Artus – A Second Generation Galileo/GPS Receiver

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BIOGRAPHY

Thorsten Lück studied Electrical Engineering at the Universities in Stuttgart and Bochum. Since 2003 he works for the IFEN GmbH in the receiver technology division as the head of R&D embedded systems.

Jón Ó. Winkel is head of receiver technology at IFEN GmbH since 2001. He studied physics at the universities in Hamburg and Regensburg. He received a PhD (Dr.-Ing.) from the University of the Federal Armed Forces in Munich in 2003 on GNSS modeling and simulations.

Michael Bodenbach has studied Communications Engineering at the University of Applied Sciences in Braunschweig/Wolfenbüttel. Since October 2003 he is working at IFEN GmbH in the receiver technology department focusing on hardware and FPGA development.

Eckart Göhler received his Diploma in physics from the University Tübingen in 1999. He finished the PhD in 2004 at the Institute for Astronomy and Astrophysics, Tübingen. Today he is working as a system engineer at IFEN GmbH.

Nico Falk received his Diploma in Electrical Engineering from the University of Applied Sciences in Offenburg in 2007. Since then he is working at IFEN GmbH where he also worked for his diploma thesis.

Angelo Consoli received the Dipl. Ing. degree in electrical engineering from the Swiss Federal Institute of Technology (ETH), Zurich, in 1989. Since 1993 Mr. Consoli is professor for telecommunications and security at the University of applied Science of Southern Switzerland. Since 2001 he is aerospace programme manager at NemeriX.

Danilo Gerna is principal RF designer at NemeriX. He received the degree of engineering (summa cum laude) from the University of Pavia, Italy in 1992. Since October 2005 he joined NemeriX SA where is involved in high performances, low power RF/Analog design for satellite navigation applications.

Francesco Piazza is Chief Scientist at NemeriX SA. He received the Dipl. Ing. degree in electrical engineering from the Swiss Federal Institute of Technology (ETH), Zurich, in 1992 and the Ph. D. in March 2000 from the same university. In May 2000 he founded TChip/NemeriX SA where he is responsible for analog and RF IC design.

Robin Granger attained a Masters Degree in Electronic Engineering from Southampton University in 1999. He now works for Roke Manor Research Ltd as a Consultant Engineer in the Electromagnetic Engineering group.

Peter Readman graduated from Imperial College London in 1986 with a degree in Physics. He joined Roke Manor Research Ltd in 1995 and now works as a Consultant Engineer in the Electromagnetic Engineering group.

Steve Simpson graduated from the University of Salford with a degree in electronics in 1974 and went on to gain a PhD from Sheffield in 1979. He currently leads the Electromagnetic Engineering group at Roke Manor Research Ltd.

Hans-Jürgen Euler works for more than 20 years in the area of precise GNSS positioning. Since more than 15 years he developed real-time algorithms at Terrasat (now Trimble) and Leica Geosystems. Now he works in consulting and development as GNSS specialist for his company inPosition gmbh.

ABSTRACT

The present paper describes the development of a second generation GNSS receiver. It is being developed in the frame of a GIU 50% funded project named Artus (Advanced Receiver Terminal for User Services) un-
Regarding the antenna, the geodetic requirement for a highly stable phase centre is examined from a basic theoretical viewpoint. To do this the relationships between beam pattern and antenna aperture distribution is examined and it is explained how these theoretical parameters relate to the mechanical layout of the antenna’s radiating structure. It is reasoned that the antenna’s phase centre is only an apparent phenomenon, as the radiation actually emanates from the whole antenna surface and not just from one point. By doing this much physical insight into why some antenna technologies can be expected to perform better than others is gained. The requirement for true wideband performance coupled with high phase centre stability results in a very demanding requirement, satisfied by only a few antenna technologies. A real world constraint is that the antenna must play its part in multi-path rejection and control. It is also necessary however that these technologies satisfy sensible size and weight constraints and can be produced at reasonable cost.

RF-Front-End Founded in 2002, NemeriX developed the world’s lowest power RF front-end for GPS L1 receivers. The front-end developed in the Artus project is based on the previously developed RF ASICs NJ1007. The NJ1007 was limited to a signal bandwidth of 24MHz, which is insufficient for Galileo. In order to accommodate the higher bandwidth for the Galileo E5ab signal, NemeriX started in 2005 the development of a new RF down-converter (NJ1008). The main new features of NJ1008, which is accommodated within the RF-Front-End section of the ARTUS receiver, are the additional IF output with a much higher signal bandwidth of up to 72 MHz as well as a fully integrated VCO.

