [1].

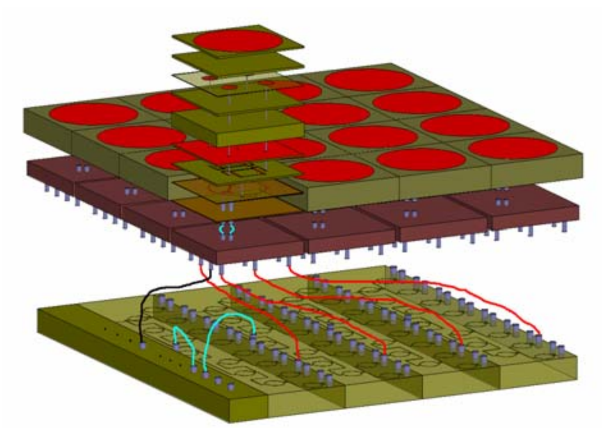

Figure 2: Architecture of the antenna array

A very important constraint for the antenna array is its physical size. On the one hand it should be small enough to make it suitable for mobile applications and related aerodynamical needs but on the other hand it must be sufficiently large to meet the demands for gain and beam-steering properties. Figure 2 shows a suggestion for the future architecture of the array. It consists of 16 antenna elements in a 4 x 4 modular configuration where the overall size does not exceed 40 x 40 cm^2 [2].

The single resonator is a circular patch antenna with broad-band impedance matching and high cross-polarisation suppression over the whole frequency range [3].

2. FRONT END

A. RF stage

The first part of each front end is a directional coupler which allows calibrating the RF front ends in phase and magnitude. Subsequently a first RF band-pass filter is utilized in order to suppress out-of-band interference, e.g. GSM.and UMTS Considering the critical position in the RF chain the insertion loss of this filter is very low and thus minimizing the impact on the noise figure of the whole system. The drawback of this low insertion loss is the relatively wide pass band. For this reason a second RF filter is necessary immediately after the low noise amplifier. This second filter has still a 32 MHz 3 dB bandwidth, which allows the reception of the Galileo L1 services. Subsequently, the signal is amplified by a RF amplifier and fed to the mixing stage and down converted to IF.

B. IF Stage

By the mixing process the frequencies symmetrical to the local oscillator frequency (LO) are transformed to IF. Although the unwanted frequency bands are suppressed by the RF band-pass filters, a strong interferer might still have an intense impact. Therefore, the down conversion of the front end is done by image-reject mixers which suppress the mirror frequencies by more than 35 dB, i.e. the out of band attenuation by the filters is more than 55 dB; overall, the unwanted images are suppressed by more than 90 dB.

After the analogue down conversion to an intermediate frequency of 62.5 MHz the signal is amplified by three amplifiers. A variable attenuator is used to adjust the power levels for the following A/D-conversion.

An anti-aliasing filter was carefully designed to keep the differential group delay low and to achieve a difference between pass band and stop band of more than 40 dB to prevent aliasing.

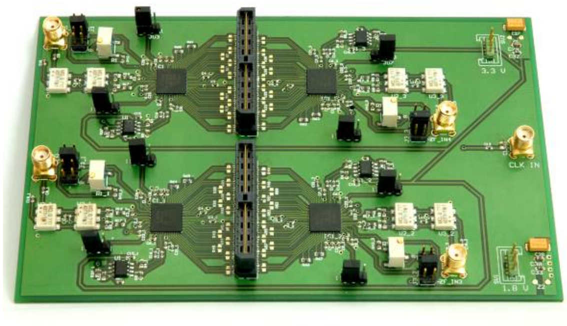

Figure 4: Quad ADC Board

3. A/D-CONVERSION SOFTWARE-BASED SIGNAL PROCESSING

This analogue IF signals are converted to the digital domain using the DLR own developed Quad ADC board, see Figure 4. This board contains four high speed ADCs, which sample synchronously the incoming data of the four antenna front ends with a rate of 250 MSPS. This gives the opportunity to sample signals with large bandwidth like Galileo E5 later on and allows an easy $f_s/4$ down conversion implementation in the FPGA. The resulting digital signals are transmitted with four eight bit wide LVDS channels with an overall data rate of one Gbyte/s to the FPGA.

