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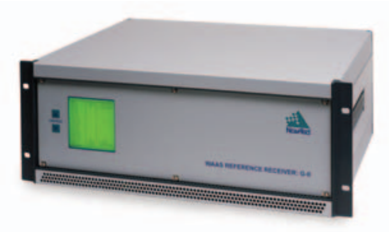
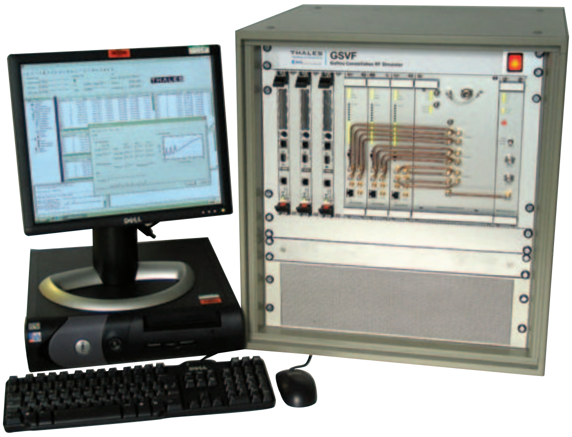
Testing a Prototype Galileo Receiver

The Galileo Test Receiver includes a new L1/E5a receiver card integrated into a modified version of a WAAS ground reference receiver. Its modular nature will enable developers to add other frequencies and services to the unit in the future. A single-channel L1/E5a Galileo transmitter, completes a final deliverable system for in-lab demonstrations and signal-in-space testing purposes.





WAAS G-II receiver enclosure of the Galileo Test Receiver, left, and TRT GSVF Galileo Constellation Simulator (right, photo courtesy Thales Research and Technology, UK)

Neil Gerein, Michael Olynik, Michael Clayton, Jonathan Auld, and Tony Murfin

Once the Galileo system is operational, the vast majority of all user receivers sold will be both GPS- and Galileo-capable. Much work needs to be done to produce Galileo-capable receivers. Multiple signal types, multiple frequencies, and the new binary offset carrier (BOC) modulation scheme make receiver design challenging. Initiating a prototype receiver design effort now, in advance of a finalized signal specification, will reduce the design risk in years to come.

The Galileo System Test Bed version 2 (GSTB-V2) satellites, scheduled for launch in late 2005/early 2006, will broadcast the first Galileo signals in space. These initial test satellites will provide a representative signal to secure frequency filing and to drive initial tests. As many as four In-Orbit-Validation (IOV) satellites will follow the GSTB-V2s in the coming years. IOV satellites may incorporate slight signal-in-space interface changes when compared to the GSTB-V2 satellites. The Full Operation Capability (FOC) phase, expected to complete towards the end of this decade, will follow the IOV phase.

User benefits from receiving signals from both constellations will include improved accuracy, reliability, and availability. Currently, GPS users may find the signal path to the satellite constellation obstructed by buildings, trees, bridges, or other forms of signal blockage. With twice as many satellites available in the sky, the probability will be much lower that signal blockage will interfere with the user navigation solution. Applications that are currently marginal or impossible will become viable and cost-effective for users.

A signal-in-space is currently not available to allow testing of prototype receivers,

NEIL GEREIN is a GPS software engineer with NovAtel Inc. He has been involved with Galileo based receiver studies for the past four years.

MICHAEL OLYNIK is a GPS software engineer with NovAtel Inc., currently involved in development and testing of Galileo receivers.

MICHAEL CLAYTON is currently Director – Aviation Programs at NovAtel.

JONATHAN AULD is a project manager in NovAtel's Aviation group working on the development of GPS and Galileo reference stations receivers.

TONY MURFIN is Vice President, Business Development at NovAtel Inc., responsible for the Wide Area Augmentation System receiver programs and the company's involvement in the European Galileo program.

and Galileo signal simulators are also still in the development stages. There are a number of possible solutions to these receiver design challenges:

- Signal generation and receiver modelling can be done entirely in the software world. This allows the receiver designer to let their imagination run wild with possible implementation choices and to test out a multitude of signal structures without the expense of procuring hardware for signal generation and reception. Common software simulation methods include the use of MATLAB/Simulink or proprietary software developed in C/C++.
- A software receiver may be implemented entirely on a desktop or laptop computer, with digital samples from an RF front end providing access to real-world signals. This method allows recording and playback of the real-world or software-generated signals and allows the receiver designer to test out many real-time computing aspects of a receiver design. Current technology limits this approach to lower bandwidth signals, with expansion to higher bandwidth signals dependent on personal computing power advances.
- A Field Programmable Gate Array (FPGA)–based software defined receiver implementation may be pursued. In this case, the high-speed portions of the signal-processing algorithms are implemented in an FPGA using a hardware-description language like Verilog or VHDL, with the lower speed processing implemented in a general-purpose embedded processor using a programming languages such as C, C++, or Ada. This prototyping method can allow for real-time processing of wider bandwidth signals. The biggest advantage is that software designs for an FPGA-based receiver can be very similar to the software design for a commercial receiver with a application-specific integrated circuit (ASIC) implementation.

