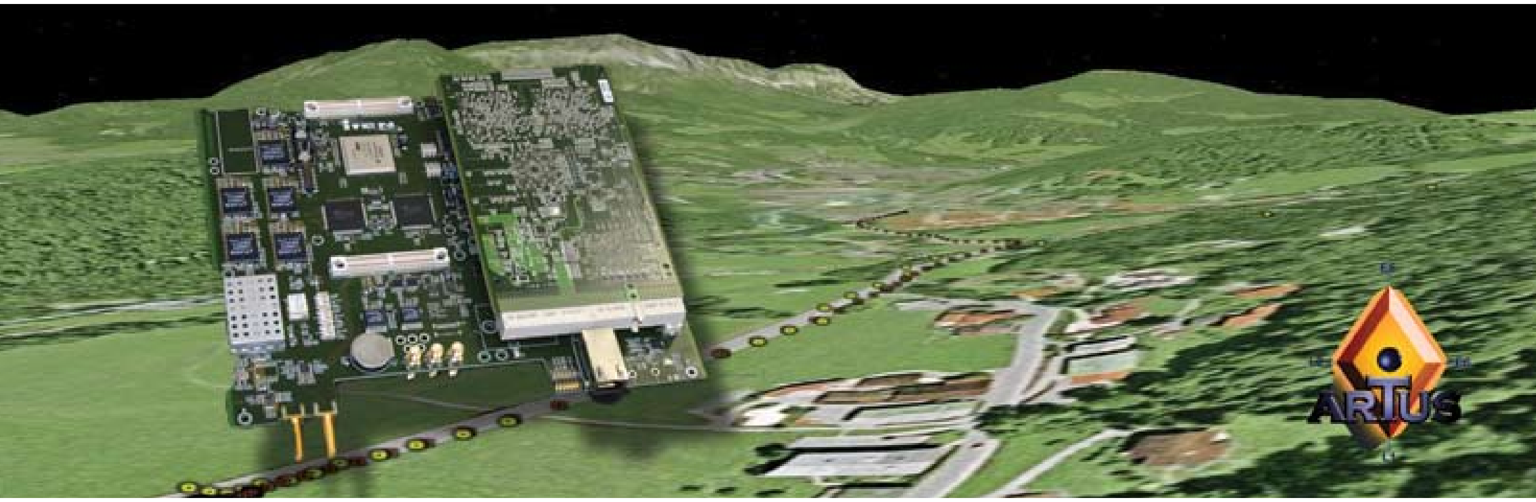
The Art of ARTUS

A Second-Generation Galileo/GPS Receiver



Europe's Galileo program is seeking to accelerate receiver technology development even as the space and ground segments of the system are being implemented. A group of companies have collaborated on development of a geodetic-grade Galileo-GPS receiver: ARTUS. The engineering team in charge of the project describes their work to date, including tests that tracked signals from China's Compass system as well as GIOVE-A and GPS.

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Creation of new global navigation satellite systems and modernization of existing ones is introducing many new signals across a wide swath of RF spectrum now and in the near future. These developments are accompanied by a growing need to design new GNSS receivers that can work with new signal structures on an increasing number of frequencies.

Europe's Galileo program has supported a number of activities intended to support innovations in receiver design, such as prototype Galileo user equipment, reference receivers, and so on.

One such activity is a project named ARTUS (Advanced Receiver Terminal for User Services), 50 percent of which is financed by funds allocated by the Galileo Joint Undertaking (GJU). A consortium of four companies is leading the ARTUS project.

ARTUS supports the development of receiver technologies to aid the research and development activities for Galileo "professional" receivers. These efforts are designed to facilitate the availability of Galileo professional receiver prototypes and antennas at an early stage.

ARTUS provides Galileo/GPS navigation capability. All three Galileo frequencies (L1, E6 and E5a/E5b) are supported as well as the GPS L1, L2 and L5 (L5=E5a) frequencies. The receiver supports any BPSK (GPS-C/A, Galileo E5a and E5b (sideband tracking), AltBOC (E5ab), Galileo L1-B/C (BOC(1,1)) as well as BOCc(15,2.5) (E1-A / E6-A); GIOVE-A transmits BPSK (E5a/E5b/E6) and BOC(1,1) (E1).

Although the receiver can track the modulations foreseen for the PRS, it cannot generate the corresponding codes. One can, however, do performance measurements using periodic substitute codes.

Although not initially planned, the consortium has 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.

The Artus design will also form the basis for a breadboard development of the next generation RIMS receivers. This development will be conducted in the frame of an ESA contract lead by IFEN with NemeriX and Euro Telematik as subcontractors.

This article describes the design and operation of the second-generation ARTUS receiver with a particular focus on innovations in four key areas: antenna, RF front-end, digital baseband processing, and navigation software. Although originally intended to focus primary on tracking Galileo and GPS signals, the flexible design of ARTUS also allows it to receive and track signals from the Russian GLONASS system and China's Beidou.

After discussing the receiver design and operation, we will briefly describe some of the results of testing using combinations of laboratory GNSS signal simulators, signals-in-space, and simulated signals generated in the German Galileo Test Bed (GATE).

Four Streams of Innovation

Figure 1 shows a simplified schematic of the elements of the ARTUS receiver development.

The antenna sub-system is responsible for the reception of the RF signals and converting them to electrical signals. An RF splitter filters and separates them according to the target frequency bands, that is, L1, L2, E6, and E5. The RF-front-end system transfers the signals in RF domain down to an intermediate frequency (or near zero baseband), which performs further filtering and prepares the signals for analog-to-digital conversion (ADC).