4. FPGA – SIGNALPROCESSING

The present FPGA architecture comprises data reduction, i.e. bandwidth limitation, down conversion to base band and data recording. The operations typical for a receiver take place in software and are discussed later on. The FPGA used for this approach is a relatively small Virtex5 (XC5VLX50T) device with about 46 thousand logical cells.

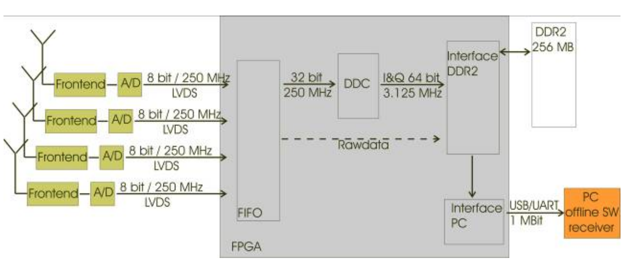

Figure 5: Present FPGA Architecture

The main steps of the signal processing in the FPGA are:

1. Synchronization of the four independent digital data streams from the different antenna elements to the system clock. This is done by a simple FIFO construction. The output of the FIFO which contains the data from the four antenna elements will be used twofold: Without further processing for the gain control of the ADC and as input for the DDC block for further processing.
2. Due to the high sampling rate and the limited memory resources, it is necessary to reduce the signal bandwidth and the data rate. Thanks to the ratio of sampling and intermediate frequency of 4 to 1, it is possible to execute the base band transformation and I/Q separation by simply multiplexing the incoming samples, see Figure 6. This makes the use of costly DSP multipliers and NCOs obsolete. After the base band transformation and I/Q separation signals are band limited by a FIR-filter architecture and down sampled by a factor of 20.
3. After the DDC block the data is stored in an external 256 MB DDR2 memory device. The size of this memory is suitable for data record length of approximately five seconds.
4. The last step inside the FPGA is the transmission of the stored data to a PC for the following (offline) signal processing by the SW receiver. This is done for simplicity reasons in a serial way using a CP2102 USB to UART bridge circuit from Silicon Laboratories. The price for this simplicity is a quite low transmission rate which is acceptable in this early stage of the project

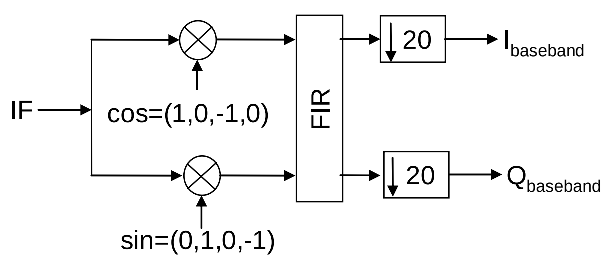

Figure 6: Digital Down Conversion

5. SOFTWARE-BASED SIGNAL PROCESSING

Currently, the complete base-band receiver including acquisition, tracking, array processing, and navigation solution is realized as a software receiver in MATLAB for offline processing.

In the next steps of development the high data rate signal processing functions like correlators will be implemented in the FPGA, but low data rate functions will be still kept in software. The signal processing in software will then complement the processing in the FPGA part taking over less time demanding processes at low data rates. It can be implemented either on an external PC or Notebook or in an integrated software or hardcore CPU on the FPGA chip. The remaining low data rate signal processing in software consists of array processing algorithms (direction finding, beamforming), navigation solution and in future additional integrity processing, but includes also some parts of the digital receiver, i.e., the correlators will be implemented directly in FPGA but the loops will be closed in the software part. This option requires a bi-directional interface to the FPGA part, but offers higher flexibility and the possibility to implement the array signal processing in the software part of the platform.

The array processing options available in the software part include direction finding with ESPRIT and MUSIC algorithms as well as adaptive beamforming. The adaptive beamforming can be used in a blind manner (without *a priori* information) applying minimum variance (MV) algorithm for placing spatial null in the radio interference direction of arrival. The assisted options include LMS beamforming using the local receiver PRN code replica as the reference signal or constrained MV algorithms with the corresponding constrains in the directions of GNSS satellites and interference. The direction finding can be optionally used to obtain the directional information about the desired and unwanted signals (radio interference, multipath) but also the GNSS almanac information can be used to calculated line of sight directions to the satellites. Because the array processing is performed on digital signals, the beamforming can be done in every signal processing channel for each tracked satellite independently by parallel implementation.

