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Tight Fit

Inertial Aided GNSS Receiver

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Robust, continuous positioning in adverse signal-tracking environments remains a formidable engineering and practical challenge. Deep integration of GNSS/inertial technologies that complement the strengths and weaknesses of each appears to be a promising approach to the problem. This article describes a European project seeking to improve the hybridization of GNSS and INS.

Hybridization of GPS and inertial measurement unit (IMU) is a well-known concept, with strong developments in the field. Up to now, however, such hybridization for civil applications has been mainly limited to either processing the navigation output of both systems (loose coupling) or integrating measurements from both systems into a Kalman filter (tight coupling). Although ongoing research is taking place on INS/GPS integration at the tight level, an INS/Galileo has not yet been investigated.

In the framework of Europe's research and development activities in the Galileo program, the Galileo Joint Undertaking (GJU) awarded a contract to DEIMOS Engenharia and Institut de Geomàtica to identify improvements and further possibilities for hybridization techniques: an initiative known as IADIRA (Inertial Aiding - Deeply Integrated Receiver Architecture) project.

The IADIRA project focuses on inertial aiding and inertial coasting using low-cost micro-electromechanical (MEMS) miniature inertial measurement units, seamlessly and transparently integrated into a GNSS receiver through an inertial antenna comprising a GPS antenna and inertial sensors. A tightly (or deeply) coupled integration approach was used.

Superior navigation performance results from the aiding provided to the carrier and code phase tracking loops through the combined inertial-GNSS derived position and velocity. The integration also allows the receiver loops to coast when satellite signals are lost.

The development of the IADIRA concept required selection of an application by which to define the final requirements that needed to be met by INS/GNSS. Based on the planned applications of Galileo (established in the so-called Galilei project) as well as the past experience of the project partners, a rail application was selected in line with anticipated future growth in that sector.

The project focused specifically on train traffic control and track surveying. Given that these applications are classified as safety-of-life applications, the requirements are rigorous in terms of system reliability and accuracy.

This article describes a test-bench developed to analyze and demonstrate the INS/Galileo concept and a receiver prototyped in a sample-based (bit-true) Galileo software receiver. It also reports the results of a data collection campaign conducted to assess the performance of the prototype receiver using real inertial sensor data. In this test, a navigation-grade IMU was used to provide a truth reference to measure the performance increase when using IADIRA concept.

