navitec 2018

9th edition of a navigation conference hosted by ESA
in coordination with CNES, DLR
and the University of the Federal Armed Forces Munich

5 - 7 December 2018, ESA-ESTEC

ABSTRACT OVERVIEW

Table of Contents

Sessions

Plenary Session – AM

Newton 1 & 2, December 5, 2018, 09:30 - 11:00

The NAVITEC 2018 Plenary session "Future Evolution and Markets" is hosted by Roger McKinlay, from the NAVAC board, Innovate UK.

Plenary Session – AM – Continued

Newton 1 & 2, December 5, 2018, 11:20 - 13:00

Plenary Session – PM – Continued

Newton 1 & 2, December 5, 2018, 14:00 - 15:00

Marco Falcone
ESA-ESTEC
Update on Galileo

Nicolas Girault
ESA-ESTEC
What ESA can do for you

Mr. Pietro Giordano
ESA - ESAC
Space GNSS SDR and In Orbit Demonstrations

Oscar Pozzobon
Qascom S.r.l.
The Gariss Mission: How we Implemented a Space Receiver Directly in Space

Eng. Paolo Crosta
ESA - ESTEC
Galileo App Competition

Analysis of GPS Block IIF and Block IIR-M Events in Transmitted Signal Power

Mr. Rui Sarnadas[1], Mr. Paolo Crosta[1], Mrs Mariana Spangenberg[2], Mr Juan de Mateo Garcia[2]
[1]ESA / ESTEC, Noordwijk, Netherlands, [2]ESA / EPO, Toulouse, France

Analysis of GPS Block IIF and Block IIR-M Events in Transmitted Signal Power

R. Sarnadas (1), P. Crosta (1), M. Spangenberg (2), J. de Mateo Garcia (2)
European Space Agency – (1) ESTEC, Noordwijk, The Netherlands, (2) EPO, Toulouse, France

In January/February 2017, the GPS constellation underwent a series of maintenance operations affecting the power allocation on signals transmitted in L1 and L2 frequencies. In particular, the operations appeared to target transmit power re-allocations for the Block IIF and block IIR-M satellites for both L1 and L2 bands.

By design, the GPS ICD already specifies the fact that these satellites provide programmable power output capabilities, as the following extract shows:
"For Block IIR-M and IIF SVs, the maximum received signal levels as a result of these factors is not expected to exceed -155.5 dBW and -153.0 dBW, respectively, for the P(Y) and C/A components of the L1 channel and L2 channel. In addition, due to programmable power output capabilities of Block IIR-M and IIF SVs, under certain operational scenarios, individual signal components of Block IIR-M/IIF SVs may exceed the previously stated maximum but are not expected to exceed -150 dBW."

Previous studies have shown interesting results when covering similar events, such as analyzing the power re-allocation in L1-P and L2-P/M (no L1 C/A power change) in September 2010, or covering the same period in 2017 and applying different methods to estimate the GPS transmit power changes, considering all signal components as well as the intermodulation product.

With the continuous increase of signals in modernized multi-constellation configurations, and the ground segment evolving accordingly, such considerations on link budget assessments and receiver design must take into account not only the ICD “nominal” power but also the real signal power available and the possible impact in-band.

The purpose of the work performed is then twofold: first, to identify and characterize the GPS flexible power (re)allocations that occurred in 2017 via multiple historical data processing; second, to perform further measurements and analysis on current GPS signals-in-space to derive the power allocation and EIRP computations needed in comparison of previous studies.

The first step consisted in collecting historical data from two separate networks to be analyzed, namely from EGNOS (RIMS) and from Galileo TGVF (GESS). For this, the events were identified in order to obtain dates, times and visibility of each satellite pass when the power change occurred. The table below shows the identification and characterization of the events for Block IIF and IIR-M satellites.

Additionally, for each event, a window of ±2 days around the date was processed, in order to capture signal power data before and after the occurrence. The figures below show examples of these events for one RIMS case and one GESS case (PRN 15 on 7 February 2017 – power change on L1 C/A). For this case – as for all Block IIR-M events – the power change event is accompanied by a NANU, marked with vertical line in the top left image.