As mentioned above, currently all the array processing options described above are realized on an external PC as a MATLAB program. Because of the limitations of the software or hardcore CPU on the FPGA board only a part of these algorithms and/or for reduced number of tracking channels can be transformed from the external PC to the CPU(s) on the FPGA board.

6. EARLY RESULTS

To verify the functionality of the prototyping platform, GPS signals were recorded from the roof of a building in nearly open-sky conditions. The currently available length of signal recording with four antenna channels and final signal bandwidth after decimation sufficient to work with GPS signals is of about 3.5 seconds.

The obtained records of GPS signals were processed offline with the MATLAB software receiver. The acquisition of GPS signals was performed by utilizing the signal of the first, the reference, antenna element. Further, the acquired signals were tracked by using traditional PLL/DLL structure in every satellite channel and consequently narrowing the tracking loop bandwidths. The narrowest PLL/DLL loop bandwidths of 7Hz and 1Hz, correspondingly, were applied after approximately 1 second of tracking depending on how fast the synchronization with the navigation data bits has been achieved. In this finest tracking stage, 20ms of the coherent integration time was used both in PLL and DLL tracking loops. Figure 7 shows the spectrum of the

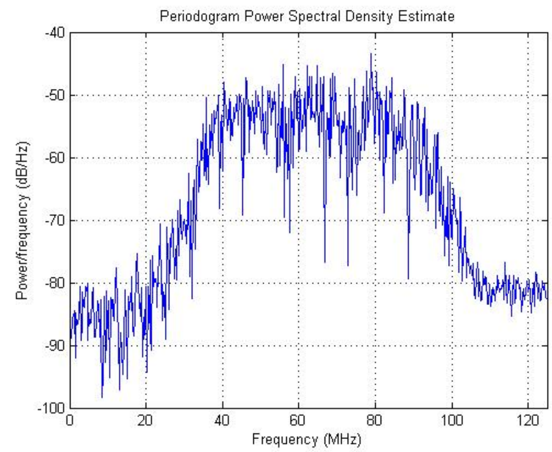

Figure 7: Band Limited Signal after Digitization

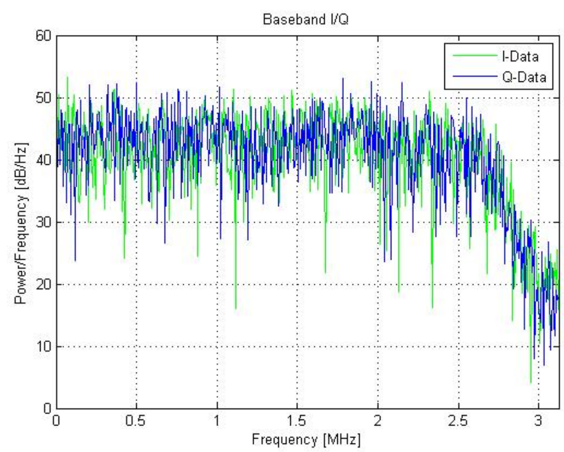

Figure 8: Baseband Signal after DDC

bandlimited IF signals after the analogue to digital conversion. Figure 8 shows the filtered and decimated baseband data, which are recorded for post processing.

Figure 9 presents the values of the carrier-to-noise density ratio (C/N_0) estimated while tracking GPS satellite with PRN 11 in each of four antenna channels.

The difference in C/N_0 values in Figure 9 is due to the electromagnetic mutual coupling between array antennas and the different noise figures of individual antenna channels. Because of the mutual coupling, the reception patterns of the antenna elements become non-symmetric and different antenna gains are observed at different elements. Also, the mutual coupling disturbs the impedance matching between an antenna and the RF front-end. The ongoing activity is directed on the resolving of this issue by more elaborated antenna and RF front end design.

