All constellation, all frequency - a receiver platform for monitoring and testing

Th. Lück, J. Winkel, M. Bodenbach,
O. Balbach, N. Falk , E. Göhler, T. Hartmann, A. Naumann
IFEN GmbH, Germany, Poing

BIOGRAPHY

Thorsten Lück studied Electrical Engineering at the Universities in Stuttgart and Bochum. He received a PhD (Dr.-Ing.) from the University of the Federal Armed Forces in Munich in 2007 on INS/GNSS integration for rail applications. Since 2003 he is working 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 modelling 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.

Oliver Balbach studied Electrical Engineering at the Technical University in Munich. He joined the receiver technology division of the IFEN GmbH in 2006.

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.

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.

Tobias Hartmann received his diploma in Telecommunication Engineering from the University of Applied Sciences in Ulm. Since then he works for the IFEN GmbH in the receiver technology department focusing on RF Front End development.

Andreas Naumann studied Electrical Engineering at the University of Applied Sciences in Munich. After developing a processor platform for distributed real time systems in his thesis, he has been working on embedded systems for telematics applications and GNSS receivers. Since 2008 he is working as embedded software developer in the receiver technology division of the IFEN GmbH.

ABSTRACT

This paper describes a recent development of the **NavX®-NTR** GNSS receiver series. The multi-frequency front-end allows to receive and process satellite navigation signals on up to six different Rf carriers. The **NavX®-NTR** is thus able to acquire and track all civil GPS, Galileo and GLONASS signals but is not limited to these signals. Different use cases for a navigation test receiver are defined and examples of these use cases are presented.

INTRODUCTION

The modernisation of existing and creation of new global and local navigation satellite systems introduce many new signals at different RF frequencies and modulations. However, the general structure of all these signals is very similar and allows a unified approach for signal acquisition and tracking. The future availability of navigation signals from different global navigation satellite systems (GNSS) in turn offers a remarkable capability for integrity monitoring - either global or regional.

The present paper discusses the need for monitoring receivers tracking the complete spectrum of navigation signals and introduces the design of a high-end receiver, which accommodates (nearly) all currently available, modern signals for satellite navigation. In essence the receiver is based on the modular design of a previous receiver development carried out by IFEN based on base band technology developed for the German Galileo Test Bed (GATE), and which underwent further development in the frame of a EU funded project named ART-X (figure 1) .

Key features of this receiver architecture are

- six radio frequency front-ends with up to 85 MHz bandwidth each
- independently assignable channels
- SC^3channel architecture to combine sub-modulations in one single hardware channel
- excellent group delay and inter-frequency bias stability
- scalable modular design
- dedicated feature expansion module to implement customer specific processing on hardware
- embedded Linux on powerful Arm Cortex A8 processor with the possibility to implement customer specific software algorithms on second processor module

The discussed receiver is based on a digital main-board, carrying up to three base band pre-processor boards, an analogue front-end board, an optional so-called feature expansion board and two processor modules. An optional 3.7 inch touch screen display with VGA resolution allows direct user interaction on the front panel of the two height units and 32.5 cm wide housing. A 19 inch rack mountable housing is optional.

Fig. 1 Multifrequency GNSS receiver **NavX®-NTR**

One of the key feature of the receiver is the capability to process any of the up to six different front-end signals with each digital base-band channels provided by the base-band pre-processor modules. This allows even to process signals from any supported GNSS simultaneously on one single base-band pre-processor module. With up to 28 channels per base-band pre-processor module a total of up to 84 independent channels are available, each comprising IFEN's SC^3(signal component combined channel) technology, allowing to track both, data and pilot signal in one SC^3channel.

The RF front-end board allows up to six different standard or customer-selected RF signals to be down-converted to an analogue intermediate frequency. A bunch of six high-speed synchronised analogue to digital converters (ADC) on the receiver main-board digitise the analogue signal. The use of ceramic RF filters as well as synchronised ADC guarantee extra stable group delay and - in turn - inter frequency biases; for instance the absolute group delay variations over 24 hours at a temperature range of 21°C ± 1.5°C is better than 100 ps (1 sigma). Code minus carrier stability over the same time interval of 24 hours is better than 120 ps.