For the prototype Galileo receiver discussed in this article, we designed an FPGA-based receiver card. The FPGA approach allowed us to reuse a vast majority of the legacy signal processing techniques found in our GPS receivers. The FPGA approach also allows for rapid prototyping of new algorithms, and for adapting to changes in the Galileo signal-in-space specification.

The current Galileo prototype development is focused on ground reference receiver applications. Ground reference receivers will be one of the first receiver applications used by the Galileo community for monitoring the signal-in-space. Ground reference receivers can all also tolerate the larger power requirements typically associated with an FPGA type implementation.

In the following sections we will describe some of the differences between GPS and proposed Galileo signals, as well as various testing experiences with the Galileo prototype receiver.

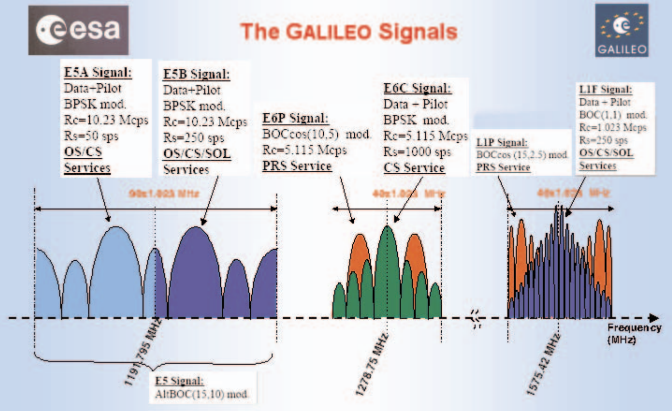


FIGURE 1 Galileo navigation signal modulation spectra

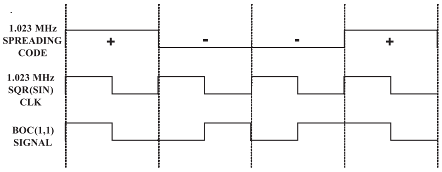


FIGURE 2 BOC(1,1) signal generation

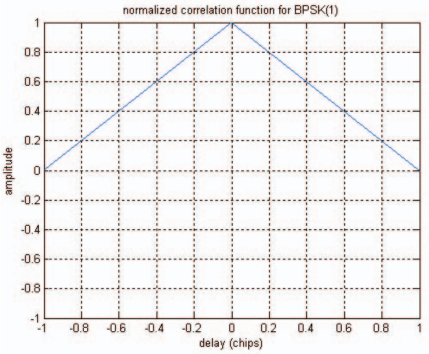


FIGURE 3 Correlation function for BPSK(1)

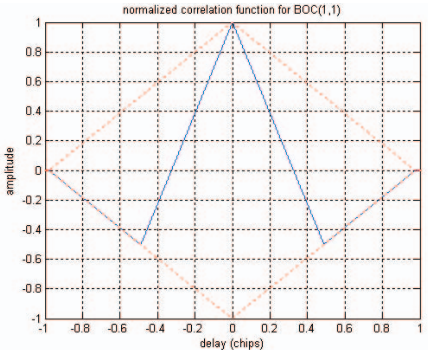


FIGURE 4 Correlation function for BOC(1,1)

GPS versus Galileo

With extensive dual-frequency design experience in the GPS market, NovAtel embarked on the design of a dual-frequency Galileo card. Modernized GPS signals are just around the corner, so a dual-mode prototype receiver that can track both Galileo and GPS is desirable. The current Galileo proposal (see **Figure 1**) is to transmit signals on four frequencies, and modernized GPS is set to transmit on three frequencies. In this case, the choice for which two frequencies to receive is a simple one because the two systems share only two frequencies — L1 at 1575.42 MHz, and E5a (L5) at 1176.45 MHz. The Galileo signal at E5a and the GPS signal at L5 have similar signal properties as far as receiver tracking is concerned. The differences between the Galileo L1 and GPS L1 signal structure are more profound, as discussed later.

The legacy GPS C/A code at the L1 frequency is a binary phase shift keying (BPSK) signal with a chipping rate of 1.023 MHz. The notation BPSK(fc) is used, where fc represents a factor of 1.023 MHz. The Galileo Open Service signal at the L1 frequency will be a binary offset carrier (BOC) signal. For BOC signals, the spreading code is mixed with a square wave at a given subcarrier frequency. The notation BOC(fs,fc) is used, where fs represents the square wave subcarrier frequency in units of 1.023 MHz, and fc represents the chipping rate in units of 1.023 MHz.