This process is repeated for each event, meaning 5 days of data from 3 RIMS and 1 GESS station per event/signal/satellite. In overall, the power increase is clearly observed, especially for L1 case.

The figure depicts additional computations performed once all signal power observations are collected. The blue lines refer to “before” the event, and the red lines refer to “after the event”. To allow for some filtering in the measurement noise and exclude possible outliers, the different symbols plotted relate to (diamond) average of the lowest 20% measurements, (triangle) simple average, and (circle) average of the highest 20% measurements. In all the cases, the red curves are always above the blue, and hence the measurements after the events confirm the power increase.

Preliminary results have shown an increase in carrier to noise ratio of 1-2 dB-Hz for L1 signals and 0.5-1 dB-Hz for L2 signals. The events appear also to have different implementations with respect to the GPS Block considered. For Block IIF satellites, both L1 and L2 signal power is increased but the effect seems to be split between both. On the other hand, Block IIR-M satellites appear to exhibit events on L1 only and the increase is more visible therein. Finally, it should be noted that each receiver has a specified uncertainty in the C/N0 estimation, which can go up to ±1dB-Hz or more, so the results collected in this work surely benefit from the increased number of data sources and measurements by using both RIMS and GESS data.

After these measurements are consolidated, the next step is to revisit particular cases for power increase observations and derive (reverse) link budgets and assumptions therein to arrive to the EIRP and received power on ground measurements, while at the same time crosschecking with the results obtained in previous studies.

For this purpose, a high-gain 3-meter dish antenna is used in the ESTEC Navigation Laboratory, connected as well to a Spectrum Analyzer for further spectral characterization and a GNSS receiver for simultaneous C/N0 monitoring. The setup is calibrated to compute the received power and EIRP directly (setup depicted in the figures below) and is used to collect all measurements for the theoretical analysis.

Galileo Antenna Gain Pattern Estimation for Signal Quality Monitoring

Dr. Gerardo Allende-Alba[1], Steffen Thoelert[1,2], Prof. Michael Meurer[1,2]
[1]German Aerospace Center, Weßling, Germany, [2]RWTH Aachen University, Aachen, Germany

One of the key factors to achieve reliable and robust navigation using GNSS is the verification of signal quality. In the particular case of critical safety applications, stringent requirements in terms of signal integrity are imposed in order to consider GNSS for integration and expansion of current systems. Due to the strong dependency of the achievable user positioning accuracy on the received GNSS signal power, a central element of the GNSS signal quality evaluation is the verification of the available power levels at user location. In particular, the state of the GNSS satellite payload and antenna may suffer some level of degradation due to the heavy strains during launch and space environment factors. As a consequence, the nominal performance of such elements is affected, leading to possible anomalies in the radiated signal power. An analysis and evaluation of the GNSS signal quality requires the investigation of such anomalies. Over the years, various methods for the computation of transmit power levels have been proposed and applied. Besides strategies based on nominal minimum received power levels and link budget calculations, some authors have explored the use of a high-gain antenna to characterize the transmitted signal performance (Edgar et al., 2002; Gatti et al., 2008; Thoelert et al., 2012). Similarly, Steigenberger et al. (2018) showed that this method can be used to estimate the transmit power levels of satellites from various GNSS constellations. Such an approach assume some knowledge of the properties of the transmit antenna (e.g. gain pattern), resulting in average transmit power levels. However, for the investigation of temporal signal anomalies, it is necessary to consider possible variations both in the transmitted power levels and the performance of the GNSS antenna gain pattern. Thoelert et al. (2012) showed that anomalies in the GIOVE-B satellite antenna gain pattern could be estimated with observations using the 30 m deep space antenna located at the ground station Weilheim in Germany. Although such an approach is suitable for analyzing possible antenna gain pattern and other signal anomalies (Thoelert et al., 2015), its applicability for monitoring several GNSS satellites is limited.