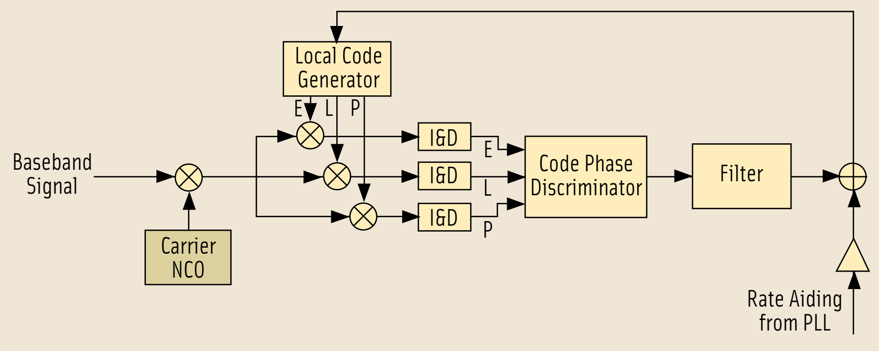

FIGURE 1 Model of a delay-locked loop with carrier rate aiding

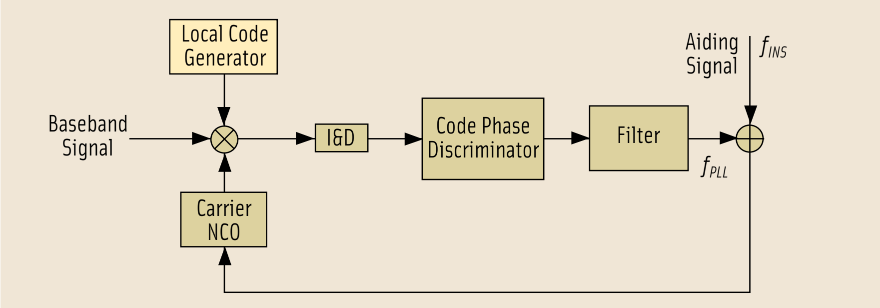

FIGURE 2 Model of a phase-locked loop with inertial aiding

Aiding Tracking Loops

The advantages of using a tightly integrated approach are clear. The combination of complementary technologies provides aiding to the receiver tracking loops, which minimizes the dynamic stress uncertainty, thereby reducing the error in GNSS measurements — an especially important consideration for high dynamic applications. In turn, the receiver's phase-locked loop (PLL) and delay-locked loop (DLL) bandwidths can be narrowed, resulting in significantly lower noise in the measurements and an improved ability to track a GNSS signal with a lower carrier-to-noise (C/No) ratio.

A rate-aided DLL can be used to increase robustness to dynamics, noise, multipath, and interference.

Integration times can be increased in a hybridized INS/GNSS system, also improving signal tracking with lower C/No, because a trajectory estimate is available at much higher frequency than with GNSS alone. Inertial aiding also reduces the occurrence of cycle slips, and even during satellite signal outages the receiver keeps local code replica aligned for some time, enabling reduced reacquisition times when a signal is available again.

Such advantages clearly result in better position and velocity accuracy and availability and overall system integrity, making IADIRA ideal for applications with stringent requirements operating in harsh environments. Last but not least, the use of lower cost sensors would allow the use of IADIRA in more mass-market oriented applications, where an inertial antenna input port would become an option in future GNSS receivers.

A rate-aided DLL can be used to increase robustness to dynamics, noise, multipath, and interference. The rate-aided DLL uses the more accurate phase measurements determined by the PLL to aid the code tracking loop. In addition to improved performance, the rate-aided DLL can also maintain synchronized code even when signal-in-space (SIS) blockage occurs. **Figure 1** illustrates the model of the rate-aided DLL.

Figure 2 illustrates a basic structure of a PLL using inertial aiding. The feedback signal from the integrated navigation algorithms f_{INS} accounts for the relative satellite-receiver dynamics, leaving only residual dynamics to be tracked (essentially due to local oscillator and residual biases in the aiding Doppler measurements) so that the output of the loop filter is given by $f_{PLL} = f_{clk} + f_{noise}$. The aiding signal is given by, $f_{INS} = f_{dopp} + f_{INS}^{resBias}$ where f_{dopp} is the Doppler shift correspondent to the satellite-receiver dynamics and $f_{INS}^{resBias}$ is the error of its estimation.

Error Characterization

A set of factors affect the accuracy of the receiver observations. Some of these factors can be modeled in order to reduce their effect on pseudorange and phase observations, as opposed to other GNSS errors (for example, ephemeris errors)

FIGURE 3 Actual data acquisition campaign trajectory (red dots)

FIGURE 4 Data acquisition hardware configuration. From left to right: GPS precision antenna, automotive grade IMU, and navigation grade IMU

that depend on the broadcast data. One of these factors is the receiver PLL and DLL noise, essentially due to thermal noise, antenna vibration, Allan deviation, and dynamic stress. Analysis of main errors for the deeply integrated receiver with different IMU sensor types was performed and summarized in **Table 1**.

Obviously, the higher the quality of the IMU, the smaller the range error. With an automotive sensor and a horizontal dilution of precision (HDOP) of 2.0, a horizontal accuracy of 0.3 meters (3-sigma) for the DLL and 0.01 meters for the PLL can be achieved. In the particular scenario of train control, additional local elements would need to provide corrections for some of the remaining errors in order to achieve the desired final accuracy. Additionally, the use of dual GPS-Galileo processing would considerably enhance overall performance.

Modulation type	Low Cost	Automotive	Tactical	Navigation
DLL E5 AltBOC (15,10)	0.180	0.150	0.070	0.070
DLL L1 BOC (1,1)	1.090	0.920	0.450	0.430
DLL BPSK (1)	1.440	1.220	0.610	0.560
PLL E5 AltBOC (15,10)	0.004	0.003	0.002	0.001
PLL L1 BOC (1,1)	0.004	0.003	0.002	0.002
PLL BPSK (1)	0.003	0.003	0.001	0.001

TABLE 1. DLL and PLL error in meters (3 sigma) for four different grades of IMU

As for coasting performance, the time to reach the integrity alarm limit of 1.5 meters, typical in train control, is about eight seconds using an automotive grade sensor. As to the Doppler error during satellite outages, the desired accuracy of 0.5Hz can be maintained for at least two seconds with an automotive-grade IMU.

