NovAtel's Galileo Test Receiver

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BIOGRAPHY

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Michael Olynik is a GPS Software Engineer with NovAtel Inc. He has a B.Sc. and M.Sc. in Geomatics Engineering from the University of Calgary. He is currently involved in development and testing of Galileo receivers.

Michael Clayton graduated from the Royal Military College in 1978 with a Bachelor of Engineering (Electrical) and from Carleton University with a Masters of Engineering (Electrical) in 1984. In 1998 Michael joined NovAtel and is currently Director – Aviation Programs.

Jonathan Auld obtained a B.Sc. (1996) and an M.Eng. (2002) in Geomatics Engineering from the University of Calgary. He is currently 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. He is responsible for the Aviation business group, and other strategic business initiatives for the Company. In this role he has been responsible for not only the Wide Area Augmentation System receiver programs, but also NovAtel's involvement in the European Galileo program. Mr. Murfin joined NovAtel in April 1994 from CMC in Montreal where he was Business Development Manager in the Avionics Division, and before that Product Manager for Microwave Landing Systems and Software Manager for the Division. He worked as a software simulation designer at CAE Electronics, and before that was a senior avionics engineer at BAE in the UK. Mr. Murfin has a B.Sc. from the University of Manchester Institute of Science and Technology in the UK, and is a UK Chartered Engineer (CEng MIEE).

ABSTRACT

The Galileo System Test Bed Version 2 (GSTB-V2) test satellites are scheduled to be launched shortly. In preparation of this highly anticipated event, NovAtel, sponsored by the Canadian Space Agency (CSA), has been developing a Galileo Test Receiver (GTR). Under the first phase of this development, NovAtel designed a single frequency transmitter/receiver pair to evaluate Galileo BOC(1,1) performance. In October 2004 NovAtel was awarded a second contract by the CSA to extend this work to an L1/E5a dual frequency GTR.

The GTR includes a new FPGA based L1/E5a receiver card. This new receiver card is integrated into a modified version of NovAtel's WAAS GUS Type 1 ground reference receiver. The highly modular nature of the GTR will allow other frequencies and services to be added to the unit in the future. To support testing and evaluation prior to a Galileo signal-in-space, a single channel L1/E5a Galileo transmitter has also been developed. The L1/E5a transmitter is based on an existing L1/L5 Signal Generator design. The final deliverable system is suitable for both in-lab demonstrations and signal-in-space testing purposes.

The overall architecture of the GTR will be discussed. An overview of the FPGA based dual-frequency receiver card will be given. The modular nature of the GTR, possible with the integrated backplane, will be presented. The initial laboratory performance results of the GTR will also be presented, and possible future work will be detailed.

INTRODUCTION

The first Galileo signals in space will be broadcast by the GSTB-V2 satellites, scheduled to be launched in late 2005/early 2006. These initial test satellites will provide a representative Galileo signal-in-space to secure frequency filing, and to provide an initial Galileo test signal. In the coming years, the GSTB-V2 satellites will be followed by up to four In-Orbit-Validation (IOV) satellites. It is noted that the IOV satellites may incorporate slight signal-in-space interface changes when compared to the GSTB-V2 satellites. The IOV phase will be followed by the Full Operation Capability (FOC) phase, which is expected to be completed towards the end of this decade.

It is anticipated that once Galileo is operational, the vast majority of all user receivers sold will be both GPS and Galileo capable. 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 significantly obstructed by buildings, trees, bridges or other forms of signal blockage. With twice as many satellites visible in the sky, the probability will be much lower that signal blockage will interfere with the navigation solution. Applications that are currently marginal, or impossible, will become viable and cost effective for users. In the meantime, 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 the 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.