This paper describes the methodology and tests performed for GNSS satellite antenna gain pattern estimation for signal quality monitoring. One of the main aims of this study is to make use of less complex monitoring facilities (e.g. with high-gain antennas) in order to increase the coverage of analysis of various GNSS space vehicles. To this end, a measurement station consisting of a Septentrio PolaRx5TR GNSS receiver and a Novatel GNSS-750 choke ring antenna has been set up at the DLR's Institute of Communications and Navigation in Oberpfaffenhofen, Germany. With this configuration, signal power observations are collected regularly for GPS and Galileo satellites. As a first goal, this study has been focused in the estimation of Galileo antenna gain patterns for IOV and FOC satellites in order observe the actual performance of transmit antennas under operative conditions. Such estimated patterns shall be used later as reference in tasks of signal quality monitoring.

Signal strength observations obtained by the GNSS receiver are used to compute transmit antenna gain values taking into account the relative position of Galileo satellites with respect to the monitoring station. Galileo satellite positions are computed using broadcast ephemeris products from the Multi-GNSS Experiment (MGEX; Montenbruck et al., 2014). By employing a yaw-steering satellite attitude model (Montenbruck et al., 2015) the computed transmit antenna gain values are referred in the body-fixed (or corresponding) spacecraft antenna reference frame. In this way, mapped satellite pass tracks are used for the estimation of the transmit antenna gain pattern. Following Thoelert et al. (2012), adjustment power factors are estimated in order to compensate mapped observations for variations in the measured signal strength in each pass. It is assumed that these variations are based on changing conditions (e.g. weather) of the propagation pass and environment of the receiving station over the observed time period. Due to the characteristics of the employed measurement setup in this study (e.g. usage of a low-gain antenna), signal power observations are smoothed using a moving average filter in order to reduce the impact of receiver noise and multipath on the applied power factor adjustment. Subsequently, the estimated (relative) transmit antenna gain values are used for the generation of a gain model by employing a spherical harmonics expansion. The presented strategy has been tested using observations from the GSAT0102 and GSAT0207 Galileo satellites. The estimated antenna gain patterns have been validated with independent calibrated observations using the 30 m high-gain antenna at the Weilheim ground station. The obtained results suggest the feasibility of estimating satellite antenna gain patterns using observations from a measurement setup of reduced complexity. These proof-of-concept tests help to pave the way for further implementation of a signal quality monitoring facility, which can significantly support safety critical applications in future.

References

Edgar, C., Goldstein, D.B., Bentley, P. (2002) Current constellation GPS satellite ground received signal power measurements. In: ION NTM 2002, San Diego, CA, pp 948-954.

Gatti, G., Falcone, M., Alpe, V., Malik, M., et al. (2008) GIOVE-B Chibolton in-orbit test – initial results from the second Galileo satellite. GNSS Solutions, September-October, pp 30-35.

Thoelert, S., Meurer, M., Erker, S. (2012) In-orbit analysis of antenna pattern anomalies of GNSS satellites. NAVIGATION 59(2):135-144.

Thoelert, S., Enneking, C., Vergara, M., Sgammini, M., et al. (2015) GNSS nominal signal distortions – estimation, validations and impact on receiver performance. In: ION NTM 2015, Tampa, FL, pp 1902-1923.

Steigenberger, P., Thoelert, S., Montenbruck, O. (2018) GNSS satellite transmit power and impact on orbit determination. Journal of Geodesy 92(6):609-624.

Montenbruck, O., Steigenberger, P., Prange, L., Deng, Z., et al. (2014) The Multi-GNSS Experiment (MGEX) of the International GNSS Service (IGS) – achievements, prospects and challenges. Advances in Space Research 59(7):1671-1697.
Montenbruck, O., Schmid, R., Mercier, F., Steigenberger, P., et al. (2015) GNSS satellite geometry and attitude models. Advances in Space Research 56(6): 1015-1029.

GUEST Platform: Enhanced Methodology and Tools for System Performance Evaluation

Dr. Nabil Jardak[1], Jose Vicente Perello Gisbert[2], Gregory Moura[3], Xavier Leblanc[4]
[1]M3 Systems, Lavernose-lacasse, France, [2]ESA / ESTEC, Noordwijk, Netherlands, [3]OKTAL Synthetic Environment, , France, [4]GUIDE, , France

The number of applications relying on GNSS receivers is constantly increasing and requirements on GNSS performance (accuracy, availability, and integrity) are becoming stronger. Indeed, GNSS is more and more used for “critical” applications (e.g. safety-critical or liability-critical) where the quality of the provided service (basically localization) shall be controlled and anticipated. In addition, the use of GNSS in constrained environment (e.g. urban canyons, sub-urban and urban environments), for which environmental issues shall be considered (effect of surrounding environment on the performance due to shadowing, attenuation and multipath), is also increasing. The evolution and modernization of GNSS shall also be considered, such as the achievement of Galileo, the improvement of GNSS, and the future multiplication of multi-constellation multi-frequency receivers.