Test-Bench Description

The IADIRA test-bench comprises the following elements:

- The data collection and trajectory generation which consists of two components: a software/hardware system that permits the collection of actual INS and GPS data along a trajectory, thus fixing the test scenario and picking its realistic environment conditions; and a standard software that permits the post-processing of the INS/GPS data for the generation of reference trajectories. (See **Figure 3**.)
- An IMU simulator, responsible for generating synthetic IMU observations (with and without systematic errors and noise) based on the previously generated trajectory, which feeds the Integrated GNSS-Inertial Navigator (IGIN) software.
- A bit-true simulator that generates synthetic GNSS signals from a reference trajectory according to user-defined satellite ephemeris and uses a GNSS software receiver simulator that recreates in detail the signal processing chain of a Galileo receiver. The results are fed to the IGIN software. The software simulator was modified to implement the IADIRA receiver and to provide a four-channel architecture.
- The IGIN software receives the observables from both IMU and GNSS outputs and determines the navigation solution data as well as feedback for the bit-true simulator. The receiver may or may not use aiding data allowing a comparison of results between the tightly coupled and loosely coupled architectures.
- A graphical user interface, used to configure and interact with different SW components and analyze main test-bench outputs.

Test Campaign Results

The following figures exemplify the improved performance (velocity, dynamic stress, pseudorange) when deep integration is used for an accelerating vehicle, with data collected using the platform shown in **Figure 4** and subsequently injected off-line into the software receiver together with BOC(1,1) signals. Various scenarios and sensors were employed using four satellites in view and position dilution of precision (PDOP) of 1.6 and C/No ratios ranging from 37 dB/Hz to 42 dB/Hz with and without carrier-smoothed code.

Partial (three satellites only) and full outage scenarios have also been tested. Other testing activities included assessing the effects of GNSS/INS syn-

chronization error and the minimum C/No where, for a PLL bandwidth of 3 Hz, tracking was achieved down to 24 dB/Hz. As to the Doppler threshold and integrity alarm (of 1.5Hz and 1.5 meters, respectively), using an automotive grade sensor, at least 6 seconds of outage can be tolerated.

Figure 5 shows the increase in velocity accuracy for a 60-second simulation using the automotive grade sensor.

When using equal loop bandwidths (3Hz for the PLL and 1 Hz for the DLL), the advantages of the aided receiver can be clearly seen in **Figure 6**, which shows the PLL filter outputs for unaided and aided receivers with an automotive grade sensor. The approximately zero mean filter outputs of the aided receiver, denoting low PLL dynamic stress, contrast with the unaided receiver's filter results. In the latter, the loop's dynamic stress (most noticeable for the final two channels) depends on the difference between the real Doppler shift and the Doppler shift estimate used to perform the Doppler removal.

For the aided receiver configuration using unsmoothed pseudoranges, the achievable pseudorange error standard deviation is similar whether navigation- or automotive-grade sensors are used. These errors' standard deviations vary between 0.6 and 1 meters (an almost 6 dB gain with relation to the unaided case), as can be seen in **Figure 7**. If smoothed pseudoranges are used, the error range drops to about 7 to 20 millimeters (additional gain of 20 dB or more).

In **Figure 8** we can observe the difficulty that the PLL of the unaided receiver has while trying to converge after a full outage (outage occurs between second 25 and 45). The receiver is not able to maintain lock of the carrier phase for two of the channels (third and fourth channels) at least until the end of the simulation. Cycle slips keep accumulating for these channels and, consequently, the carrier phase estimate keeps diverging even after the outage has ended.