The generation of a BOC(1,1) signal is shown in **Figure 2**, where the top line is a 1.023-MHz spreading code (with a chip sequence of [+1, -1, -1 +1] shown), the middle

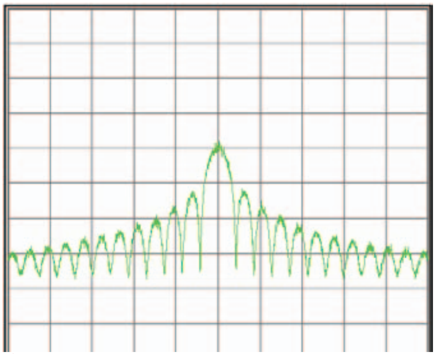


FIGURE 5 Transmitter output as seen on spectrum analyzer : BPSK(1), 24 MHz span, 10 kHz resolution bandwidth

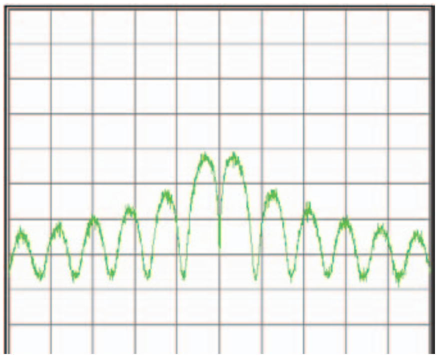


FIGURE 6 Transmitter output as seen on spectrum analyzer : BOC(1,1), 24 MHz span, 10 kHz resolution bandwidth

line is a 1.023-MHz square wave, and the bottom line is the resulting BOC(1,1) modulation signal. For this BOC(1,1) example, the square wave has a sine-phase relationship with the spreading code (1.023-MHz square wave = square(sine(1.023 MHz))).

Tracking in a receiver is accomplished by correlating the incoming spread spectrum signal with a locally generated replica. The normalized ideal correlation function for a BPSK(1) signal is shown in **Figure 3**. The correlation function for a BOC(1,1) signal is shown in solid blue in **Figure 4**. Compared with the BPSK(1) correlation function, the square wave subcarrier modulation used with BOC(1,1) causes the autocorrelation function to have a sharper main peak and two smaller negative side peaks. The sharper main peak will result in improved code tracking performance for the BOC(1,1) signal and improved performance in the presence of multipath. The dotted red line in Figure 4 is the envelope of a BPSK(1) signal.

The BOC modulation also has an effect on the frequency spectrum of the signal. A single channel Galileo RF transmitter was used to generate the frequency plots in **Figure 5** and **Figure 6**. Figure 5 is a screen capture from a spectrum analyser, with the transmitter in BPSK(1) mode (24 MHz span, 10 kHz resolution bandwidth). Figure 6 is the spectrum analyzer screen capture with the transmitter in BOC(1,1) mode. Figure 6 illustrates how the square wave subcarrier modulation used in BOC(1,1) shifts the main lobe of the frequency spectrum to higher and lower frequencies, and increases the necessary minimum RF front end bandwidth to receive L1 open service signal.

Primary and Secondary Codes. **Table 1** shows the code sequence duration for the Galileo signals currently implemented in the Galileo Test Receiver (GTR). The primary code sequence is further modulated with a secondary code. The secondary code has two main effects: it improves the auto- and cross-correlation properties of the code; and it aids in reliable bit synchronization for the data channels.

Memory Codes. Current generation GNSSs and SBASs, including GPS, GLONASS, WAAS, EGNOS, MSAS, and SNAS, generate the pseudorandom spreading codes using linear feedback shift registers (LFSRs). All the GPS C/A codes and L1 SBAS codes for WAAS, EGNOS, MSAS and SNAS can be generated with two 10-bit hardware registers and a relatively small amount of decoding logic. Generally, each receiver hardware channel in a GPS receiver will have a single C/A code generator.

One proposal for the Galileo L1 signal is to use memory codes. With memory codes, the pseudorandom number (PRN) for each spreading code can be selected by the Galileo system designer to optimize the cross-correlation and interference mitigation properties. The receiver design must therefore implement these same memory codes within the receiver. The memory codes for all possible satellites must be stored in the receiver, ready for use. Assuming 30 satellites, with two PRNs per satellite at the L1 open service frequency (one for the data signal, and one for the pilot signal), and a PRN length of 4092 bits, $30 \times 2 \times 4092 = 245520$ bits of memory are needed.

Although memory codes will provide an increase in receiver tracking performance, the implementation has a direct implication on the receiver design: memory increases the hardware cost, complexity, signal processing resource utilization, and power consumption of the receiver when compared to LFSRs. As manufactures move towards low-cost and low-power ASIC implementations, memory-code implementation will become more challenging.