The baseband 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

Antenna Design

The two main ARTUS requirements, from the perspective of antenna design, are the capability to handle all the Galileo and GPS carriers as well as provide a very stable phase center 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 antenna commonly used for GPS. However, the phase center specification is arguably even more difficult to meet than the bandwidth requirement.

The current generation of geodetic-grade receivers is able to correct for phase center variation (PCV) with elevation of the LOS (line of sight) signal by using a priori knowledge of the antenna's characteristics. However, azimuthal variation of the LOS signal is not usually corrected; hence, the latter variation must be sufficiently small so that calibration is unnecessary for a geodetic-grade receiver.

Unlike patch or microstrip designs, a spiral antenna is essentially frequency independent: a true broadband antenna. If an antenna's dimensions extended infinitely, the antenna would exhibit no lower frequency limit.

Of course, a practical antenna will exhibit low frequency cut-off. Above the cut-off frequency, however, the radiation pattern and impedance characteristics are relatively independent of frequency. A spiral antenna's inherent mechanical symmetry also lends it a high degree of phase center stability in relation to azimuth angle.

The chosen design features a four-arm cavity-backed planar spiral. It measures 125 millimeters in diameter and has a cavity 55 millimeters deep.

The spiral itself, approximately Archimedean in nature, is only 105 millimeters across (approximately 1.2 wavelengths in circumference at the lowest frequency), but good operation down to 1.1 GHz has been proven experimentally. Sufficient circular symmetry is obtained by approximately three turns per conductor.

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-degree hybrid and two baluns, using commercially available components in chip form.

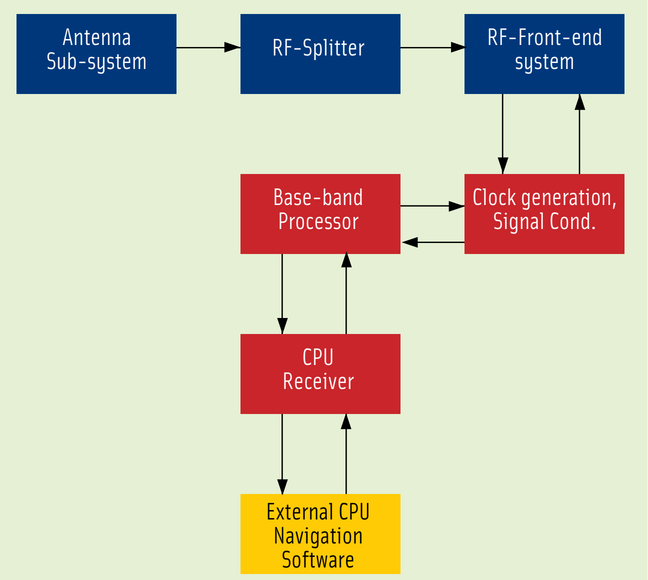

FIGURE 1 The ARTUS GNSS receiver concept

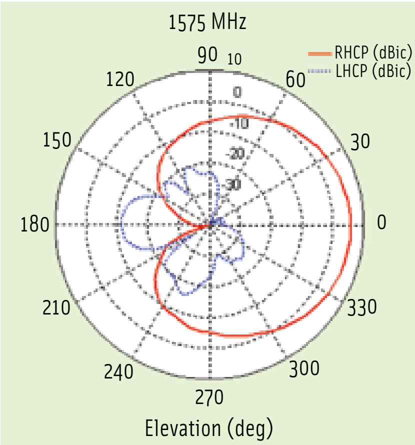

FIGURE 2 Typical measured RH- and LH-CP gain versus elevation angle at the Galileo E2-L1-E1 band centre

The balun phase imbalance is approximately four degrees across the frequency band of interest, and this error is compensated by including a short delay line at one of the outputs. The antenna exhibits such a high degree of mechanical symmetry that the dominating factor in the measured phase center variation is due to phase imbalance in the feed network.

Computer simulation played a key role during the design process — particularly in the early stages — in providing insight into the effects of the many design parameters without the need for time-consuming and costly prototypes.

To validate simulations and characterize finished designs, an anechoic chamber at the antenna manufacturer 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 2**), axial ratio, phase center offset (PCO), and PCV.

The antenna's 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 6 dBic (without the LNA), axial ratio is better than 3 dB over 120 degrees of the beam, and the right-hand to left-hand circular polarization (RH-to-LHCP) isolation ratio is about 30 dB at zenith. PCV is on the order of ±3 mm with elevation and ±1 mm with azimuth.

RF Front End

The front-end development in the frame of the ARTUS project is based on a previously developed RF ASIC that is limited to a signal bandwidth of 24 MHz, insufficient for receiving some Galileo signals. In order to accommodate the higher bandwidth needed, e.g., for the Galileo E5ab signal, the RF ASIC manufacturer began development of a new RF down-converter in 2005 that features additional IF output with a much higher signal bandwidth — up to 72 MHz — as well as a fully integrated voltage-controlled oscillator (VCO). (See **Figure 3**.)