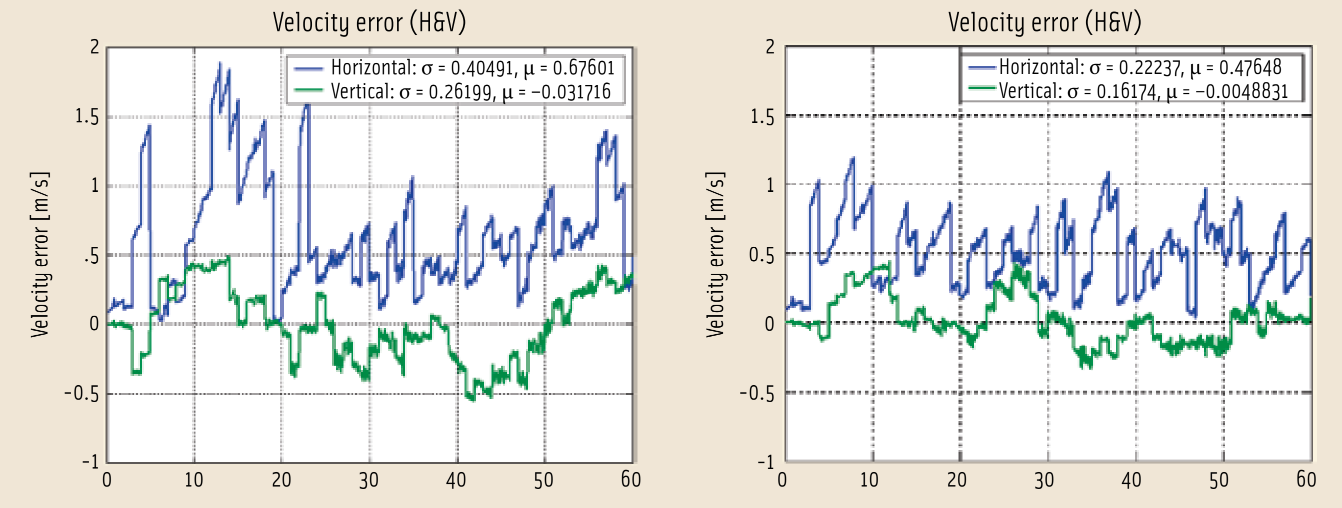

FIGURE 5 Horizontal and vertical velocity errors with deeply integrated approach (right) and without deeply integrated approach (left)

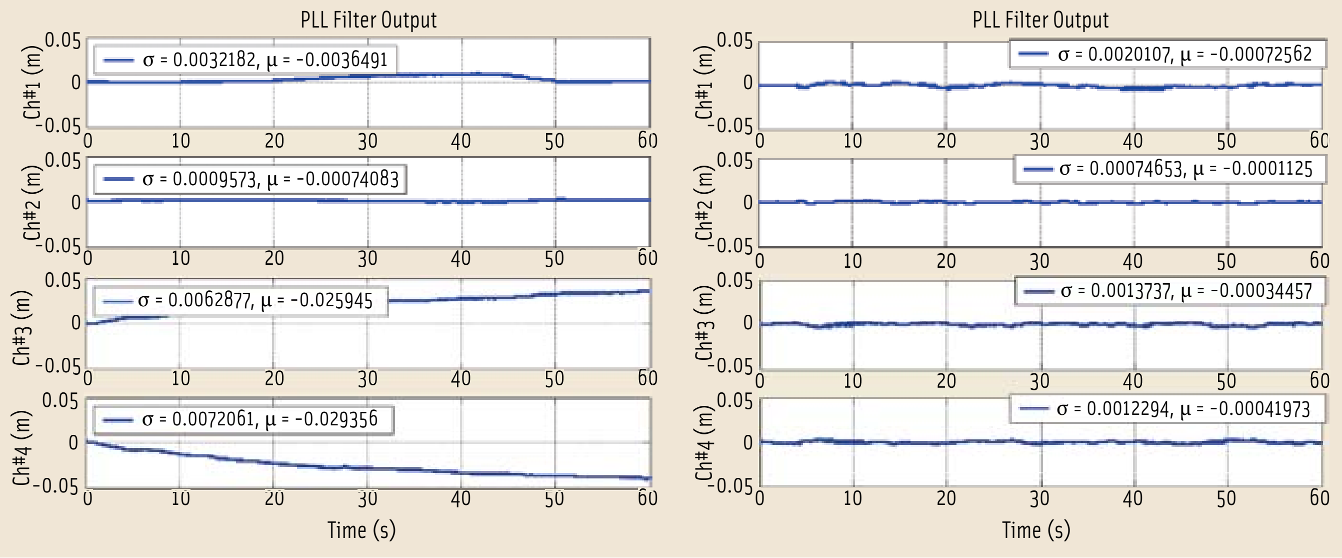

FIGURE 6 PLL filter output illustrating dynamic stress with deep INS/GNSS integration (right) and without deep integration (left)