Galileo Test Receiver

The GTR consists of an enclosure containing individual receiver cards. The receiver card dedicated to tracking Galileo signals is the Galileo L1/E5a receiver card, a dual-mode (Galileo/GPS) and dual-frequency (L1/E5a) receiver that can operate as a standalone receiver when not in the GTR enclosure. It is populated with an FPGA and can be configured to track as many as 16 channels of any combination of Galileo L1, Galileo E5a, GPS L1, GPS L5, WAAS L1, or WAAS L5. An FPGA implementation was preferred for this prototype since the jump to full ASIC is cost and time prohibi-

Table 1: Spreading codes main characteristics (based on Hein, *GPS World* 2003)

Channels	Primary code chip rate	Symbol rate	Code sequence duration	Primary code length	Secondary code length	Secondary code chip rate
E5aI	10.23 Mcps	50 sps	20 ms	10230	20	1 kHz
E5aQ	10.23 Mcps	no data	100 ms	10230	100	1 kHz
L1B	1.023 Mcps	250 sps	4 ms	4092	-	-
L1C	1.023 Mcps	no data	100 ms	4092	25	250 Hz

Table 2: Secondary code alignment improvements

Signal	Secondary Code Alignment Method	Mean (s)	Standard Deviation (s)
L1	Old	21.770	13.058
L1	New	10.542	6.026
E5a	Old	11.552	8.239
E5a	New	6.794	2.334

tive. An ASIC implementation would also be risky for a GNSS in which the signal structure continues to evolve.

Both the FPGA and baseband processor can be reprogrammed with new firmware via the serial port interface. The ability to reprogram the receiver during development is an attractive feature. As new features are implemented, new baseband software and FPGA files can be loaded into the receiver. A Windows-based loading utility provides a simple interface to initiate the reprogramming download.

The receiver as designed can operate with the GSTB-V2 signals, as well as the currently defined IOV signals. The design includes Galileo L1 civil signals defined as memory codes, with the design turn around time to implement new codes on the order of minutes.

The GTR enclosure will initially contain two receiver cards, one Galileo L1/E5a card (as described in the previous paragraph) and one GPS L1/L2 card. The GPS receiver card in the GTR is the Euro-3M card, developed for the WAAS G-II receiver.

The Euro-3M card will be used to determine the position and time solution during the GSTB-V2 test campaign, when only one or two Galileo satellites will be in operation. The time solution will be provided to the Galileo L1/E5a card.

Figure 7 provides a block diagram of the GTR with one Galileo L1/E5a card, one Euro-3M GPS L1/L2 receiver card, an I/O Master card contained in an EIA standard 19-inch enclosed rack with an LCD on the front panel, and eight receiver card slots available for future expansion. Possibilities for expansion include additional cards for Galileo E6, E5b, and AltBOC tracking, or for signal quality monitoring of Galileo signals. The additional receiver cards and receiver sections may be used to track any of GPS, Galileo, or SBAS signals.

The receiver cards are connected to the I/O master card through a passive backplane, allowing digitized intermediate frequency (IF) data to be shared between multiple receiver cards. This increases the number of available correlators while eliminating intercard radio frequency (RF) biases. The backplane also allows intercard communication via a built-in USB interface. The I/O master card coordinates the inter-card communication and provides the timing synchronization for the receiver cards.

Test Signal Generator

The Galileo Test Signal (GTS) generator broadcasts one signal for each of the L1 BOC (1,1) and E5a frequencies. A 10-MHz reference signal and 1 PPS are required as input to the GTS. The GTS incorporates L1 memory codes and L1 and E5a secondary codes as currently defined for the IOV satellites.

The GTS is controlled by a graphical user interface (GUI) allowing selection of the PRN, a configurable Doppler, and configurable code chip advances. This allows the receiver to be tested under a specific set of known inputs. The GUI, shown in **Figure 8**, controls both the L1 and E5a sections of the GTS and displays status data.

The navigation message for the GTS is generated in an external device known as the data source. The data source has two sections, which can each output pregenerated L1 or E5a messages to the GTS. A 1-PPS signal from the GTS synchronizes the message generation. In turn, the GTS receives a 1-PPS signal from a GPS receiver. The GTS can output a signal on any Galileo PRN.

Testing Experiences

The obvious first addition to the receiver is the ability to track the new spreading codes. BOC(1,1) has the added complication that when the receiver initially acquires and tracks the BOC(1,1) signal, the receiver may be tracking one of the two side peaks located at ± 0.5 chips from the main peak, with a power 6 dB lower than the main peak power (see **Figure 9**). Tracking on the incorrect peak will cause a pseudorange error on the order of 146 meters.