The chip provides a low-noise amplifier (LNA) and a heterodyne down-converter from L-band to an IF of approximately 240 MHz, followed by quadrature

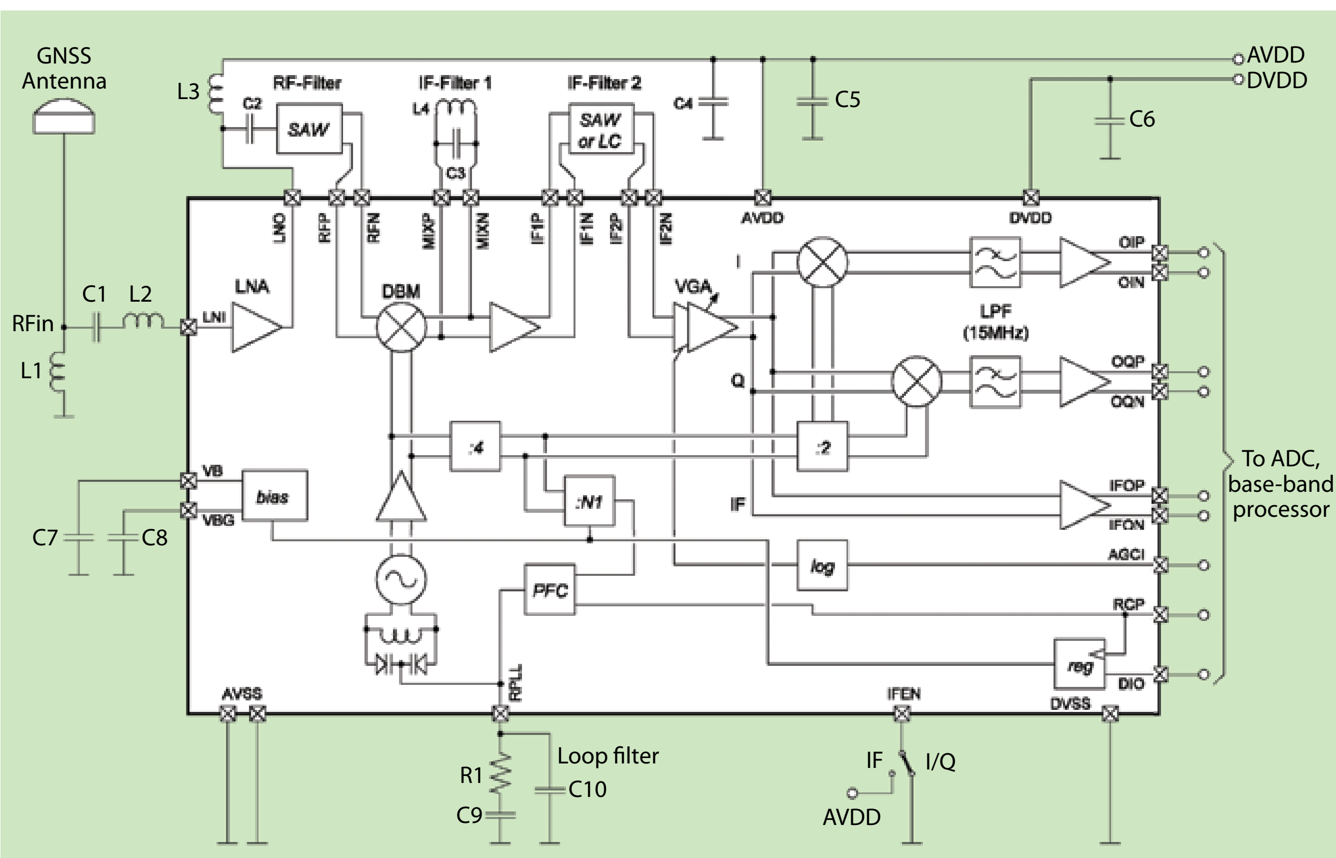

FIGURE 3 RF ASIC downconverter internal block diagram

down-conversion to baseband and active 15 MHz low-pass filtering. The ASIC allows access to the signal either at IF or after the quadrature down-conversion to baseband. 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 phase lock loop (PLL) dividers. In fact, the downconverter ASIC is able to receive and down-convert to baseband all GPS, Galileo, and GLONASS signals up to a bandwidth of 24 MHz.

Signals with wider bandwidths are not converted to baseband but outputted directly at IF. To down-convert signals from the different GNSS frequency bands only minor variations of the components used in external filters and matching elements have to be made, together with proper PLL-dividers programming.

The stability of the inter frequency biases is of great importance for a multi frequency receiver. A common design for all frequency bands (L1, L2, E5 and E6) facilitates this as it is likely that variations due to temperature, aging, and the like will have a similar effect on all frequencies. Therefore the Artus design exclusively utilizes the 240 MHz IF output of the RF-ASICS on all frequencies.