Digital signal conditioning in terms of digital filtering and complex down-conversion is performed in a main-board located field programmable gate array (FPGA), which also communicates with the RF modules for signal identification or automatic gain control. In addition this FPGA is responsible for interference mitigation by implementing mitigation technologies like e.g. pulse blanking.

The digital complex data stream of all six analogue channels is streamed to the base-band pre-processor modules, currently realised by additional FPGAs on dedicated modules. This opens the opportunity to replace the FPGAs with ASICs or other FPGA technology on availability. These modules incorporate the correlation engine with up to 28 SC^3channels per module. Each of these channels is freely assignable to any of the six input data streams. The modules have a direct connection to the feature expansion board, allowing additional functionality to be implemented like IF data streaming interface or PRS tracking.

Using a general purpose memory interface, the modules can be easily accessed using a standardised general purpose memory controller (GPMC) interface which is commonly available on many modern processors. The main-board allows to plug in up to two so-called System on Module (SOM) boards, of which one has the GPMC connected to the base-band pre-processing modules. The SoM modules are based on a powerful ARM Cortex A8 processor core running at 600 MHz. While the one connected to the correlation engine is responsible for software based signal acquisition and tracking, the second processor module performs navigation processing and channel management. Both processors - running an embedded Linux - are connected via internal LAN interface.

The main user interface is realised through a 100BASE-T LAN interface. Commanding is performed through a text-based telnet interface, which may be tunneled through a SSH connection for enhanced security. All measurements (observations, navigation message, etc.) can be transmitted either through UDP or TCP datagrams.

The discussed receiver platform is used in a variety of flavours, e.g. as monitor receiver for the German Galileo