To be able to directly observe this expected error, the receiver was set to search for the transmitted BOC(1,1) code on multiple channels. Cases were observed in which one channel would acquire and track the main peak, while another channel would acquire and track the side peak. This is shown in **Figure 10**, where the channel tracking the main peak is at the expected power of 48 dB-Hz, while the channel tracking the side peak is at the expected side peak power 6 dB lower at 42 dB-Hz. The receiver was then updated with a new firmware load to monitor and correct for side peak tracking. The design turnaround time for implementing the changes on the FPGA was short enough that a number of different approaches to the side peak detection and correction algorithm were tested, and a final candidate solution was chosen.

Another example of the power of an FPGA-based prototype development was witnessed during refinement of the acquisition routines. After the receiver was successfully tracking Galileo signals, the design engineers came up with a potential improvement on how the secondary code alignment could be implemented. An update to the FPGA was necessary to implement the new algorithm. If an ASIC implementation had been chosen for the prototype, the new algorithm would have to wait for the next revision of the chip to be implemented, but with the FPGA the new algorithm could be tested the same day. With any type of acquisition test it is always desirable to run as many acquisitions as possible to get a decent statistical results. With software simulation the amount of input data needed, and the time required to process it, can become unwieldy. With a real-time FPGA-based receiver connected to a RF signal generator, this type of test can be done easily and quickly.

The before and after results for secondary code alignment improvements are shown in **Table 2** and **Figure 11**. Two receivers were connected in a zero-baseline configuration, one using the old secondary-code alignment method, and the other receiver using the new secondary-code alignment. A total of 500 acquisitions were made for each receiver.

In May, 2005 the GTR was successfully demonstrated (see photo, next page) to the CSA. The GTR is the first operational dual-mode, dual-frequency receiver in North America.

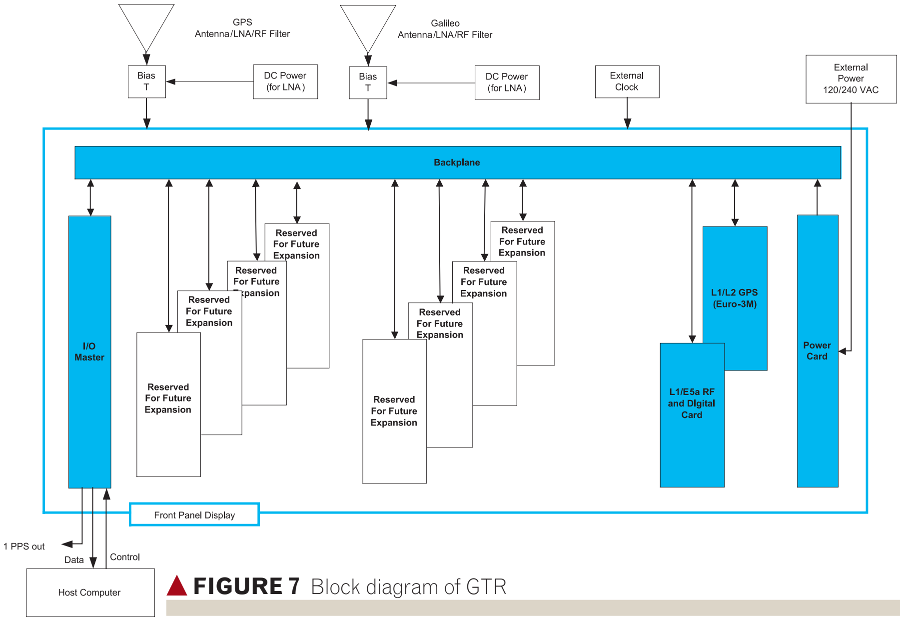


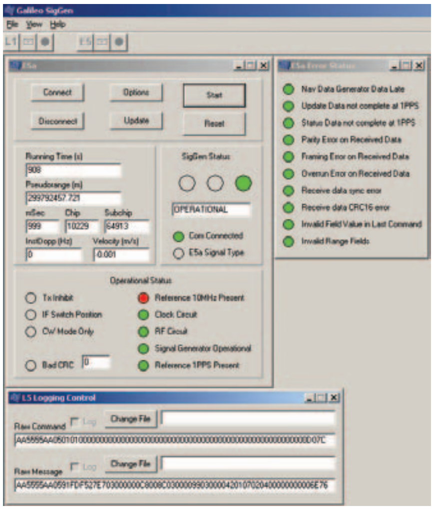
FIGURE 7 Block diagram of GTR

Performance Testing Goals. A full test campaign for the completed GTR enclosure is planned for late 2005/early 2006. The goal of the initial testing described herein was to verify the operation and performance of the single L1/E5a Galileo receiver card.

Two separate sets of initial performance tests have been performed so far. The code tracking performance has been validated previously using the GTS. A second set of tests was run using the GSFV Galileo Satellite Constellation Simulator, part of the Galileo Signal Verification Facility version 2 (GSVF-2) at the European Space Agency (ESA) European Space Research and Technology Centre (ESTEC).