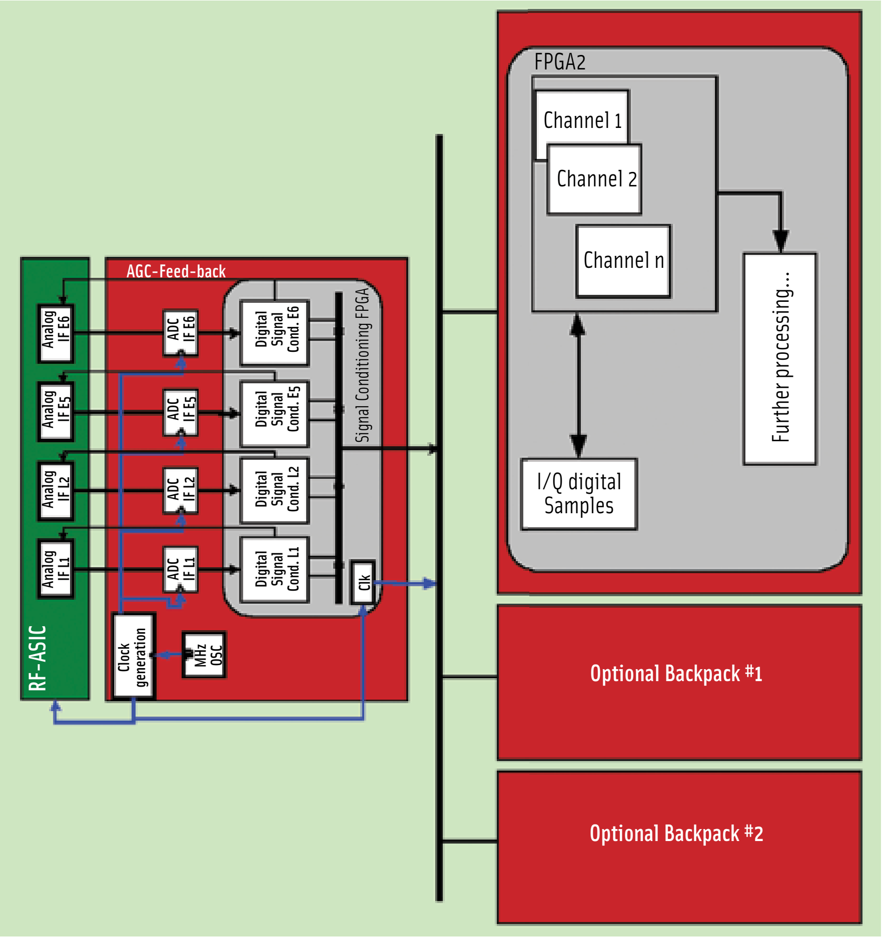

FIGURE 4 Digital signal conditioning and baseband processor

Digital Baseband Processing

Figure 4 shows the communication between the RF ASIC board and the digital signal conditioning portion of the receiver. The signal conditioning part provides a 2 MHz clock signal, which is synthesized from a 10 MHz reference clock, to the RF-ASICs (the green block in Figure 4).

The common 10 MHz clock source is generated by a temperature compensated crystal oscillator (TCXO). The higher clock frequency required for the ADCs are synthesized by a PLL.

For each frequency, the IF output of the RF chips is used. All IF signals are sampled at 300 MHz. This simplifies the design and ensures that all frequency bands are treated as similarly as possible, which is important for minimizing inter-frequency biases.

It is also important that the clock signal, derived from the same source, is used for both the analog and digital chains. 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 AGC and fed back to the RF board.

Figure 5 shows the routing of the signals and clock output from the signal conditioning to each baseband processor. The advantage is that each baseband processor can then be configured to process at any signal band. For example, all baseband processors can be configured to process L1 or, alternatively, one baseband 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, the daughter board connectors have been chosen so that the GATE baseband board can be used as an optional expansion board. (However, due to the Eurocard form factor of the GATE baseband board, only one GATE board can be plugged onto the ARTUS motherboard and, in this case, no optional expansion board is available).

The accompanying photograph shows the ARTUS motherboard enhanced with one GATE baseband board (the back-packed board on the right side). Two other connectors on the left side of the board hold another optional daugh-

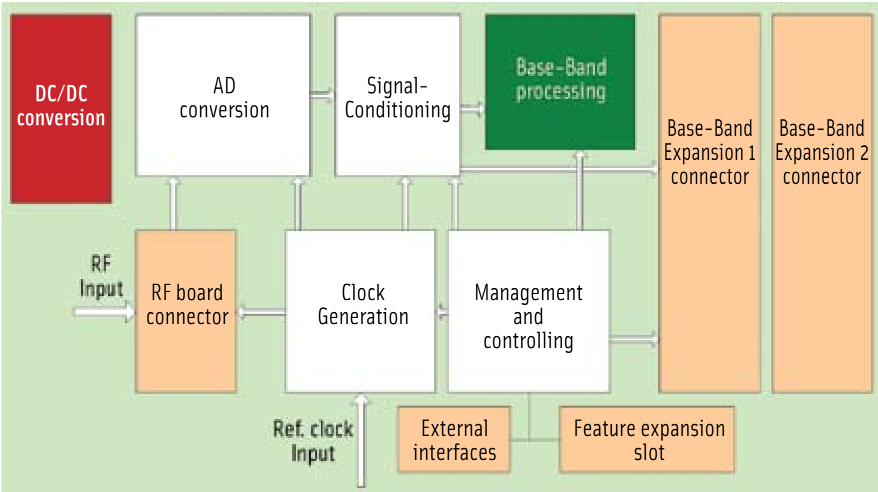

FIGURE 5 **Block diagram of base band processor (including A/D conversion, digital signal conditioning and optional daugtherboards**

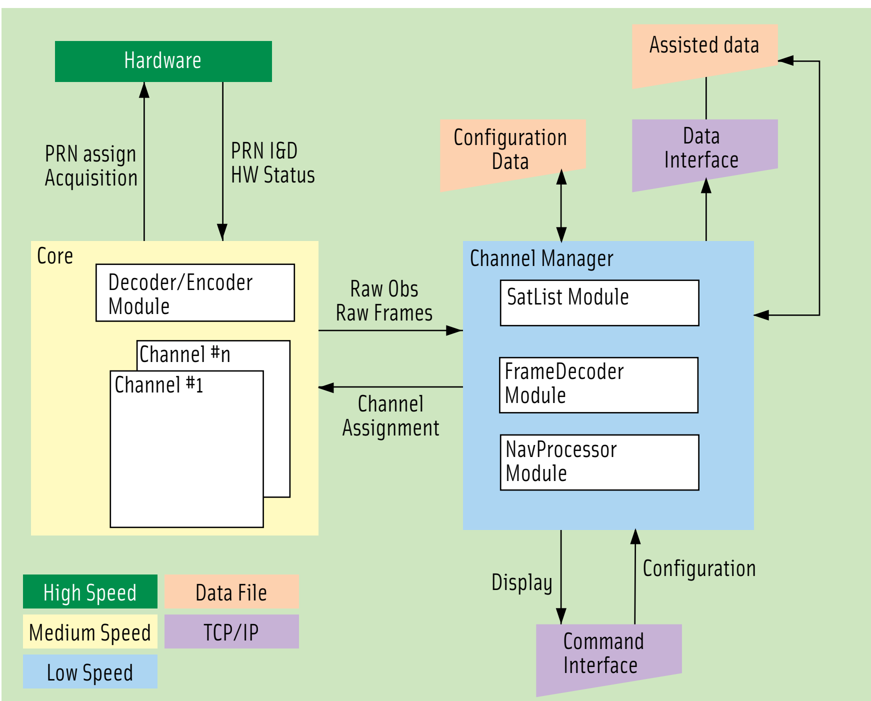

FIGURE 6 **Detailed base band block diagram.**

ARTUS motherboard with optional daughter board.

ter board (upper connector) and the RF front end. (Neither is connected in the photo on the left.)