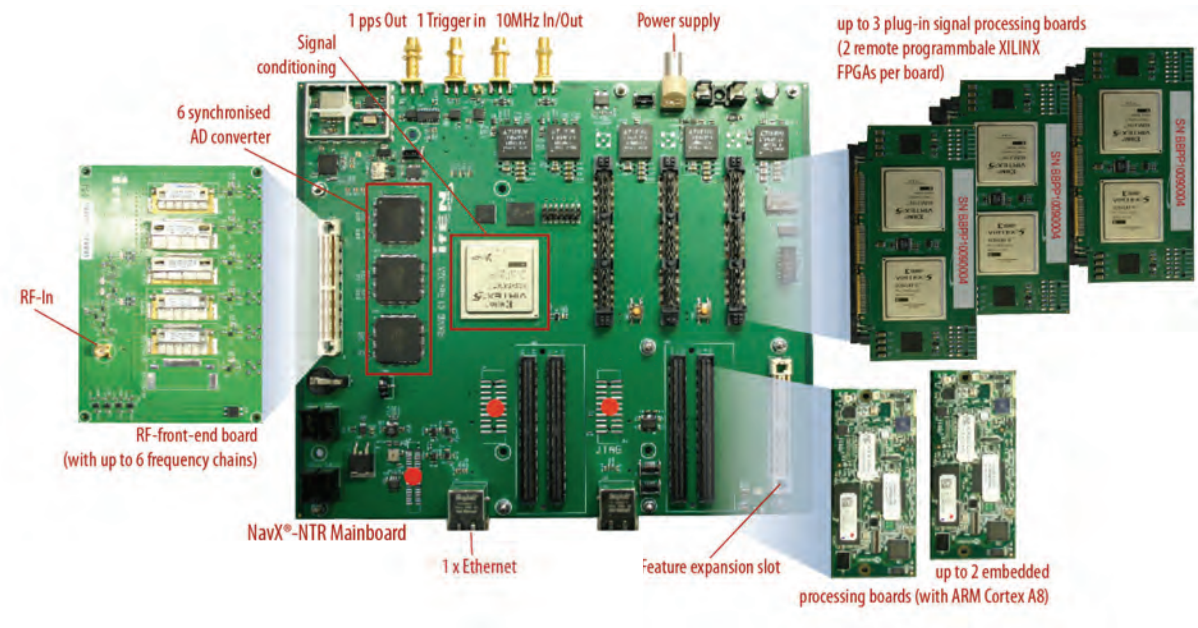

Fig. 2 Architecture of **NavX®-NTR**

Test Bed (GATE), as payload test receiver for the Galileo IOT phase or as test user receiver within GATE. It has also been tailored for the breadboard of the next generation regional integrity monitoring receiver using five RF signals (out of six), allowing to process signals on L1/E1, E5 (with E5a/L5 and E5b), E6, L2 and Glonass L1, which is also planned as baseline for the test user receiver within the European high integrity testbed.

The base band processing currently supports the complete Galileo spectrum (OS and CS) including CBOC and AltBOC, GPS L1 (including TMBOC), L2 (semi-codeless P(Y), L2C) and L5, SBAS L1 and L5 and Glonass G1 and G2. Where a signal supports both, data and pilot channel, the SC3 channel tracks the pilot signal but also correlates against the data signal to decode the navigation message. This mode is supported for interplex, QPSK or time multiplexed modulations. Compatibility with GIOVE SiS ICD allows an early performance verification in the range domain before Galileo full constellation deployment. Beneath the standard features the RIMS Next Generation breadboard offers an additional reference clock input and a serial interface to monitor a receiver external rubidium frequency standard.

This paper discusses the demanding requirements a receiver must fulfil as an integrity monitoring receiver and how these can be achieved. Beneath the presentation of performance results a major topic is the discussion on measurement engineering and instrumentation. In addition, a "performance analysis tool" (PAT) is presented which is used for receiver performance analysis.

Overall, the modular design and flexibility in hardware and software evolution allows this receiver not only to be used for monitoring purposes but keeps the door open to evolve to a full test user receiver with additional data processing being implemented in software on the second processor module. The sixth RF path is currently used for Glonass L2 processing, adding a second source for dual frequency measurements before Galileo is available.

The next section will give a more detailed view on the architectural design of the receiver, pointing out specific features to fulfil the demanding requirements for a test and reference GNSS receiver following a section providing some performance features and assessments.

Special emphasis is placed on different use-cases for a test and reference receiver in the sub-sequent chapter.

A more detailed overview of the architectural design of the receiver is shown in figure 2.

ARCHITECTURAL OVERVIEW

The IFEN 3rd generation GNSS receiver **NavX®-NTR** is accommodated in a 19 inch, rack mountable, 2 HU frame (figure 1).

Receiver functionality is implemented though re-configurable hardware on the main board and base band pre-processor boards as well as through software modules for signal acquisition and tracking, channel management, PVT and user interface.

Fig. 3 Fully configured **NavX®-NTR**

Figure 3 shows the system in its full configuration: three pre-processing modules and two SoMs. The six frequency RF front-end system consisting of two PCBs is also shown.

The main board is designed to host two system-on-a-chip modules (SOM). The primary role of these modules is to perform the loop-closure (DLL/PLL/FLL) in software as well as generating the PVT solution and implement the overall high-level control of the receiver.

The signal coming from the antenna enters the so called “filter-board” of the front-end sub-system consisting of two pcb’s: the “filter-board” and the “mixer-board”. To support low- or no-gain-antennas (passive antennas) a 15 dB gain low noise amplifier can be enabled in the radio-frequency path by on-line commanding. With this LNA, the noise-figure of the radio-frequency front-end is almost better than 1.2 dB. A subsequent two-way splitter following a second LNA and three-way splitter divides the Rf signal into six path before the Rf filtering is applied by means of 6th order ceramic band-path filters (figure 4). A standard configuration comprises the following six typical GNSS signals: L1/E1, L2, E5 (including L5), E6, GLONASS L1 and GLONAS L2

The “mixer-board” (figure 5) down-converts the radio-frequency signal to an intermediate frequency of approximately 80 MHz. A final gain controlled amplifier (AGC) allows a dynamic range of 30 dB. Together with the first stage 15 dB LNA, the total dynamic range is 45 dB allowing the use of a wide variety of different GNSS antennas and/or long antenna cables.