Digital base band processing Based on extensive experience made within the German Galileo Test Environment (GATE), the base-band processor is based on a highly flexible FPGA design. Providing 30 channels in the basic configuration and up to 120 channels when fully equipped, each of these channels can be configured to track any signal at the L1, L2, E5 (E5a/L5 and E5b) and E6 frequency band. The analog IF signal from the four different RF-Front-Ends is digitized at a sample rate of 300 MHz with 8-bit sample resolution. The following digital signal conditioning also realized in a single FPGA for all four input bands – ends up with four digital I-Q data stream at 100 MHz sample rate. These digital IQ data of all four frequency bands is streamed to every base-band processor. With the correlators being realized in fast base-band FGPA of the most modern Xilinx Virtex5-type and the correlator steering in terms of signal acquisition, loop closure and tracking performed through several Microcontrollers realized by soft-cores within dedicated controller-FPGAs, maximum flexibility is achieved and allows easy adoption of new technologies and algorithms. An additional hardcore CPU within a master Virtex5-FPGA collects the measurements and navigation data from all independent channels and performs a rudimentary PVT solution to allow a flexible channel management and fast (re-) acquisition. All measurements can be made available for the user through a USB or LAN interface for further processing.

Navigation solution The navigation software is the last of important key elements for use of GNSS in positioning. For maximum flexibility it has been decided in the ARTUS project to have the navigation software component on a separate computer board. The positioning itself is designed to perform the traditional navigation solution in parallel to differential positioning solutions. The paper will highlight the novel design of the navigation software component. Furthermore it will summarize positioning results based on Galileo only and in combination with GPS observations.

Based on these four core technology issues, the ARTUS professional receiver for Galileo and GPS has been realized. This paper presents in detail the key elements of this modern GNSS professional receiver and characterizes their single performance as well as the overall receiver performance based on signals simulated using a constellation simulator like IFEN’s NavX-NCS and signal in space simulated within the German Galileo Test Environment (GATE)[5].

INTRODUCTION

The Artus receiver is a prototype GNSS receiver, including antenna providing Galileo/GPS navigation capability. All three Galileo frequencies (L1, E6 and E5a/E5b) are supported as well as the GPS L1, L2 and L5 (=E5a) frequencies. Although not initially planned, the consortium
decided to also implement the GPS L2 band for commercial reasons. The unit performs the measurements and processes the raw-data to provide an RTK solution.

From a functional point of view the breakdown as shown in figure 1 can be defined. The Antenna sub-system is responsible for the reception of the RF-signals and converting them to electrical signals. The RF-splitter filters them and separates them according to the target frequency bands L1, L2, E6 and E5. The RF-front-end system transfers the signals in RF-domain down to an intermediate frequency (or near zero base-band), performs further filtering and prepares the signals for analogue to digital conversion.

The base-band processor performs high-speed signal processing (code generation and correlation) and prepares the data stream for tracking and data demodulation. The result is a low-speed data stream that can be further processed on a CPU. The receiver CPU implements the tracking loops for the tracking of code and carrier. After bit-sync and frame sync as well as de-interleaving and Viterbi decoding, the raw measurements and the navigation data are generated. The navigation software is installed on an external x86 based PC. Here the higher-level navigation algorithms are carried out. Note that the companies responsible for each functional element are shown in the colour coded legend of figure 1.

The prototype receiver with its main components is shown in figure 2.

**ANTENNA AND FRONTEND DESIGN**

The two main Artus requirements, from the antenna viewpoint, are:

1. that all the Galileo and GPS carriers should be catered for; and
2. the antenna needs a very stable phase centre at all the carrier frequencies.

To fulfill the first of these requirements, the necessary bandwidth is prohibitively large, or at least difficult to achieve, for some antenna types, including the Patch commonly used for GPS. The phase centre requirement is arguably more difficult to meet than the bandwidth requirement. The current generation of geodetic grade receivers are able to correct for phase centre variation (PCV) with elevation, by a priori knowledge of the antenna’s characteristics. However, it is not usual for azimuthal variation to be corrected, hence the azimuthal variation must be sufficiently low that calibration is unnecessary.