The motherboard can accommodate both ADC ICs (four ADCs in two chips) and the field programmable gate array (FPGA) for signal conditioning above the RF front-end connector.

Figure 6 visualizes the further baseband processing following signal conditioning. This 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 (pseudorange, accumulated Doppler range, and so on).

While 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. Further, the main system CPU, which performs channel management and user IO, is realized as soft-core within a 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 that 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 implemented easily. Therefore, an ARTUS receiver can always acquire and track additional signals so long as the basic design of those signals is similar to the established GNSS signals. To acquire the Compass signal, for example, we only had to make minor software changes and download the spreading codes to flash memory, as will be discussed later.

Navigation Software

The navigation software of the prototype receiver is hosted outside of the receiver on a separate laptop. 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 also allows positioning employing the input of data from additional stations or auxiliary information obtained through the Internet.

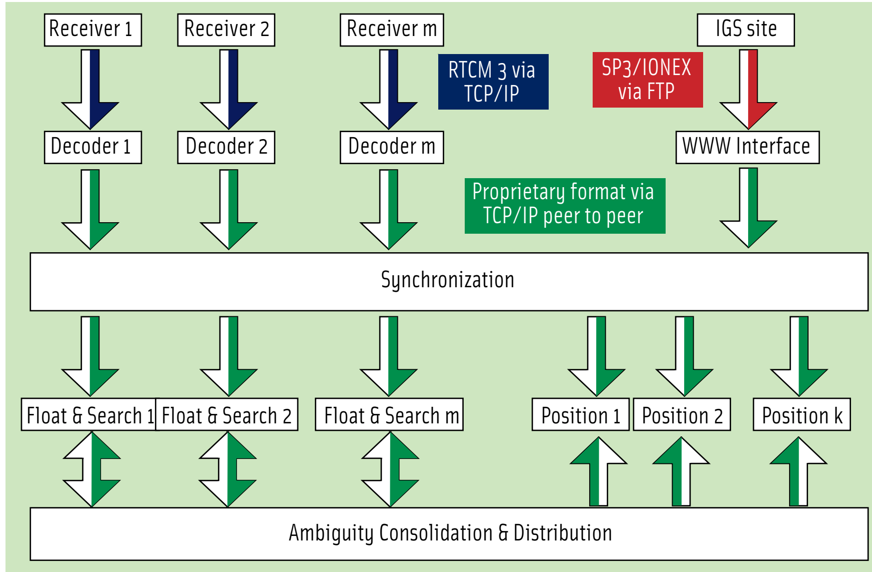

FIGURE 7 **Schematic of navigation software module layout**

The navigation software is based on object-oriented design in C++. **Figure 7** shows an overview of the navigation software's internal design. The application consists of a number of different modules performing the various computational tasks.

Beginning at the top level, various *decoder modules* receive information from a connected ARTUS receiver or information from reference stations that can be used for the positioning. Each connected receiver/station will have an associated independent decoder module.

The role of these modules is to transform in-coming data to an internal data representation. For maximum flexibility, we chose a standard protocol for the interface of the raw observation information. This is the popular Radio Technical Commission, Maritime (RTCM) V3 (2006) supported by all manufacturers of high-end GNSS user equipment.

Standard RTCM V3 messages have already been released for GPS operations. Suitable Galileo messages have also been drafted within the RTCM Special Committee 104, but those are not ready for release. The ARTUS implementation for Galileo is based on the draft version of an RTCM working group document. Connectivity is guaranteed based on the TCP/IP protocol.

Another module enables Internet connectivity for updated information on long-term orbit (LTO) predictions or other auxiliary information such as observation biases and antenna phase center offsets. Both types of modules increase the interface to offboard data sources, handing over the information to the synchronization module.

The next level down shows a *synchronization module* that has the responsibility for buffering in-coming information until it is used for processing. This is especially important for information received via the Internet with associated delays. The module also needs 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 receive all their information via the synchronization module. An *ambiguity consolidation and distribution module* is responsible for collecting and storing any detected integer ambiguities and holds them ready for use within the different processing modules.

The actual processing of the observations is performed in *data processing modules,* which use identical source code. Their actual task is determined through various properties that define the complete computational scheme for processing. (A detailed description of the property scheme can be found in the article by H-J. Euler and J. Wirth listed in the Additional Resources section near the end of this article.)

- *Float and search modules* carry out float ambiguity solutions and the subsequent integer ambiguity search and integer fixing. After having the integers confirmed by statistical means, these are communicated to the *ambiguity consolidation and search module.* The float and search modules may also obtain integer information for constraining a solution.

A final category, the *position* or *production modules*, receive the integer ambiguities from the ambiguity consolidation and distribution module. These position modules then carry out the calculations defined through a set of properties supplied during their start-up in the application.