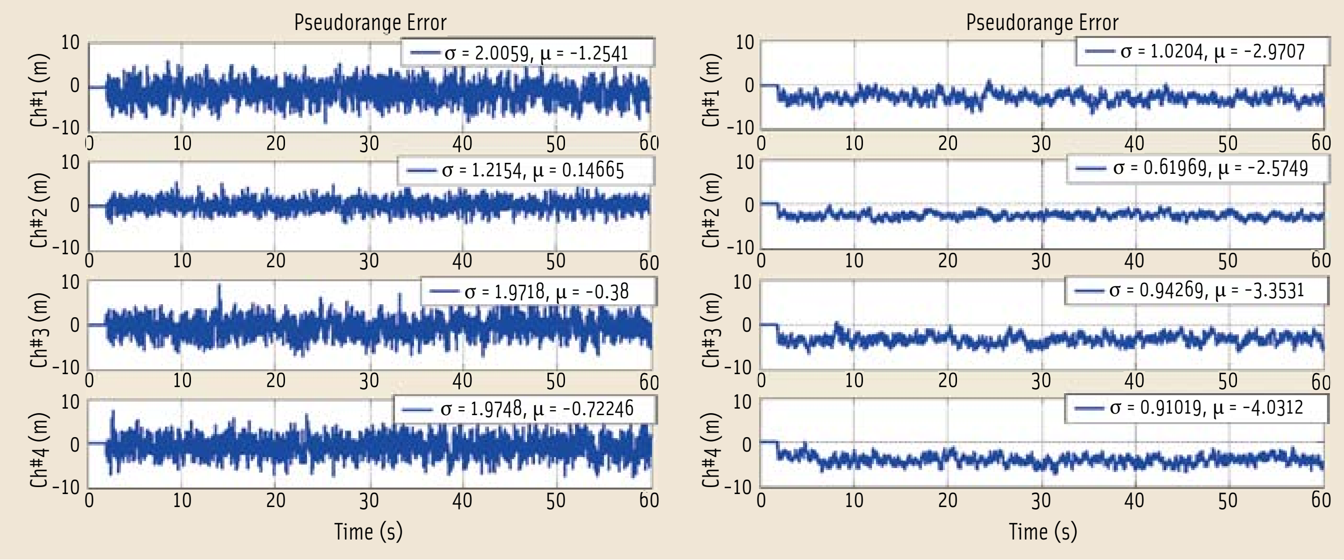

FIGURE 7 Pseudorange error without deeply integrated approach (left) and with deeply integrated approach (right)

The DLLs also have trouble keeping lock. In fact, when aiding was not used, after the outage the DLL locks in a secondary autocorrelation peak leading to a biased and noisier pseudorange estimate (as seen in **Figure 9** for the third and fourth channels). This is due to the multi-peak correlation function of BOC modulations — as is the case for the Galileo L1 signal, which has a BOC(1,1) modulation.

Conclusion and the Way Ahead

GNSS-INS deep integration increases application robustness, service availability, integrity, accuracy, and precision. The main advantages of GNSS-INS deep integration are:

- Acquisition and tracking of weaker signals and better quality of measurements
- Navigation solution available with fewer than four satellites in view and even under full signal blockage
- Nearly instant reacquisition after signal blockage
- Increased robustness to interference and cycle slips

Next generations of GPS and Galileo receivers can take advantage of such low-cost and fully integrated GNSS-IMU systems based on miniaturized sensor technology, thus allowing for innovative and more challenging applications of satellite navigation. This will be possible thanks to the availability of the new Galileo signals, such as BOC or Alt-BOC, combined with inertial aiding and coasting as described in IADIRA concept. Testing activities with lower cost sensors and operational validation in real environment followed by industrialization of IADIRA are the next logical steps.