Test Setup. The test configuration for the GTS and two L1/E5a Galileo receiver cards is shown in **Figure 12.** A computer controls the GTS via the GUI. The RF output from the GTS is combined with the RF from a GPS antenna. This combined RF signal is then split and directed to two GTR receivers. The receivers output range logs to a host computer. All of the connections to and from the computers are via serial port interfaces.

Tests were performed on both the L1 and E5a signals. A calibrated noise source and computer-controlled variable attenuators were used to vary the C/N$_0$ over time. The receivers were set up to output range measurements, which were logged by the host computer. The signal generator was connected to two receivers and single differences were computed between the range measurements.



Running Time (s): 908
Pseudorange (m): 299792457.721
mSec: 999
Chip: 10229
Subchip: 64913
InstDopp (Hz): 0
Velocity (m/s): -0.001
SigGen Status: OPERATIONAL
● Com Connected
○ E5a Signal Type

● Nav Data Generator Data Late
● Update Data not complete at 1PPS
● Status Data not complete at 1PPS
● Parity Error on Received Data
● Framing Error on Received Data
● Overrun Error on Received Data
● Receive data sync error
● Receive data CRC16 error
● Invalid Field Value in Last Command
● Invalid Range Fields

Operational Status
○ Tx Inhibit
○ IF Switch Position
○ CW Mode Only
○ Bad CRC: 0
● Reference 10MHz Present
● Clock Circuit
● RF Circuit
● Signal Generator Operational
● Reference 1PPS Present

L5 Logging Control
Raw Command ☐ Log
AA5555AA0501010000000000000000000000000000000000000000000000000007C
Raw Message ☐ Log
AA5555AA0591FDF527E703000000C8008C0300009903000042010702040000000006E76

FIGURE 8 Galileo Test Simulator GUI

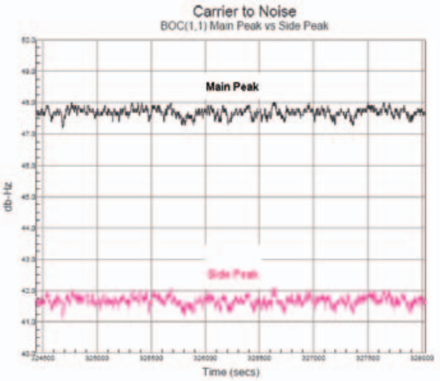


FIGURE 10 C/No main peak 48 dB-Hz, C/No side peak 42 dB-Hz

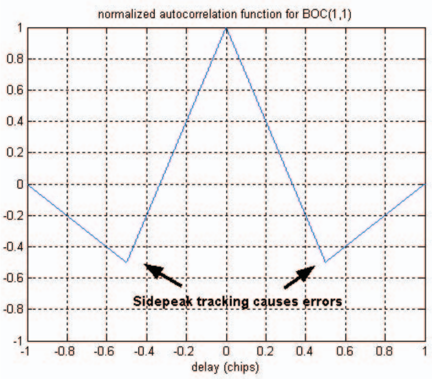


FIGURE 9 BOC(1,1) correlation function – multiple tracking points

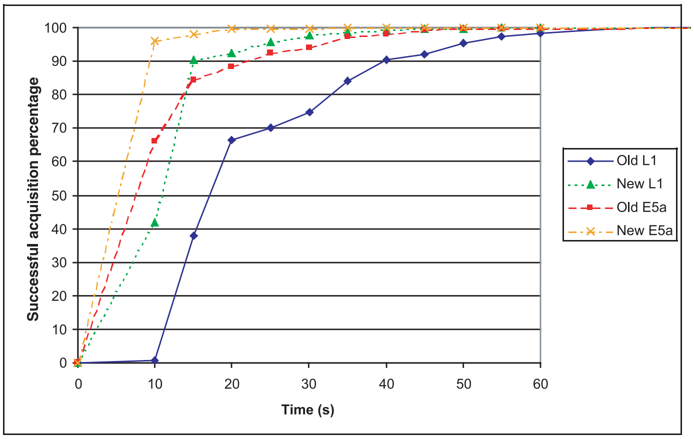
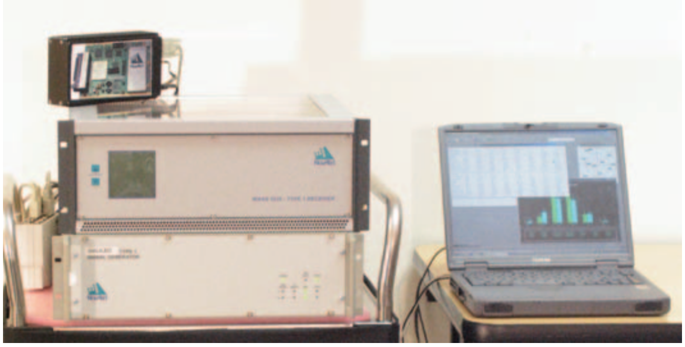


FIGURE 11 Secondary alignment improvements - percent of acquisitions that were successful in a given time period

Results. Figure 13 shows the L1 pseudorange noise results, using the GTS as the signal source. The results fall in line with the expected BOC(1,1) performance. **Figure 14** gives the E5a pseudorange noise results, again in line with the expected performance.