Three 12 bit analog to digital converter chips with two ADC’s each digitise the analog intermediate frequency signal at a rate of 340 Mega samples per second. All ADCs are synchronised to each other with respect to the 10 MHz reference clock to guarantee constant inter frequency biases and phase delays also over power cycles. The generation of the local oscillators on the front end board is controlled by an embedded micro controller in the signal conditioning FPGA, based on stored values in an EPROM of the front-end. This allows to change the front-end to allow other frequency plans easily.

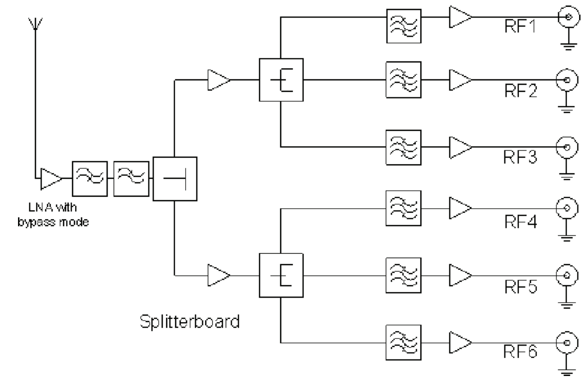

Fig. 4 Rf splitter board

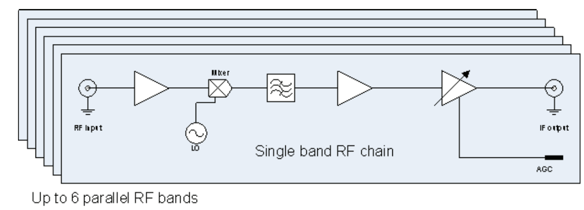

Fig. 5 RF to IF mixer board

The signal of each digital IF path is pre-processed by the signal conditioner before fed to the correlator banks located in the base-band pre-processing boards. This signal conditioning comprises digital down-conversion to near base-band as well as configurable band limitation and in-band interference detection and mitigation (“pulse blanker”).

Signal correlation (“high speed base band processing”) is performed in up to three pre-processor boards. They implement in two FPGAs per pre-processor board up to 15 SC^3channels [2] as shown in figure 6. Each pre-processor board is connected to all six digital signal pathes. This allows great flexibility in channel assignment to a dedicated signal.

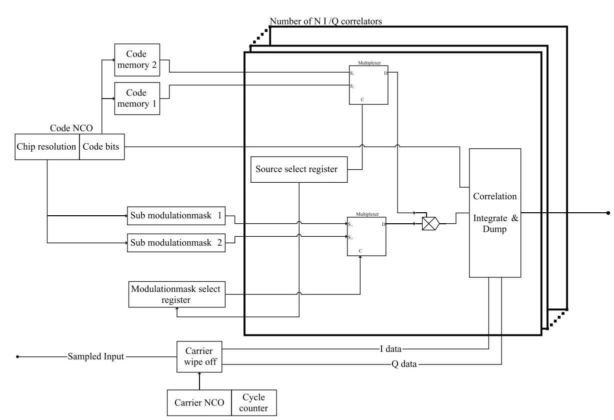

Fig. 6 Complex Channel Structure

The SC^3architecture also allows to use - beneath memory based codes - long generated codes like GPS L2C, GPS L2P or Glonass P. *Non-coherent* coupling of two adjacent channels allows to track GPS L2P(Y) using a semi-codeless approach while by *coherent* coupling of two adjacent channels the number of correlators are be doubled allowing to track the complete AltBOC signal in one coherently coupled channel (using two SC^3channels). Depending on the configuration, 8 or 10 correlators are located in each channel. Free correlators which are not used for tracking can be used to scan the autocorellation function. This can be achieved as every correlator can be positioned within ± 1 chip around the prompt position.