Since 2001, NovAtel has worked on several Galileo projects. These are:

- Galileo Signal Validation Study (Spring 2001)
- Galileo Phase B2 Users (Dec 2001 – June 2002)
- Galileo Phase B2 GSS Receiver (July 2002)
- Galileo/GPS Interoperability (July 2002 – October 2002)
- Galileo Reference Receiver (October 2002 – April 2004)
- Galileo BOC(1,1) Receiver (December 2003 – July 2004)

A description of the Galileo BOC(1,1) Receiver is given in (Gerein et al., 2004). The receiver was based on software modifications to an existing card and a new FPGA. A transmitter was modified to broadcast a BOC(1,1) signal. This contract was sponsored by the Canadian Space Agency (CSA). Results for tracking of the BOC(1,1) signal were in line with expectations.

In October 2004, NovAtel began work on a contract for the development of an L1/E5a Galileo prototype receiver. This contract is sponsored by the CSA under the Space Technology Development Program (STDP). Canada is a participating member of the European Space Agency. The CSA is the principle Canadian body involved in European satellite infrastructure programs and is the Canadian sponsor for NovAtel's participation in both EGNOS & Galileo.

This Galileo Test Receiver (GTR) will include a new L1/E5a hardware receiver card, an L1/L2 GPS receiver card, and an I/O Master Card (described in the following sections). The L1/E5a receiver card can also be used as a stand-alone receiver. The enclosure for the GTR is being developed to allow future expansion to include cards to track E5b and E6 signals.

The contract also includes the modification of a GPS L1/L5 signal transmitter to output Galileo signals. The Galileo Test Signal generator (GTS) can output one L1 and one E5a signal simultaneously.

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 shown in Figure 1. The Galileo L1/E5a receiver card is a dual-mode (Galileo/GPS) and dual-frequency (L1/E5a) receiver, and can operate as a standalone receiver when not in the GTR enclosure. It is populated with an FPGA and can be configured to track up to 16 channels of any combination of Galileo L1, Galileo E5a, GPS L1, GPS L5, WAAS L1, or WAAS L5. The receiver includes digital pulse blanking on both frequencies to mitigate in-band pulsed interference. Both the FPGA and baseband processor can be reprogrammed with new firmware via the serial port interface. The ability to reprogram the receiver in the field is an attractive feature, considering the Galileo signal structure is still in flux. The receiver 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.

Figure 1: Galileo L1/E5a Receiver Card

The GTR enclosure will initially contain two receiver cards, one Galileo L1/E5a receiver card (as described in the previous paragraph) and one receiver card dedicated to GPS L1/L2. The GPS receiver card in the GTR is the Euro-3M card, which was developed for the WAAS G-II receiver. The Euro-3M is based on NovAtel's OEM4-G2 receivers and features several enhancements such as Signal Quality Monitoring (SQM), improvements to NovAtel's patented Multipath Estimating Delay Lock Loop (MEDLL), NovAtel's SafeTrak™ cross correlation detection, bit synchronization check and the addition of L2 digital pulse blanking. The Euro-3M card will be used to determine the position and time solution during the Galileo System Test Bed version 2 (GSTV-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.

A block diagram of the GTR is shown in Figure 2. The enclosure for the GTR will be a modification of the enclosure built for the NovAtel WAAS G-II. A photo of the front of the WAAS G-II is shown in Figure 3, and a top view in shown in Figure 4. The GTR consists of one Galileo L1/E5a card, one Euro-3M GPS L1/L2 receiver card, and an I/O Master card contained in an EIA standard 19-inch enclosed rack with an LCD on the front panel.