Figure 15 shows the performance improvement of



GTR demo setup

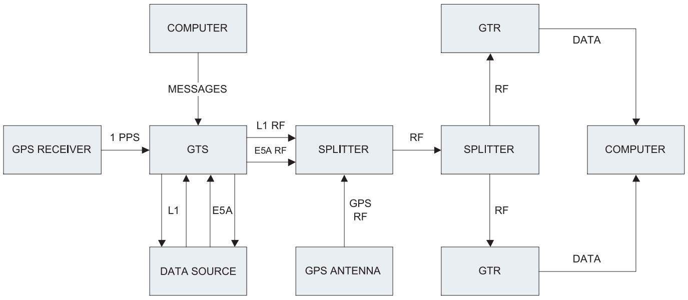


FIGURE 12 Test setup

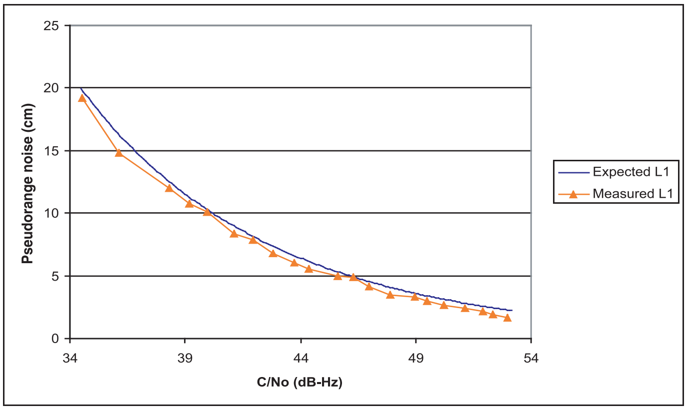


FIGURE 13 Measured and expected pseudorange noise of Galileo L1 signals with GTR generated signal

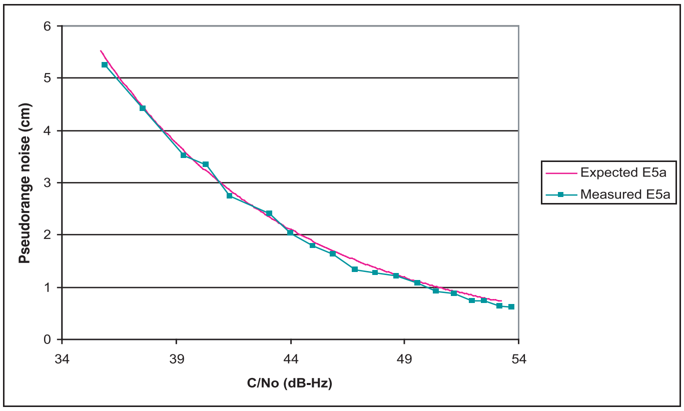


FIGURE 14 Measured and expected pseudorange noise of Galileo E5a signals with GTR generated signal

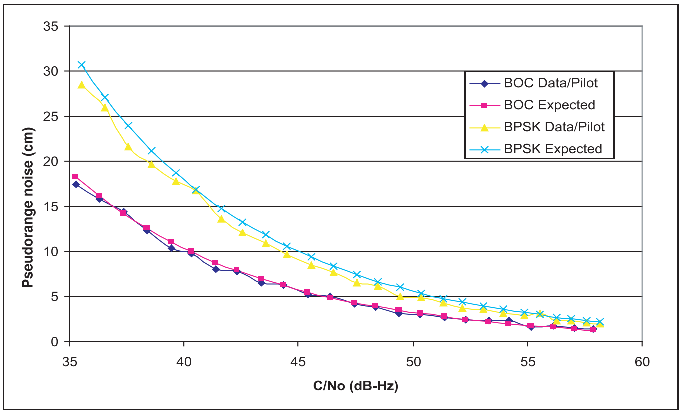


FIGURE 15 Measured code tracking performance BPSK(1) versus BOC(1,1)

BOC(1,1) over BPSK(1), using the same discriminator spacing, integration period, and delay lock loop bandwidth. The figure shows the improvement in pseudorange code tracking performance by approximately a factor of $1/\sqrt{3}$.