Several of these modules may run in parallel. For instance, one module may provide a navigation solution while another is providing a rover position involving different reference stations. Or the production of network real-time kinematic (RTK) information may be supplemented by monitoring the reference station coordinates. The flexibility of the ARTUS concept's implementation allows many different application constellations.

Proof of Concept Tests

Several tests have been performed with the ARTUS breadboard to prove the basic system conception.Although the GATE test bed is not fully functional yet, IFEN had the opportunity to perform some testing in GATE as part of the test facility's final qualification review process. Because the GATE system has not reached operational status yet, these tests are to be considered preliminary; so, no performance figures are derived here.

The purpose is simply to show that the ARTUS prototype is fully functional within the GATE test bed. However, generally it can be said that the performance corresponds to what is to be expected (such as code phase jitter as function of C/No).

GATE Trials. To test the receiver performance for Galileo signals, several static and kinematic tests were performed in the German Galileo Test and Development Environment (GATE). These were

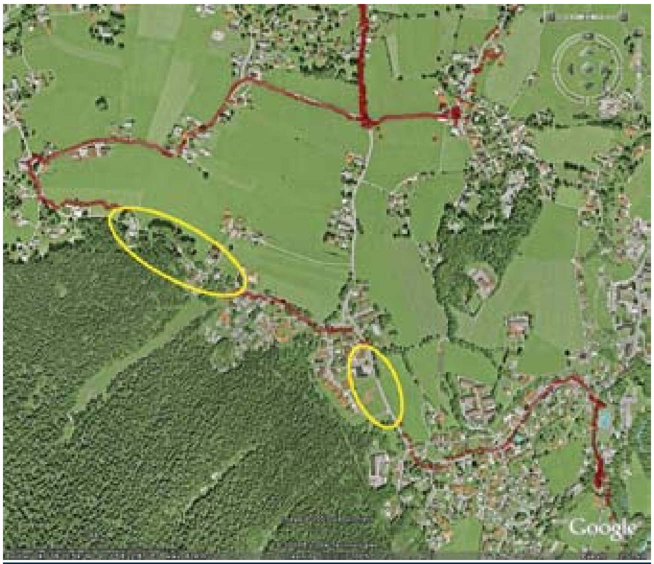

FIGURE 8 GATE dynamic positioning test in extended base mode

low-dynamic tests with an average speed of about 30 kilometers per hour.

Figure 8 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-sight (LOS) signals from some GATE transmitters by trees and buildings (marked by yellow ovals), a position fix could not always be achieved, especially in the southern portion of the test area. A more detailed result is shown in **Figure 9** for a fast accelerated vehicle employing Galileo L1 signals only.

SIS Trials. By proper configuration of the base band processor, the breadboard was able to track — beneath GPS and GIOVE-A signals — the Compass E2 and E5b signals in space. **Figure 10** shows the user interface to the receiver listing the first 13 channels. Channel 1 and 17(not visible) are tracking the Compass signal on E2 and E5b while channel 2 is assigned to the GIOVE-A signal on L1-B (shown in Figure 10 as Galileo signal on PRN 51).

The figure shows 10 GPS signals being tracked (listed in the "Measurement Viewer" widget in the upper right-hand corner). The map view indicates the position, represented by the + sign on the map, 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 wideband 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

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

and uploading the relevant primary and secondary codes to the correlators, the Compass signal could be easily tracked