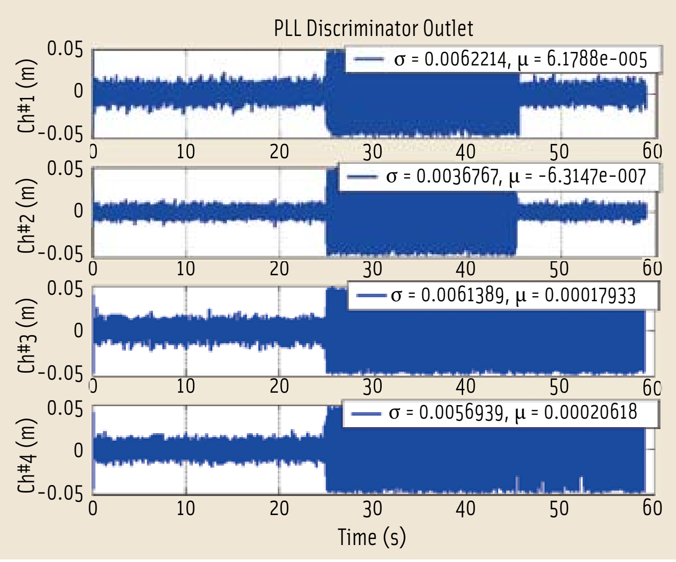

FIGURE 8 PLL discriminator outputs during outage

Manufacturers

The IMUs used are iMAR iVRU-SSKS-C167 (automotive grade) and iMAR iNAV-FJI-001 (navigation grade) from **iMAR GmbH**, St. Ingbert, Germany. The GNSS receiver used is the Millennium OEM 3 from **NovAtel, Inc.**, Calgary, Alberta, Canada. The GRANADA software receiver is provided by **DEIMOS Space**, Madrid, Spain. It has been adapted in IADIRA to provide a capability to operate and receive input data from external inertial aiding sources in high dynamic scenarios.

Additional Resources

[1] "Characterization of the Pseudorange Error Due to Code Doppler Shift in Galileo E5 and L1 Receivers Using the GRANADA Bit-True Simulator," *Proceedings ION GNSS 2005*

[2] "IADIRA: Inertial Aided Deeply Integrated Receiver Architecture," *Proceedings NAVITEC 2006*

[3] <www.deimos.pt>

[4] <www.deimos-space.com/granada/>

[4] <www.galileoju.com>

[5] <www.garda-project.it>

Acknowledgments

Part of the work performed by the IG in this project has been funded by the

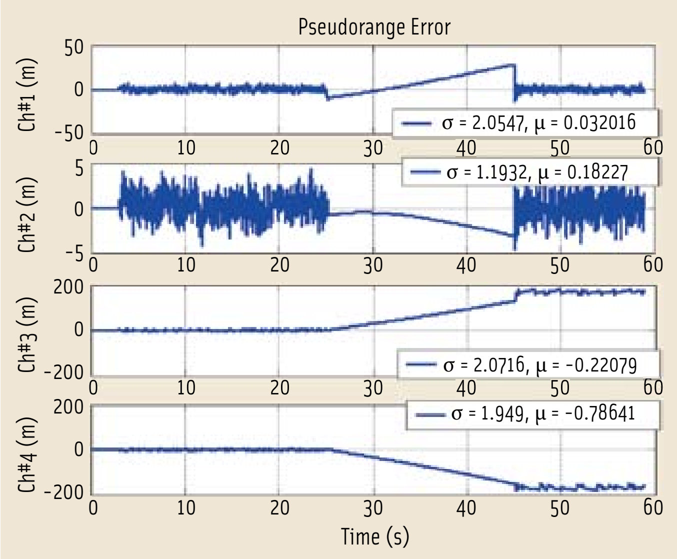

FIGURE 9 Pseudorange error during full outage simulation without deep integration

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(above) IADIRA project team at final presentation . From left to right: Antonio Fernández, Mariano Wis, João Simões Silva, Pedro Freire da Silva, Vincent Gabaglio, Eulalia Pares, Augusto Caramagno, Ismael Colomina, Jan Skaloud, Miguel Belló Mora