Galileo Simulator

The **opening photo on page 26** shows the GSFV Galileo Constellation Simulator, a full constellation simulator capable of providing the Galileo GSTB-V2 signals in space. The GSFV simulator simultaneously generates satellite signals for each of the Galileo frequencies, for as many as 16 satellites. For each signal, the simulator takes into account behaviors such as the motion of the satellite and user platforms, ionospheric and tropospheric propagation effects, and the multipath environment of the receiver. Available RF signals include L1, E6, and E5. The E5 signals can be generated as individual E5a and E5b QPSK signals, or as AltBOC.

ESA–ESTEC provided access to the GSVF simulator for two days in September 2005. The use of the simulator allowed us to verify the receiver operation with an independently produced signal source.

An external GPS antenna feed was connected to the antenna input of the simulator. The output from the simulator was a composite live GPS plus simulated Galileo signal, connected directly to the antenna input port of the L1/E5a receiver card. The satellite clone function of the simulator was used to allow satellites with separate PRNs to occupy identical orbital locations. The L1/E5a receiver card was then commanded to track both PRNs on separate channels while outputting RANGE logs containing the pseudorange, carrier phase, Doppler, and C/N_0. The data was then processed to calculate the single difference between the independent cloned satellites.

Figure 16 shows the L1 pseudorange noise results, using the GSVF simulator as the signal source. The results are in line with the expected performance.

Figure 17 gives the E5a pseudorange noise results (again using the GSVF simulator), with the expected performance. In this case the estimated and measured values are off by as much as 1 dB. This discrepancy may be due to a relatively small data set being collected for E5a.

Conclusion and Future Work

As part of a broader effort to advance the development of the Galileo system, NovAtel designed a Galileo L1/E5a receiver card to be used as a stand-alone receiver or within the GTR enclosure. This dual-mode receiver can track both Galileo and GPS. In addition, a GPS L1/L5 signal generator was modified to output Galileo L1 and E5a signals. Testing with the single-channel GTS signal generator and the GSFV Galileo constellation simulator successfully tracked the generated Galileo signals.

Work continues on the I/O Master card and GTR box level integration. A full test campaign is anticipated, including live tracking of the GSTB-V2 signals in space. Going forward, the modulator nature of the GTR will allow future expansion to track all Galileo transmitted frequencies, including E5b and E6. 🌐

Acknowledgments

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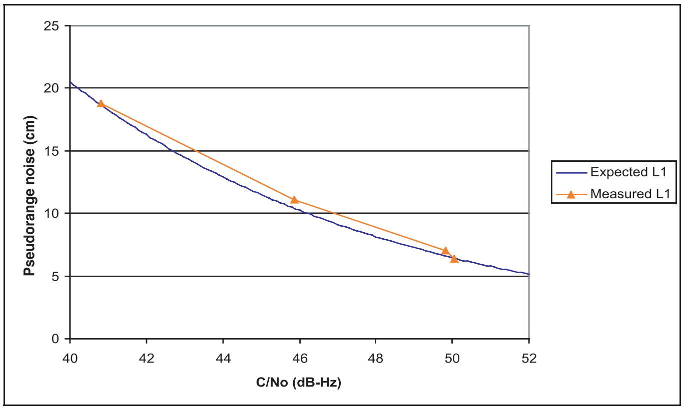
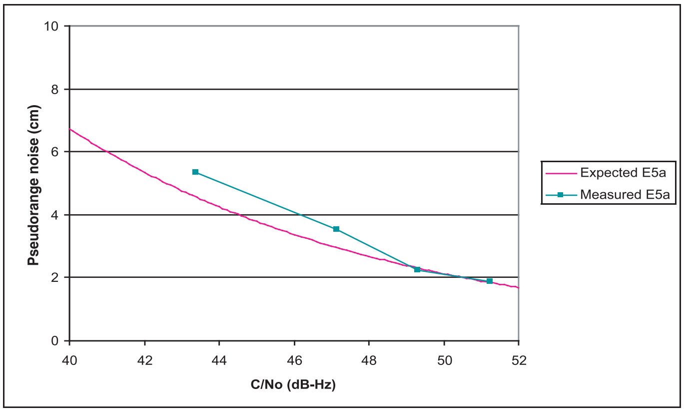
Manufacturers

The GTS is a modified version of the WAAS GUS – Type 1 signal generator designed by **GPS Silicon Valley**, commercialized by **NovAtel** (www.novatel.com) for **Raytheon**'s (www.raytheon.com) GCCS program. The GSVF Galileo Satellite Constellation Simulator was produced by **Thales Research and Technology (UK)** (www.thalesresearch.com).



▲ **FIGURE 16** Measured and expected pseudorange noise of Galileo L1 BOC(1,1) signals with GSVF simulator-generated signal



▲ **FIGURE 17** Measured and expected pseudorange noise of Galileo E5a signals with GSVF simulator-generated signal

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