The spiral antenna is essentially frequency independent; a true broadband antenna. If the antenna’s dimensions extended infinitely the antenna would exhibit no lower frequency limit. A practical antenna will exhibit low frequency cut-off, but above the cut-off frequency the radiation pattern and impedance characteristics are relatively independent of frequency. Its inherent mechanical symmetry also lends it a high degree of phase centre stability versus azimuth angle.

Figure 3 illustrates the chosen design: a four-arm cavity-backed planar spiral. It measures 125mm in diameter and has a cavity 55mm deep. The spiral itself, approximately Archimedean in nature, is only 105mm across (approx. 1.2 wavelengths in circumference at the lowest frequency) but good operation down to 1.1GHz has been proven experimentally. Sufficient circular symmetry is obtained by approximately three turns per conductor.
Fig. 3 A photograph of the prototype antenna

The bottom surface of the cavity is made from a second printed circuit board which also contains the phase forming network, interference rejection filters, a Low-Noise Amplifier (LNA) and power supply circuitry. The phase forming network comprises a 90° hybrid and two baluns, using commercially-available components in chip form. The balun phase imbalance is approximately 4° across the frequency band of interest, and this error is compensated by including a short delay line at one of the outputs. The mechanical symmetry of the antenna is to such a high degree that the dominating factor in the measured phase centre variation is due to phase imbalance in the feed network.

Computer simulation was a key part of the design process, particularly in the early stages, in order to develop insight into the effects of the many design parameters without the need for many time-consuming and costly prototypes. To validate simulations and characterise finished designs, an anechoic chamber at Roke was adapted to perform high mechanical accuracy measurements. The measurement data were processed numerically, using proprietary code, to determine such parameters as gain (see Figure 4), axial ratio, phase centre offset (PCO) and PCV.

Performance has been shown to be good across all the GPS and Galileo bands required for Artus, and in fact also at GLONASS frequencies. Peak gain is typically around 6dBic (without the LNA), axial ratio is better than 3dB over 120° of the beam and RH-to-LHCP isolation ratio is around 30dB at zenith. PCV is on the order of ±3mm with elevation and ±1mm with azimuth.

Founded in 2002, Nemerix is worldwide known for the development of the world's lowest power RF front-end and base-band for GPS L1 receivers. The front-end developed in the frame of the ARTUS project is based on the previously developed RF ASIC NJ1007. The NJ1007 is limited to a signal bandwidth of 24MHz, which is insufficient for some Galileo signals. In order to accommodate the higher bandwidth needed e.g. for the Galileo E5ab signal, Nemerix started in 2005 the development of a new RF down-converter: the NJ1008. The main new features of the NJ1008, which is accommodated within the RF-Front-End section of the ARTUS receiver, are the additional IF output with a much higher signal bandwidth of up to 72 MHz as well as a fully integrated VCO.

The chip provides a low-noise amplifier (LNA) and a heterodyne down converter from L-band to an intermediate frequency (IF) of approximately 240 MHz, followed by quadrature down-conversion to base-band and active 15MHz low-pass filtering. The NJ1008 offers the possibility to access the signal either at IF or after the quadrature down-conversion to base-band. Several amplifier stages, including a voltage controlled amplifier for automatic gain control (AGC), boost the signals to adequate levels.

The chip contains registers for controlling chip power management and for configuring the PLL dividers. The NJ1008 is in fact able to receive and down-convert to base-band all GPS, Galileo and GLONASS signals up to a bandwidth of 24 MHz. Signals with wider bandwidths are not converted to base-band but outputted directly at IF. Only minor variations of the components used in external filters and matching elements have to be made, together with proper PLL-dividers programming, to down-convert signals from the different GNSS frequency bands.

**DIGITAL BASEBAND PROCESSING**

In figure 6 the communication between the RF-ASIC board and the digital signal conditioning part is shown. The signal
conditioning part provides the 2 MHz clock signal, which is synthesized from a 10 MHz reference clock, to the RF-ASICs (green block in figure 6).

The common 10 MHz clock source is generated by a TCXO. The higher clock frequency required for the analogue-to-digital conversions are synthesised by a PLL from Analog Devices. For each frequency, the IF output of the RF-chips will be used. All IF-signals will be sampled at 300 MHz. This simplifies the design and ensures that all frequency bands are treated as similarly as possible. This is important in order to minimize inter-frequency biases.