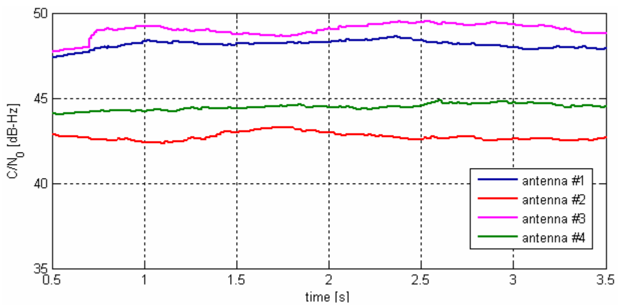

Figure 9: Array reception pattern and direction finding results for GPS satellite signal with PRN 11

A sky plot of the GPS constellation observed when performing the tests is presented in Figure 10 (only satellites which were acquired and tracked are shown). As can be observed from Figure 10, both low- and high-elevation satellites could be received by the array demonstrator. The signal acquisition was performed by using the output of the element #1 that was chosen as the reference element in the array. Some of the low-elevation satellites (not shown in Figure 10) could not be acquired by using the output of the reference element but could be acquired and tracked by using the output of one of the other array elements. Because of low C/N0 values of about 25-28 dB-Hz and large differences in the antenna gains for these satellites the beamforming operation did not noticeably improved the tracking performance and therefore these satellites were not further used.

The results of direction finding by using ESPRIT algorithm that was utilized after PRN-code correlation with the observation time of 50 ms are presented in Figure 11. A simple calibration procedure based on the knowledge of the GPS constellation has been used here. We used the direction of arrival of the GPS signal with PRN11 for estimating the carrier phase corrections to be applied to each antenna channel. For this purpose the phases of the prompt I&Q correlators after every antenna elements were compared to the phase of the reference antenna channel #1. For a known direction of arrival of the GPS signal, the carrier phase differences between antenna channels should take some predefined values which can be easily calculated by using the array geometry and the narrowband signal assumption. In this simple calibration procedure we did not account for the difference in the phase responses between the array elements. As can be observed in Figure 11 the simple calibration resulted a good match for PRN11 but the direction of arrivals of all other satellites are far from the true ones. This result indicates the necessity for a more complex calibration procedure with accounting for different characteristics of the array elements. Moreover, for wideband GNSS signals the calibration procedure should also account for the frequency dependency of the antenna and RF front end characteristics.

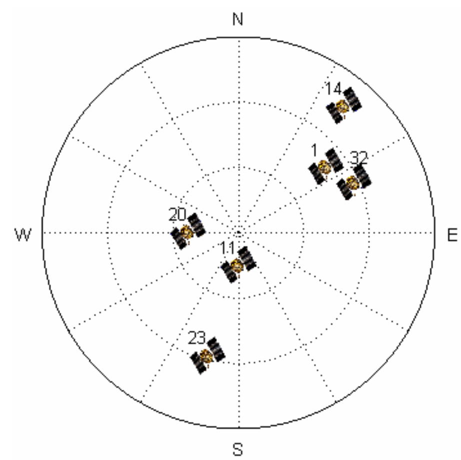

Figure 10: Sky plot of GPS satellites which were acquired and tracked

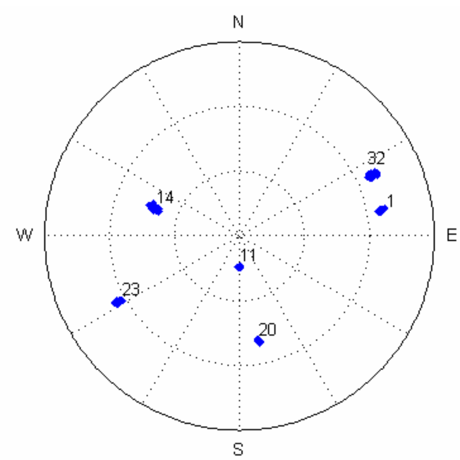

Figure 11: Array reception pattern and direction finding results for GPS satellite signal with PRN 11

The estimated directions of arrival of the GPS signals were used to steer the maximum of the array beam pattern with the help of the linearly constrained minimum variance (LCMV) algorithm. The improvements of C/N_0 performance metric due to the LCMV beamforming are illustrated by Figure 12. The optimum gain of C/N_0 in a 4-element antenna array is 10*log10(4) = 6 dB. The use of beamforming in our test resulted in the improvements of C/N_0 which are smaller and higher than the optimum value. This is due to the variance of C/N_0 values of a GPS satellite signal in the individual antenna channels. Similar effects were also observed in [10].