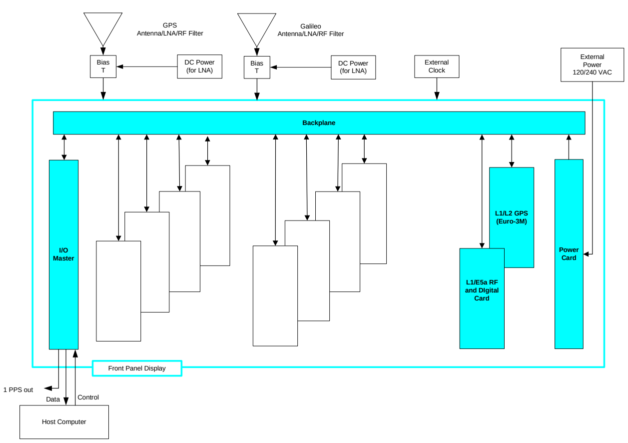

Figure 2: Block Diagram of GTR

Figure 3: WAAS G-II receiver enclosure

The GTR has the provision for future expandability and is capable of holding up to ten Euro form factor cards. The additional receiver cards and receiver sections may be used to track any of GPS, Galileo, or SBAS signals.

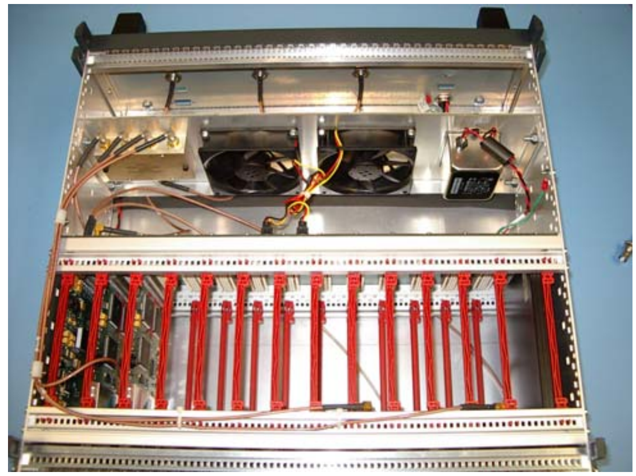

Figure 4: Top View of WAAS G-II Receiver

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

GALILEO TEST SIGNAL GENERATOR (GTS)

The GTS is a modified version of the WAAS GUS – Type 1 Signal Generator designed by GPS Silicon Valley, commercialized by NovAtel for Raytheon's GCCS program. Photos of the front and back of the GUS Signal Generator are shown in Figure 5 and Figure 6. The GTS 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 L1 and E5a navigation messages are interleaved and FEC encoded.

Figure 5: GUS Signal Generator

Figure 6: GUS Signal Generator Back Panel

The GTS is controlled by a Graphic User Interface (GUI). The GUI allows selection of the PRN, a configurable Doppler, and configurable code chip advances. The GUI controls both the L1 and E5a sections of the GTS and displays status data. The GUI is shown in Figure 7.

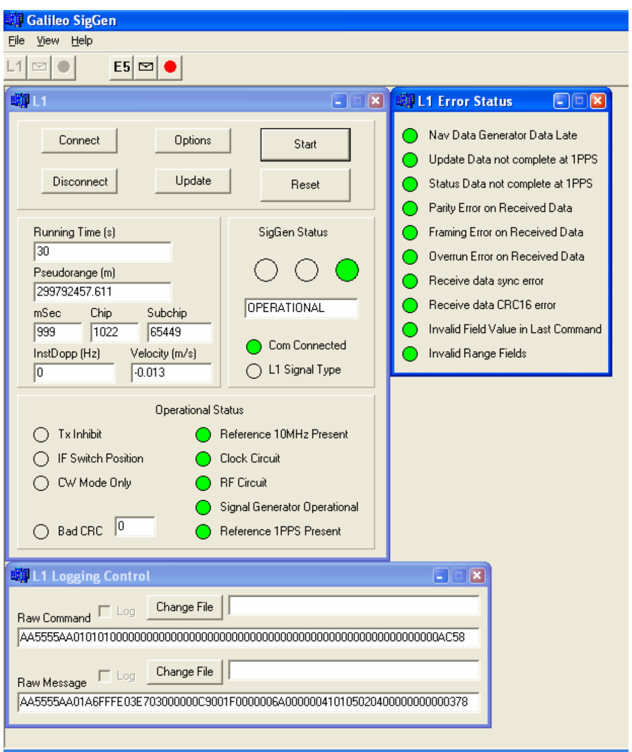

Figure 7: Galileo Test Simulator GUI

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 pre-generated L1 or E5a messages to the GTS. A 1 PPS signal from the GTS is used to synchronize 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.