It is important that the clock signal, derived from the same source, is used for both analogue and digital chain. The IF-samples provided by the RF-ASICS are converted to digital samples in the ADC. The resulting digital samples are further processed (digital signal conditioning). During this process a steering signal is generated for the automatic gain control (AGC) and fed back to the RF-board.

The signals and clock output from the signal conditioning are routed to each base-band processor (figure 7). The advantage is that each base-band processor can then be configured to process at any signal band. For example all base-band processors can be configured to process L1 or alternatively one base-band processor could process signals from two or more frequencies.
The Artus motherboard has two connectors to carry up to two additional daughter boards to expand the number of channels. Each daughter board provides up to 40 additional channels and is connected to any of the four digital signal bands. As the design of the digital base band processor is based on the monitor receiver developed for GATE [5], the daughter board connectors have been chosen such that the GATE base band board can be used as an optional expansion board (however, due to the euro card form factor, only one GATE board can be plugged onto the Artus motherboard and in this case, no optional expansion board is available).

![Fig. 7 Block diagram of base band processor (including A/D conversion, digit signal conditioning and optional daughterboards)](image)

Figure 7 shows the Artus motherboard enhanced with one GATE baseband board (back packed board on the right side). Two other connectors on the left side of the board hold another optional daughter board (upper connector) and the RF front end (both not connected). Above the RF front end connector both analog to digital converter IC’s (four ADCs in two chips) and the Virtex5 FPGA for signal conditioning can be realized.

![Fig. 8 Artus motherboard with optional daughter board.](image)

The further base band processing after signal conditioning is visualized in figure 9. It can be divided into three speed domains:

- **High speed processing at 100 MHz to integrate the incoming signal (correlators)**
- **Medium speed processing at 1 kHz per channel for acquisition and tracking (loop closure)**
- **Low speed processing at 0.1 – 10 Hz per channel for range generation (pseudo range, accumulated Doppler range, etc.)**

Where the high speed domain is fully realized in VHDL, the medium and low speed processing domains are implemented in software on softcore CPUs (Microblaze) within the FPGA.

Also the main system CPU which performs channel management and user IO is realized as softcore within a Virtex5 FPGA and runs an embedded µCLinux.

All software for signal acquisition, tracking and also channel management and basic PVT calculation is based on a platform independent, object oriented C++ library which has been optimized for embedded systems.

Due to the generic design of all components - whether in FPGA hardware or software - new algorithms or additional signals can be easily implemented. Therefore it is always possible to acquire and track additional signals as far as the basic conception is similar to the established GNSS signals. To acquire Chinese’ Compass signal, only minor software changes have to be made and the spreading codes had to be downloaded to flash memory (see below).

![Fig. 9 Detailed base band block diagram.](image)

**NAVIGATION SOFTWARE**

The navigation software of the prototype receiver is being hosted outside of the receiver on a separate laptop (Figure 2). This provided more flexibility during the process of the whole development of all components of the prototype receiver. Furthermore the navigation software is not limited to navigation solutions such as stand-alone position, speed
and timing information of only one unit. Extended functionality allows the positioning based also on input of additional stations and auxiliary information obtained through the internet.

The navigation software is based on objected-oriented design in C++. Figure 10 shows an overview of the navigation software’s internal design. The application consists of a number of different modules performing the different computational tasks.

Different decoder modules are receiving the information of the connected ARTUS receiver or information from different reference stations to be used for the positioning. Each receiver/station connected will have its independent decoder module associated. Their responsibility is the transformation of in-coming data to an internal data representation. For maximum flexibility a standard interface has been chosen for the interface of the raw observation information. This the most popular RTCM V3 (2006) as supported by all manufacturers of high-end GNSS user equipment [6]. Standard messages for GPS operation have been already released. Suitable Galileo messages have been drafted within RTCM SC104, but those are not ready for release. The implementation for Galileo is based on the draft version of an RTCM work group document. The connectivity is guaranteed based on the TCP/IP protocol.