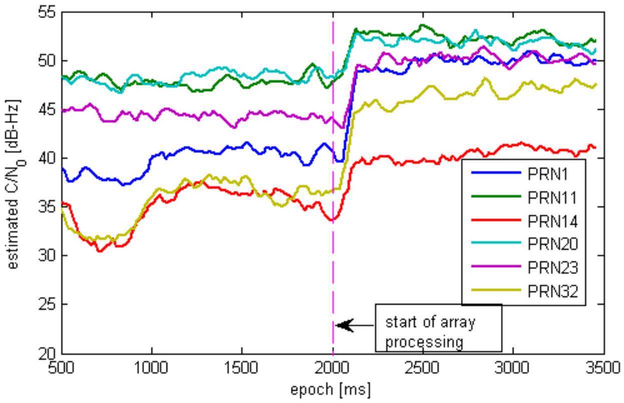

Figure 12: C/N_0 time evolution

The presented results verify the main functionality of the realised prototype of a GNSS antenna array system. The identified shortcomings of the first prototype are currently being improved.

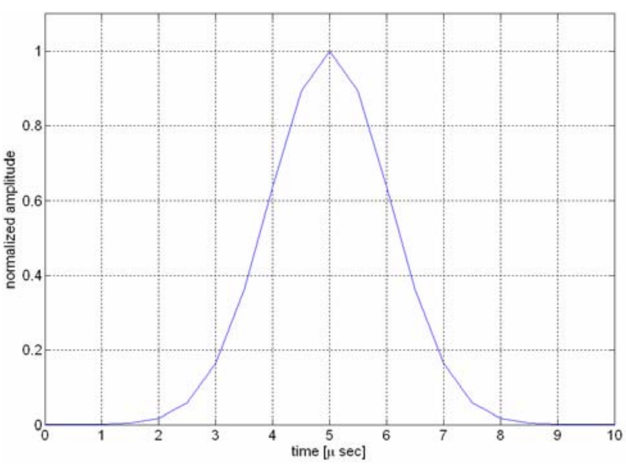

Figure 13: DME like pulse in time domain

Another early test was to demonstrate the general ability of operation in case of strong interference. For this case a DME like pulse (see Figure 13) with a repetition rate of 15000 pps and a pulse width of 3.5 µsec was generated by a programmable signal generator (Agilent's E8267D). The power was fixed to -60 dBm. Due to the fact that the receiver prototype is capable of Galileo L1 only the carrier of the pulse was shifted to the L1 band.

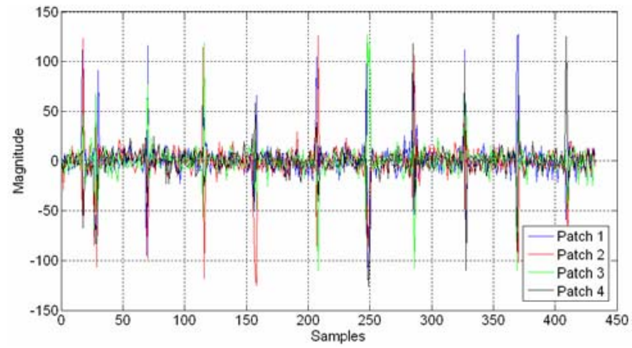

Figure 14: Digitized IF signal after ADC with pulsed interferer

Figure 14 shows the digital IF signal after the ADC in case of interfering DME like pulses. Most of the time the signal appears to be noise because the signal is buried below the noisefloor. The noise occupies approximately 3 to 4 bit. In case when the pulse is present the ADC is not in saturation but the output values are much higher (approximately 7 bit ($2^7 = 128$). Nevertheless the signal is represented correctly.