An ARM CortexA8 based processor performs the signal acquisition- and tracking tasks. Embedded in a System-on-Module (SOM) it allows easy adaptation to changed processor performance needs by switching to a newer version of this SOM.

A second SOM is responsible for range calculation, PVT processing and implements the user interface. This also opens the opportunity for user based processing within the receiver.

An embedded web-server allows basic configuration tasks (e.g. change of IP-address or basic configuration files). Using this interface, all soft- and firmware (including all FPGA configuration files) can be updated (remote upgrade facility).

Channel configuration is performed through a text based telnet-like TCP interface and comprises along others channel assignment, configuration of loop-bandwidth, early-late spacing, coherent integration time or switch between internal/external reference controller. Observations are provided via a binary UDP or TCP interface and comprise range observations (code-/carrier-range), CN0, Doppler, PVT-solution, residuals, visible satellites and other.

The receiver design includes a special feature expansion bus, connecting signal conditioning, base-band–preprocessing and the CPU using a feature expansion board. This interface can be exploited for customer specific needs, e.g.

- Real-time signal generation of e.g. Line-of-sight PPS
- Real-time signal generation of carrier or code-NCO derived values (phase, frequency)
- Streaming of IF samples via e.g. PCI express

To complete the receiver, a graphical user interface is available to configure the receiver and visualise the observations. This utility can also be used to log all observations to a file and convert them to standardised Rinex 3.0 files (figure 7). IFEN's GNSS Simulation and Processing Framework **GSPF®** can also be connected to the receiver for real time and post-processing user processing or performance assessment (see below).

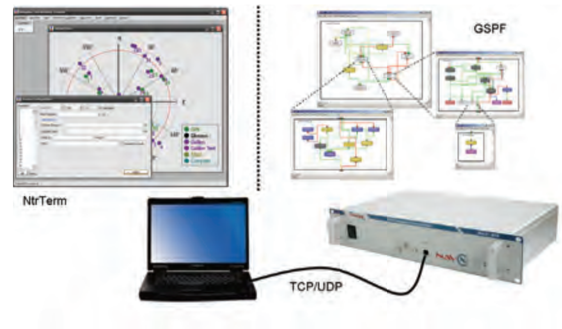

Fig. 7 NTRterm - The Graphical User Interface to the **NavX®-NTR**

PERFORMANCE ASSESSMENT

The receiver as described in the previous section allows to process the complete spectrum of currently available disclosed (and partially undisclosed) GNSS signals (see also figure 8):

- GPS L1 C/A (TMBOC[1])
- GPS L2 P-Code (codeless/semi-codeless[1]) & L2C
- GPS L5
- Galileo E1 (BOC / CBOC)
- Galileo E5ab (AltBOC)
- Galileo E6 (w/o encryption)
- GLONASS G1 (standard/precision[1])
- GLONASS G2 (standard)
- SBAS (WAAS, EGNOS, MSAS) L1, L5
- COMPASS B1
- COMPASS B2

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Supported signal modulation schemes are

- Phase Shift Keying (BPSK, QPSK)
- Binary Offset Carrier ($BOC_{cosine,sine}$, up to BOCc(15,2.5), CBOC, AltBOC)
- Tri-Phase Interplex (CASM)
- FDMA

In the default configuration, the front-end uses the following Rf bands:

[1] prepared for / upcoming Q4/2011

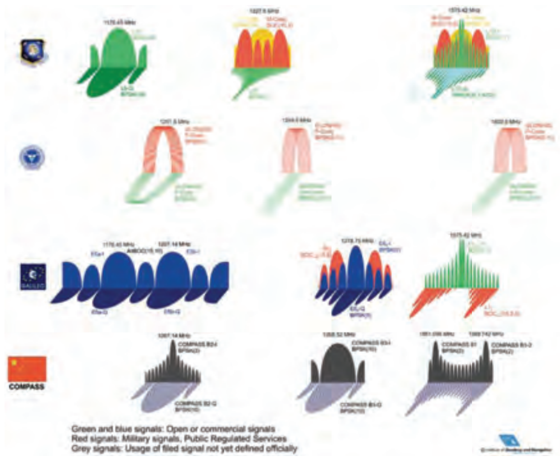

Fig. 8 Current and Upcoming GNSS Frequency Bands (University FAF Munich / Germany)

Name	Center Frequency	Bandwidth
E1 / L1	1,575.42 MHz	42 MHz
L2	1,227.60 MHz	24 MHz
E5	1,191.79 MHz	72 MHz
E6	1,278.75 MHz	42 MHz
G1	1,602.00 MHz	17 MHz
G2	1,246.00 MHz	17 MHz

The nominal input level of the receiver is at $-148\ dBm$, designed for use with a standard 25 dB medium gain GNSS antenna (first LNA in by-pass mode). The digital bandwidth is limited by the digital sample rate and allows a Nyquist bandwidth of 85 MHz. During system design, special attention has been turned to stability of the analog reception chain. Therefore the main characteristics can be stated to (1 sigma):

Description	Stability
Single channel group delay stability [24h]	$< 50ps$
Single channel phase stability [24h]	$< 10ps$
Inter channel group delay stability	$< 15ps$
Inter channel phase stability	$< 10ps$
Inter frequency group delay stability	$< 15ps$
Inter frequency phase stability	$< 10ps$
Group delay temperature dependency	$< 100ps/^oK$

These excellent performance values can be exploited to use this receiver also for payload and/or signal generator characterisation.

MEASUREMENT ENGINEERING AND INSTRUMENTATION

For a test and reference receiver several use cases can be defined. An overview is given in table 1. In the following, these use cases are defined, typical characteristics are presented and examples are given.

Payload Test Receiver

The receiver is used to characterise the transmitted signal of a signal generator like a payload generator or constellation simulator (e.g. validate satellite payload performance before launch (Payload Test System, PTS) or use as GATE test receiver (German Galileo Test Environment)). For this use case, the receiver is typically directly connected to the signal generator (probably attenuated). The receiver is used to characterise the signal performance with respect to

- Code-carrier coherency
- Code-code coherency
- Group delay stability
- Phase stability
- S-curve Bias
- Absolute group delay

To eliminate clock effects, the measurement setup is coherent with the receiver and signal generator sharing the same reference clock. To asses the performance with sufficient accuracy within reasonable time, a high signal to noise ratio is mandatory.

While C/N0 values of better than 110 dBm are theoretically possible (e.g. with ≈ -60 dBm channel power), the realised C/N0 is typically limited to ≈ 70 dB-Hz, depending on the sample resolution (digital noise).

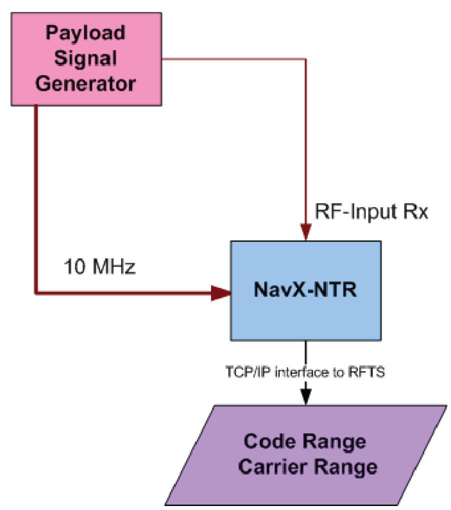

Fig. 9 Measurement setup for payload tests.