DEMOSTRATION OF GALILEO RECEIVER

On May 30, 2005, the GTR was successfully demonstrated to the CSA. The GTR is the first operational dual-mode, dual-frequency receiver in North America. A photograph of the demonstration setup is given in Figure 8.

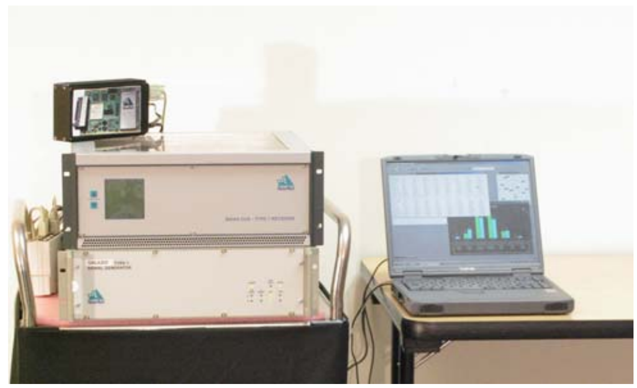

Figure 8: GTR Demo Setup

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 is to verify the operation and performance of the single L1/E5a Galileo receiver card.

Two separate sets of initial tests have been performed so far. The code tracking performance has been validated previously using the GTS as reported in (Gerein et al., 2005) and provided in part here as reference. A second set of tests was run using the GSFV Galileo Satellite Constellation Simulator from Thales Research and Technology (TRT). The TRT simulator is part of the Galileo Signal Verification Facility version 2 (GSVF-2) at the European Space Agency (ESA) European Space Research and Technology Centre (ESTEC).

EXPECTED RESULTS

Before testing was executed, analysis was completed to determine the expected code noise for the Galileo L1 and E5a signals. The derivations of the approximate expression to predict the code tracking performances have been published previously, and are based on the classic

Narrow Correlator™ paper (Van Dierendonck et al., 1992). It has been previously determined (Gerein et al., 2004) that the approximate expression for the pseudorange noise for the L1 BOC code, given the GTR's L1 normalized bandwidth and pre-detection integration time, is:

$$\sigma_c = T_c \frac{1}{\sqrt{3}} \sqrt{\frac{B_L D}{2\frac{C}{N_0}} \left[1 + \frac{2}{T\frac{C}{N_0}(2-D)} \right]} \qquad (1)$$

where:

D	is the normalized early-late spacing,
T	is the pre-detection integration time,
T_c	is the chip period,
B_L	is the DLL bandwidth,
C/N_0	is the carrier to noise ratio,

and:

$B_L T \quad \ll 1.$

For comparison, the expected 1-sigma code tracking performance of the BPSK signal from (Van Dierendonck et al., 1992) is:

$$\sigma_c = T_c \sqrt{\frac{B_L D}{2\frac{C}{N_0}} \left[1 + \frac{2}{T\frac{C}{N_0}(2-D)} \right]} \qquad (2)$$

The approximate expression for pseudorange noise for the E5a signal, given the GTR's E5a normalized bandwidth and pre-detection integration time, is given in (Betz, 2000):

$$\sigma_c = T_c \sqrt{\frac{B_L}{2\frac{C}{N_0}} \left[\frac{1}{b} + \frac{b}{\pi - 1}\left(D - \frac{1}{b}\right)^2 \right] \left[1 + \frac{2}{T\frac{C}{N_0}(2-D)} \right]} \qquad (3)$$

where:

b	is the normalized front end bandwidth,

and:

$B_L T \quad \ll 1.$

TEST SETUP WITH GTS

The test configuration for the GTS and two L1/E5a Galileo receiver cards is shown in Figure 9. A computer is used to control 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 in Figure 9 are via serial port interfaces.