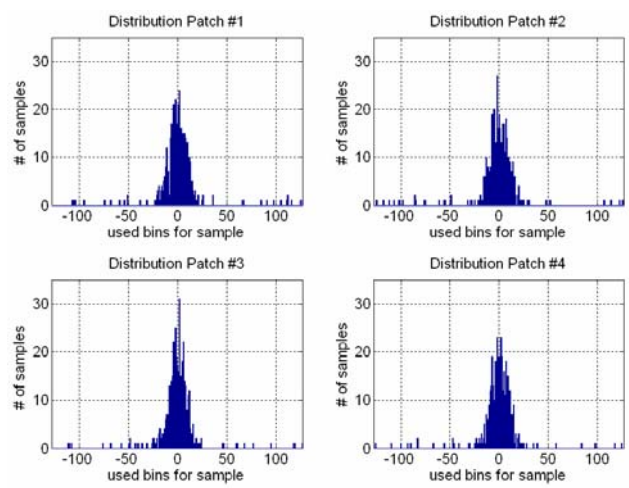

Figure 15: Histogram in case of DME like pulses are present

For the same test the histogram is shown in Figure 15. In the middle of each of the four sub plots a more or less Gaussian distributed "noise" is visible as expected. The outliers are due to the much more powerful interfering pulses. The distribution is not perfect due to the small number of samples used. .

CONCLUSIONS

The paper describes architecture of the prototype for GNSS array processing system with enhanced capabilities for improved signal reception and interference mitigation. The first results are presented showing the main functionality of the prototype: multi-antenna signal processing with direction finding and beamforming. The improvements of the prototype in several identified issues are already on the way.

The final goal of this activity is to obtain the demonstrator of a very promising technology for GNSS applications with high requirements to performance and reliability of positioning and timing services.

REFERENCES

[1] M. Cuntz, A. Konovaltsev, A. Hornbostel, E. Schittler-Neves and A. Dreher, "Modular smart antenna array for GPS and Galileo applications," *European Navigation Conference ENC-GNSS 2005*, Munich, July 2005. ("GALANT – Galileo Antenna and Receiver Demonstrator for Safety-Critical Applications," Proceedings of the 10th European Conf. Wireless Technology, Munich, Germany, Oct. 2007, pp. 59-61.

[2] E. S. Neves, P. de Vita and A. Dreher, "Smart antenna arrays for GPS and Galileo applications," 2nd ESA Workshop on Satellite Navigation User Equipment Technologies, Noordwijk, The Netherlands, Dec. 2004, (8 pp. CD-ROM).

[3] E. S. Neves, P. de Vita and A. Dreher, "Modular smart antenna array for GPS and Galileo applications", European Navigation Conference ENC-GNSS 2005, Munich, July 2005. (12 pp. CD-ROM).

[4] G. Seco Granados, "Antenna Arrays for Multipath and Interference Mitigation in GNSS Receivers," PhD thesis, Department of Signal Theory and Communications, Universitat Politecnica de Catalunya, 2000.

[5] G Seco Granados, J. A. Fernandez-Rubio, and C. Fernandez Prades. "ML Estimator and Hybrid Beamformer for Multipath and Interference Mitigation in GNSS Receivers," *IEEE Trans. Signal Process., vol. 53(3)*, March 2005.

[6] D. de Lorenzo, J. Gautier, J. Rife, P. Enge, and D. Akos, "Adaptive Array Processing for GPS Interference Rejection," *Proc. ION GNSS 2005*, Long Beach, CA, September 2005.

[7] D. de Lorenzo, J. Rife, P. Enge, P., and D. Akos, "Navigation Accuracy and Interference Rejection for an Adaptive GPS Antenna Array," *Proc. ION GNSS 2006*, Fort Worth, TX, September 2006.

[8] D. de Lorenzo, F. Antreich, H. Denks, A. Hornbostel, C. Weber, P. Enge: "Testing of Adaptive Beamsteering for Interference Rejection in GNSS Receivers," *Proc. of ENC GNSS 2007*, Genf, Switzerland, May/June 2007.

[9] A. Konovaltsev, B. Belabbas, H. Denks and A. Hornbostel, "Adaptive antenna against multipath," *Proc. of the 8th European Navigation Conference GNSS 2004*, Rotterdam, The Netherlands, May, 2004.

[10] Morgan Quigley, Pieter Abbeel, Dave S. De Lorenzo, Yi Gu, Sara Bolouki, Dennis Akos, and Andrew Y. Ng. "Portable GNSS Baseband Logging," *Institute of Navigation (ION) 2007 GNSS Conference, Ft. Worth, TX, September 2007*