![Fig. 10 Schematic module layout](image)

A further module allows the connectivity to the Internet for updated information on precise predicted orbits or other auxiliary information such as observation biases and antenna phase center offsets. Both types of modules are building up the interface to the outside. They are handing over the information to the synchronization module. One synchronization module has the responsibility of buffering of in-coming information until it is used for processing. This is important especially when the information is possibly received via the Internet with delay. The module needs also to ensure that outdated information, which is no longer of use for processing, is being removed from the buffer. The subsequent modules performing the processing are receiving all their information via the synchronization module. One Ambiguity Consolidation and Distribution module is responsible for collecting and storing the found integer ambiguities and holds them ready for use within the different processing modules. The actual processing of the observations is performed in different data processing modules. These modules are using identical source code. Their actual task is defined through different properties defining the complete computational scheme for processing. A detailed description of the property scheme can be found in [3]. More from a conceptual viewpoint and not from the source code utilized the processing modules may be distinguished. Float and Search modules are carrying out a float ambiguity solution and the subsequent integer ambiguity search and integer fixing. After having the integers confirmed based on statistical means the integers are communicated to the Ambiguity Consolidation and Search module. The Float and Search modules may also obtain integer information for constraining its solution. The other category, the position or production modules, are receiving the integer ambiguities from the Ambiguity Consolidation and Distribution module. Position or production modules are carrying out the calculations defined through the set of properties as supplied during their start-up in the application. Several of the modules may run in parallel. For instance one module provides a navigation solution while another one is providing a rover position involving different reference stations. Or the production of Network RTK information is supplemented by the monitoring of the reference station coordinates. The concept implemented is flexible allows many different application constellations. The capabilities are highlighted through some test examples in Euler and Wirth (2007).

**PERFORMANCE**

Several tests has been performed with the Artus breadboard to prove the basic system conception:

**Tests within GATE**

To test the receiver performance for Galileo signals, several static and kinematic tests has been performed in the German Galileo Test and Development Environment (GATE). The dynamic tests cover low dynamic tests with an averaged speed of about 30 kilometers per hour. Figure 11 shows the position solution from a dynamic positioning test in the GATE area in the extended base mode (EBM). Due to shadowing of the direct line of sights by trees and buildings to some transmitters, especially in the south of the GATE area, a position fix can not always be reached (marked in yellow). A more detailed result is shown in figure 12 for a
fast accelerated vehicle for Galileo L1 only. Further results can also be found in [2].

By proper configuration of the base band processor, the breadboard was able to track - beneath GPS and GIOVE-A - the Compass E2 and E5b signal in space. Figure 13 shows the user interface to the receiver listing the first 17 channels. Channel 1 and 17 show are tracking the Compass signal on E2 and E5b while channel 2 is assigned to the GIOVE-A signal on L1-B (internal shown as Galileo signal on PRN 51). In addition 10 GPS signals are tracked (listed in the “Measurement Viewer” widget. The map view shows the position of IFEN’s roof antenna derived from the GPS signals.

Whereas the Compass E5b center frequency is identical to the Galileo E5b frequency, the Compass E2 is 14.322 MHz below the Galileo L1 center frequency of 1.57542 GHz. Due to the 40 MHz wide band front end currently configured for the L1 band, both Compass L1 signals (E2 and E1) fit into the Rf bandwidth of the ARTUS receiver. Thus by configuring the appropriate intermediate frequency to

$$f_{IF_{E2}} = f_{IF_{nom}} - 14.322 \text{ MHz}$$

and uploading the relevant primary and secondary codes [1] to the correlators, the Compass signal could be easily tracked at E2 and E5b. By configuring the preamble and navigation message length [7] it was also possible to perform frame sync and to calculate a pseudo range measurement (figure 15).

Figure 14 and 15 show the pseudo range and pseudo range noise (code noise) for Giove-A and Compass.

CONCLUSION

The described GNSS receiver offers a rich flexibility regarding different configurations on different RF bands. The high performance antenna in conjunction with a flexible RF frontend design offers excellent performance on all currently available GNSS signal bands including upcoming Galileo. With the availability of up to 120 channels, the receiver is well equipped for future navigation systems however also offers a low budget configuration with 20 or 40 channels for current available GPS (L1 and L2).

The modular concept even for the firmware of the base band processor FPGAs allows easy adaptation of the used or even fast implementation of new algorithms. As for the user interfaces the IP protocol is used, any user interface can easily connect even remotely to the receiver - whether for navigation or monitoring purposes.
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REFERENCES