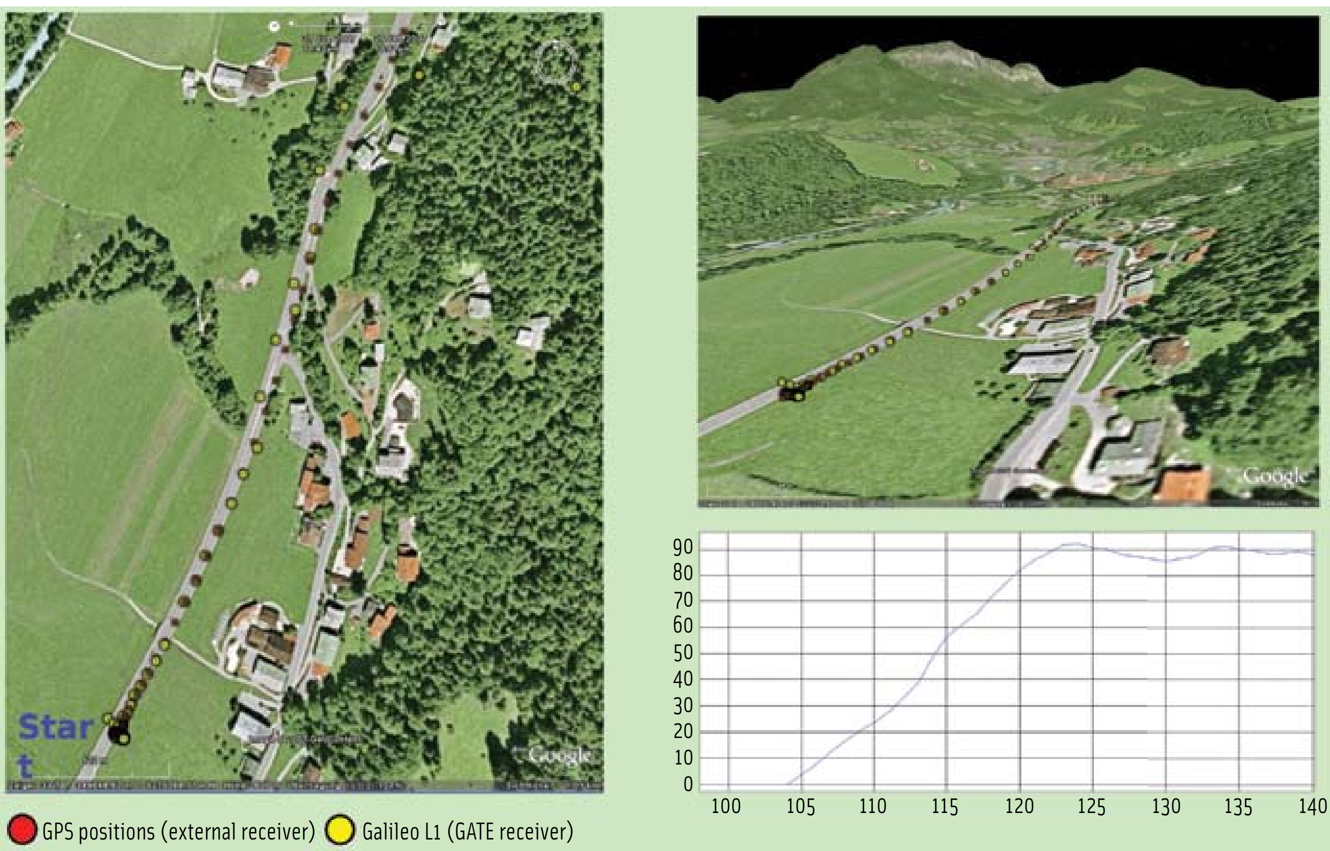

FIGURE 9 Dynamic positioning on Galileo/GATE L1 versus GPS

at E2 and E5b. By configuring the preamble and navigation message length, using information from the article by W. De Wilde et alia listed in Additional Resources, we were also able to perform frame sync and to calculate a pseudorange measurement (Figure 12).

Conclusion

The ARTUS GNSS receiver described in this article offers a rich flexibility for various configurations of signals on different RF bands. The high performance antenna in conjunction with a flexible RF front-end design offers excellent performance on all currently available GNSS signal bands, including the upcoming Galileo system.

With the availability of up to 120 channels, the receiver is well equipped for future navigation systems; however, it can also be configured in a version with only 20 or 40 channels for tracking the currently available GPS (L1 and L2) alone.

The modular concept, applied even for the firmware of the baseband processor FPGAs, allows easy adaptation of the algorithms developed for the ARTUS receiver or fast implementation of new algorithms. And if the IP protocol is used, any user interface can easily connect — even remotely — to the receiver — whether for navigation or monitoring purposes.

The ARTUS project is now in its qualification phase. Further developments aim for the commercialization of the receiver.

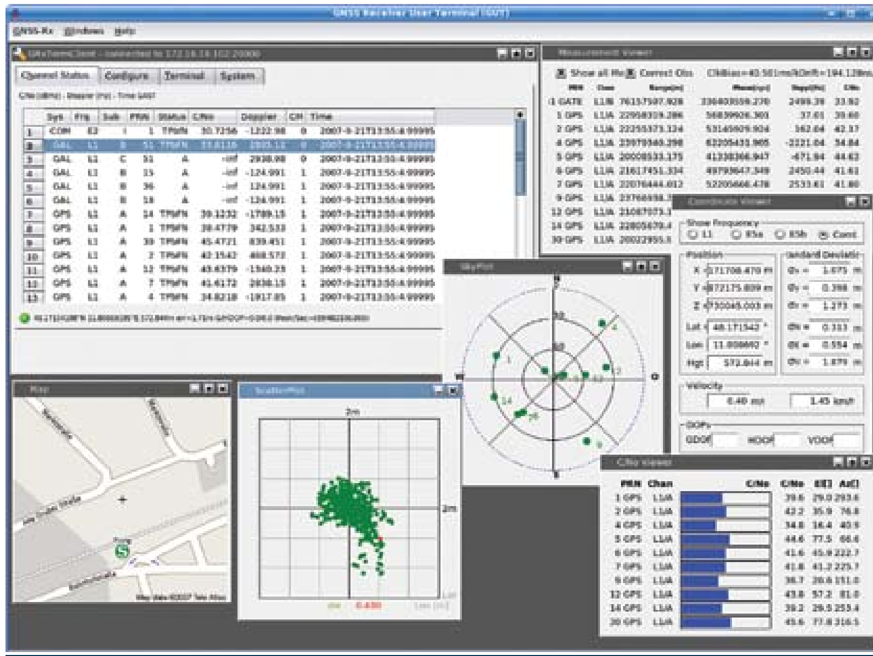

FIGURE 10 User interface showing tracking of GPS, Compass (E2 and E5b) and Giove-A