To minimise band-limiting effects, the analog filter shall be at least twice the signal bandwidth. As the receiver is directly connected to the payload, there is no need to reject unintended signals and the filter can be designed as anti-aliasing filters only. As the **NavX®-NTR** accomplishes an analogue-to-digital conversion rate of 340 MHz, the analog filters can be up to 170 MHz wide.

	Payload Test Receiver (PTR)	In-Orbit Test Receiver (IOTR)	Reference Station Receiver (e.g. RIMS)
Description	Payload directly connected to receiver (no antenna)	Single Satellite observed with high gain antenna with high directivity (high antenna gain)	Constellation observed with medium to high gain antenna (medium antenna gain; medium to high LNA)
Signal power at RF input	$\approx -55\mathrm{dBm}$	$\approx -140\mathrm{dBm}$ (assuming 30 dB LNA and 30 dB antenna gain)	$\approx -140\mathrm{dBm}$ (assuming 30 dB LNA)
RF bandwidth	Twice signal bandwidth	Signal bandwidth	Signal bandwidth
Expected C/N0	$> 100(> 70*)\mathrm{dB-Hz}$	$60-80\mathrm{dB-Hz}$	$30-50\mathrm{dB-Hz}$
Number of physical channels	low (track each signal component of one single payload)	low (track each signal component of one single payload)	high (track all in view)

Table 1 Overview of use cases for a navigation test and reference receiver (NTR)

A typical instrumentation like it is used for the Galileo FOC Payload Test System is shown in figure 9. The used **NavX®-NTR** has been customised to bypass the second stage amplifiers and populated with RF and IF filters with double signal bandwidth.

Due to the high input power level, the signal after despreading is well above the noise level - not only the main correlation peak but also the secondary lobes. Therefore the acquisition engine has been modified to identify the correct signal main lobe for tracking.

As only one satellite is tracked, the requirements with respect to number of channels are minimal. For Galileo, a receiver with eight channels is sufficient to track each signal component independently (E1 OS data and pilot, E1 PRS data and pilot, E6 CS data and pilot, E6 PRS data and pilot, E5 a and b data and pilot).

In-Orbit Test Receiver

The receiver is used to validate the transmitted signal of a satellite after launch (e.g. Galileo IOT, GIOVE A/B) using a high gain antenna with a small aperture (e.g. 7m dish with approx. 30 dB antenna gain). To mitigate near base-band and out-of-band interference, the bandwidth of RF and IF filter are chosen to comply to the signal bandwidth according to SiS-ICD. The expected C/N0 is well above 60dB-Hz, thus the signal is not necessarily embedded in the noise floor. Therefore special attention has to be turned to signal acquisition to avoid side-lobe tracking (see above).

The requirements with respect to number of channels are similar to the payload-test use-case as only one satellite is tracked at a time.

Monitor / Reference Station Receiver

The receiver is used to monitor the signal of one or more GNSS signals using a medium to high gain antenna covering the upper hemisphere (e.g. Roke Manor Tri-G08). This use case has the widest application spectrum and has been realised for e.g.

- RIMS-NG (next generation regional integrity monitoring station)(breadboard)
- Monitor station for the German Galileo Test Environment (GATE)
- User receiver for GATE
- Permanent monitoring station (24/7) at IFEN premises
- Experimental receiver platform to evaluate new receiver algorithms (e.g. SX5)

The RF front-end must be designed to mitigate near- and out-of-band interference. Furthermore the front-end shall mitigate in-band continuous wave (CW) and/or pulsed interference by means of pulse blanker and variable notch filters.