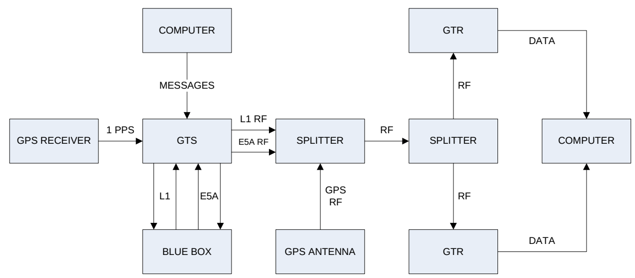

Figure 9: Test Setup

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 noise and signal levels were calibrated using a spectrum analyzer prior to the test. 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.

TEST RESULTS WITH GTS

The L1 pseudorange noise results, using the GTS as the signal source, are shown in Figure 10. The results are inline with the expected performance described by equation 1.

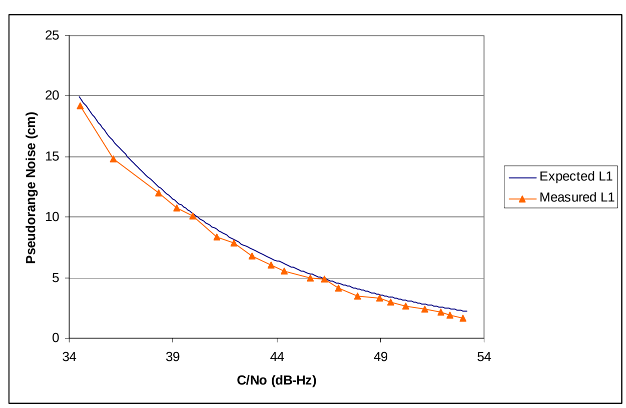

Figure 10: Measured and Expected Pseudorange Noise of Galileo L1 Signals with GTR Generated Signal

The E5a pseudorange noise results are given in Figure 11. The results are in line with the expected performance described by equation 3.

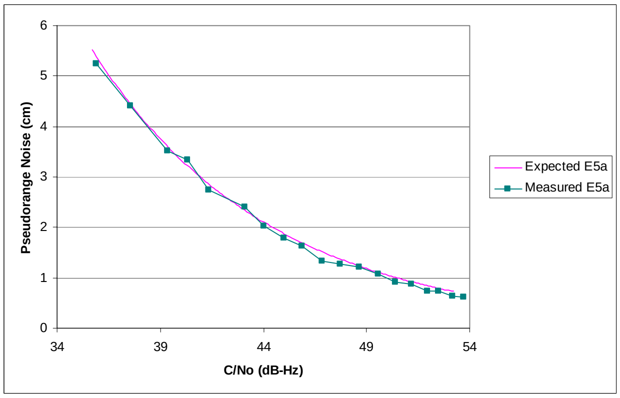

Figure 11: Measured and Expected Pseudorange Noise of Galileo E5a Signals with GTR Generated Signal

For illustrative purposes, a comparison of the L1 and E5a pseudorange noise results is shown in Figure 12. The E5a noise is lower due to the higher chipping rate.