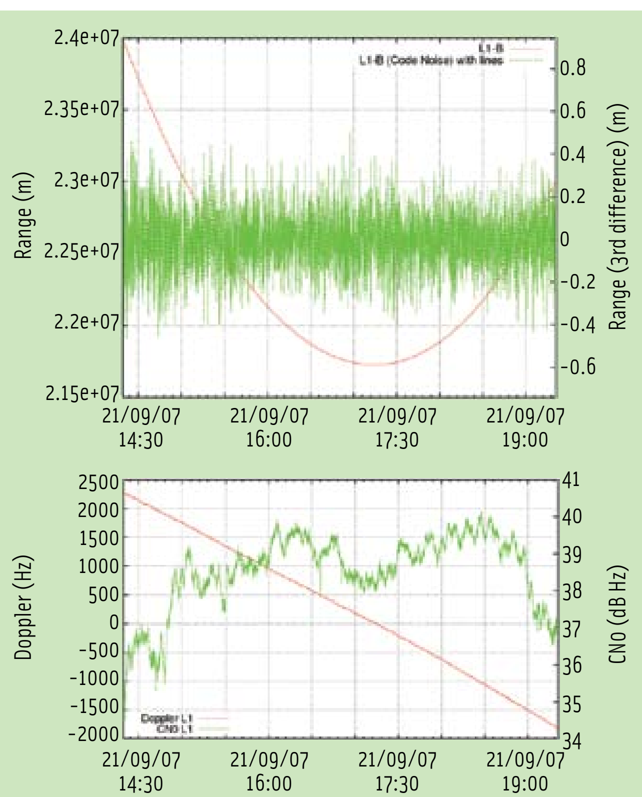

FIGURE 11 GIOVE-A signal in space tracking on L1

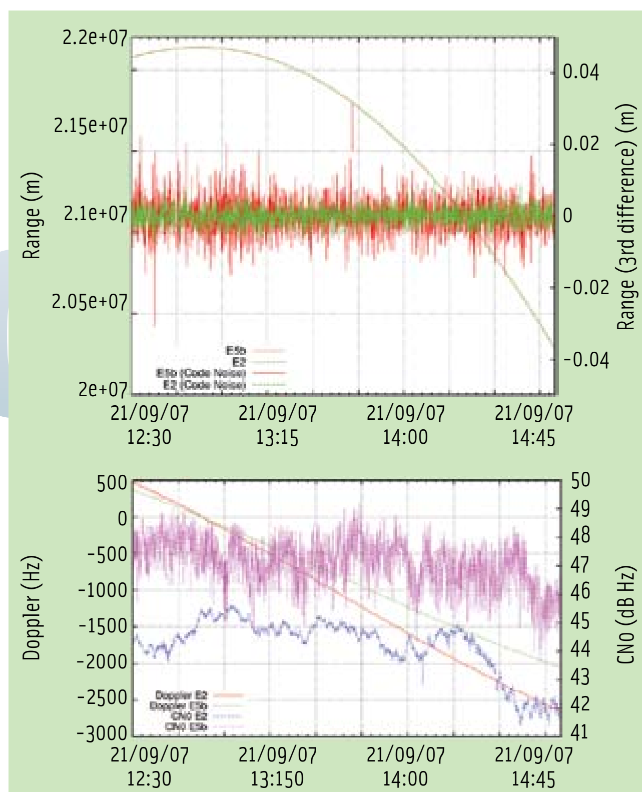

FIGURE 12 Compass SIS tracking on E2 and E5b

Acknowledgment

ARTUS was developed in the framework of a GJU 50 percent–funded project, contract GJU/05/2414/CTR/ARTUS. These activities have been taken over by the European GNSS Supervisory Authority (GSA). This support is gratefully acknowledged. IFEN served as the principal contractor for ARTUS.

The consortium members involved in the ARTUS receiver development are IFEN (overall system design and baseband processing), NemeriX (analog RF-front-end), Roke Manor Research (antenna and RF splitter), Leica Geosystems and inPosition (RTK software). In essence the ARTUS design is based on previous receiver developments carried out by IFEN in the frame of the German Galileo Test Bed (GATE).

GATE is being developed on behalf of the DLR (German Aerospace Center, Bonn-Oberkassel) under contract number FKZ 50 NA 0604 with funding by the BMWi (German Federal Ministry of Economics and Technology). DLR kindly gave its permission to publish the preliminary test results.

Manufacturers

The RF ASIC used in ARTUS is the NJ1008 from **NemeriX**, Manno, Switzerland; the earlier generation RF ASIC is the NemeriX NJ1007. The simulated GNSS signals were generated by a NavX-NCS from **IfEN GmbH,** Poing, Germany. The ARTUS receiver integrates the TRI-G07 antenna from **Roke Manor Research Ltd.**, Romsey, Hampshire, United Kingdom, Virtex5 FPGAs from **Xilinx**, San Jose, California, USA, and ADF4110 PLLs from **Analog Devices**, Norwood, Massachusetts, USA. The medium- and low-speed baseband processing following signal conditioning is executed on Xilinx Microblaze soft-core CPUs. Figures 8 and 9 are displayed on Google Maps by **Google Inc.**, Mountain View, California, USA.

Additional Resources

[1] De Wilde, W., and F. Boon, J-M. Sleewagen, and F. Wilms, "More Compass Points—Tracking China's MEO Satellite on a Hardware Receiver," *Inside GNSS,* 2(5):44–48, July/August 2007

[2] Euler, H-J., and J. Wirth, "Novel Concept in Multiple GNSS Network RTK processing," ION GNSS 2007, The Institute of Navigation, Fort Worth, Texas, September 2007

[3] Gao, G. X., , and A. Chen, S. Lo, D. De Lorenzo, and P. Enge. "GNSS over China - The Compass MEO Satellite Codes." *Inside GNSS,* 2(5):36–43, July/August 2007

[4] Heinrichs, G., and E. Loehnert, E. Wittmann, and R. Kaniuth, "First Outdoor Positioning Results with Real Galileo Signals by Using the German Galileo Test and Development Environment - GATE," ION GNSS - 2007, The Institute of Navigation, Fort Worth, Texas, September 2007

[5] Lück, T., and E. Gohler, M. Bodenbach, J. Winkel, and F. Forster, "The GATE Receiver—A Full-Scale Galileo/GPS Monitor Receiver," ION GNSS 2006, The Institute of Navigation, Fort Worth, Texas, September 2006

[6] RTCM Special Committee Number 104, *RTCM Standard 10403.1 for Differential GNSS (Global Navigation Satellite Systems) Services,* v3 edition, October 27, 2006

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Steve Simpson graduated from the University of Salford with a degree in electronics and went on to gain a P.hD. from Sheffield. He currently leads the electromagnetic engineering group at Roke Manor Research Ltd., Romsey, Hampshire UK.

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