Depending on the application, the requirements for the number of channels are high. E.g. to track all in view of GPS, Galileo and Glonass, 94 channels are needed (maximum visibility in 99% of all cases):

- GPS: 10 satellites $\Rightarrow$ 30 SC^3channels (L1, L2, L5)
- Galileo: 11 satellites $\Rightarrow$ 44 SC^3channels (E1, E6, E5a/b or AltBOC)
- Glonass: 10 satellites $\Rightarrow$ 20 SC^3channels (G1 (CA/P), G2 (CA))

PERFORMANCE ANALYSIS TOOL

To asses the performance of the receiver (or the signal generator under test) IFEN's GSPF can be directly connected to the receiver. This GNSS Simulation and Processing Framework can be used for user processing (e.g. data preprocessing, PVT solution, integrity calculation, EGNOS, RAIM) but also for signal characterisation (e.g. multipath detection and mitigation, interference detection) and performance assessment (code/carrier noise analysis).

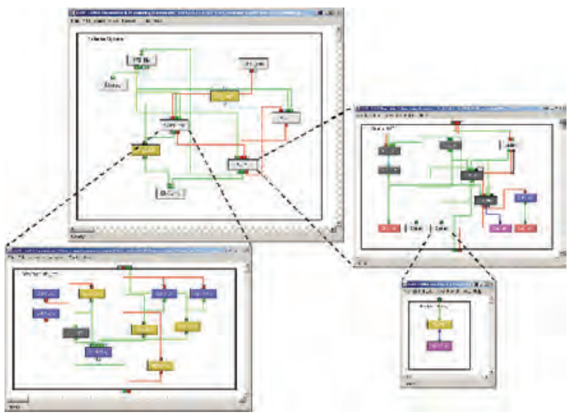

Fig. 10 GSPF Framework with GSPF kernel, data processing libraries and (default) configurations

Using unused correlators, it is also possible to produce "scans" of the autocorellation function, e.g. for the AltBOC function or sub-signals like the BOC(6,1) part of the CBOC signal (figure 11).

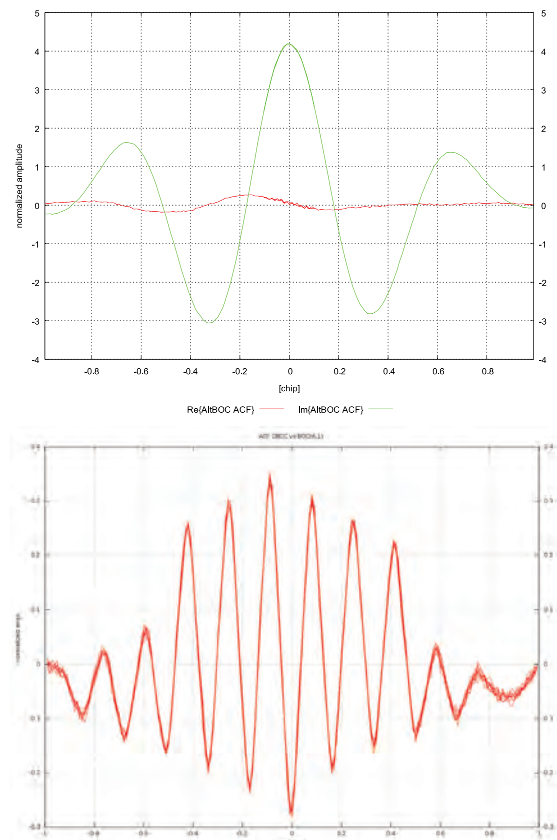

Fig. 11 Autocorrelation function reproduced using free correlators (upper: AltBOC, lower: BOC(6,1) component of CBOC).

REFERENCES

[1] Thorsten Lück, Jon Winkel, Michael Bodenbach, Eckart Goehler, Nico Falk, Angelo Consoli, Francesco Piazza, Danilo Gerna, Robin Granger, Peter Readman, Steve Simpson, and Hans-Juergen Euler. Artus - A Second Generation Galileo/GPS Receiver. Forth Worth, Texas, September 2007. The Institute of Navigation.

[2] Thorsten Lück, Jon Winkel, and Micheal Bodenbach. A Complex Channel Structure for Generic GNSS Signal Tracking. Savannah, Georgia, September 2009. The Institute of Navigation.