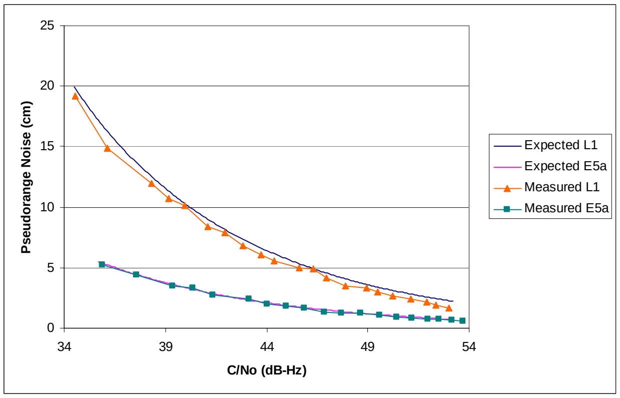

Figure 12: Pseudorange Noise of Galileo Signals with GTR Generated Signal

TRT GALILEO SIMULATOR

The Thales Research and Technology GSFV Galileo Constellation Simulator is shown in Figure 13. The simulator is 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 up to 16 satellites. For each signal, the simulator takes into account such behaviours as the motion of the satellite and user platforms, ionospheric and tropospheric propagation effects, and the multipath environment of the receiver (Burden, et.al., 2004). Available RF signals include L1, E6, and E5. The E5 signals can be generated as individual E5a and E5b QPSK signals, or as AltBOC.

Figure 13: TRT GSVF Galileo Constellation Simulator (photo courtesy Thales Research and Technology)

ESA-ESTEC was able to provide NovAtel access to the GSVF simulator for two days in September 2005. The use of the simulator allowed NovAtel to verify receiver operation with an independently produced signal source.

An external GPS antenna feed was connected to the antenna input of the TRT 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.

TEST RESULTS WITH TRT GALILEO SIMULATOR

The L1 pseudorange noise results, using the GSVF simulator as the signal source, are shown in Figure 14. The results are inline with the expected performance described by equation 1.

The E5a pseudorange noise results (using the GSVF simulator as the signal source), with the expected performance described by equation 3, are given in Figure 15. In this case the estimated and measured values are off by up to 1 dB. This discrepancy may be due to a relatively small data set being collected for E5a.

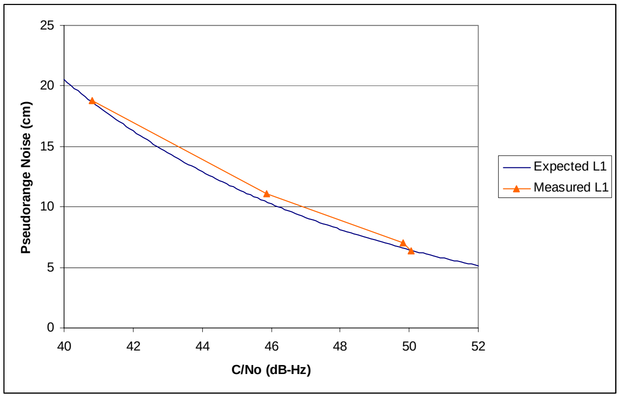

Figure 14: Measured and Expected Pseudorange Noise of Galileo L1 BOC(1,1) Signals with GSVF Simulator Generated Signal

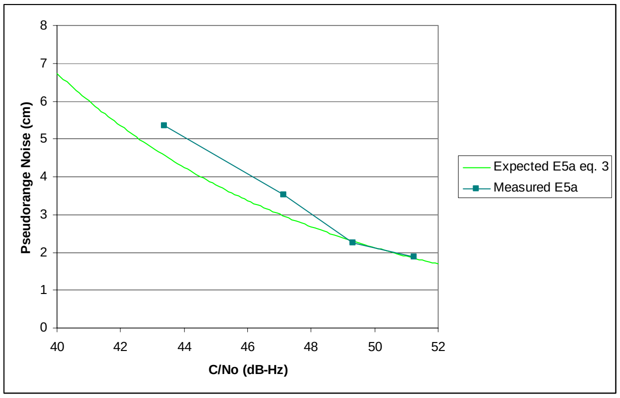

Figure 15: Measured and Expected Pseudorange Noise of Galileo E5a Signals with GSVF Simulator Generated Signal – Expected Value Calculated with Equation 3.

CONCLUSION AND FUTURE WORK

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

Work is continuing 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.

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