This way, it is of utmost importance to be able to assess the GNSS performance in various conditions (specially in urban) with a high level of fidelity. This can of course be done by means of in-field campaigns for existing GNSS signals, but with a limited number of scenarios and statistics (e.g. due to the cost of such campaign). There is thus a strong need for the development of a high-fidelity simulation suite allowing testing of different receivers’ architecture or algorithms in different environments, as well as simulating the GNSS improvements and optimizations. Due to the urban environment modeling complexity, and to ensure the modeling representativeness, this simulation suite shall include a 3-D simulation tool modeling the environment effects and allowing to reproduce the signal impairments (mainly blockage and multipath), whereas existing simulation tools today are based on LOS (Line of sight) analysis only and either do not consider multipath or the multipath is based in statistical models that provide very limited insight into the results not allowing to understand them in detail.

In this context, the GUEST Platform aims to provide a GNSS performance assessment platform to calculate the GNSS performance in different environments (mainly urban) and scenarios targeting GNSS characterization, being able to consider the multitude of constraints and environments and to ensure flexible and configurable simulations. The developed platform includes nominal GNSS constellations (on multiple frequencies) as well as future ones, including MEO satellites, IGSO satellites and combinations of them. It also models two types of COTS receivers (Ublox 6T as Mass Market receiver and PolaRx4 as Professional receiver).

Those representative simulations require the ability to reproduce “real world scenarios”, that means that the GNSS simulation platform must take into consideration the characteristics of the receiver environments to assess GNSS signals reception. The effects to reproduce are signal blockage and attenuation, multipath, interference impairments in all types of environments, with special emphasys in irban environment. This is achieved by representing the receiver environment into 3-D virtual scenes, and modelling the signal propagation in this environment.

Another characteristic of the platform is to be able to execute easily a number of different configurations and simulation options to enable the GNSS performance characterization such as different constellations and different user dynamic dimensions. It has to provide a number of performance indicators (FOM) at the output of the receiver model, to be compared with the reference scenario. It shall also be highly configurable and flexible to enable parameterization of the scenarios and be able to evolve to cover future signals and use cases, in particular G2G characteristics.

Finally, the GUEST platform have been intensively validated (environment, signals and receiver modeling), in particular by comparing the simulated results with both GNSS simulator signals (StellaNGC©) and in-field campaigns on real SIS signals with COTS receivers (mass-market and professional). The platform is also characterized by running a set of representative scenarios, providing numbers of performance results, in particular for future scenarios (G2G performance characterization).

Validation results have shown GUEST capability to closely reproduce the COTS receiver's behaviors in urban environments. Some discrepancies observed in comparison with respect to the real world results are shown to be due to uncertainty on the reference trajectory in deep urban, non-modeled objects in the 3D scene (cars, chairs,…) and pedestrians, non-modeled propagation phenomenon (the scattering which may explain fewer multipath availability, and short term variation on the signal magnitude) as well as the uncertainty on the receiver antenna diagram model (mainly the cross-polar component that is not available in the COTS data sheets). Although some discrepancies, the propagation model (based on ray tracing and geometry optic and the uniform theory of diffraction) is shown to have a very good replication of the urban environment.

This paper thus presents the GUEST platform specification and design. The platform validation methodology will be described in detail. It is based on two steps: first, the validation in controlled environment in order to validate and tune the receiver's models and parameters. Second, by comparing the simulation results with real data collection counterparts using the modeled COTS receivers. This second step represents at the same time a validation step and a performance assessment step. The main challenges were to obtain receiver models that reproduce the behavior of two COTS receivers (Mass Market and Professional GNSS receivers) and to tune the propagation channel model parameter in order to best fit with the in-field tests in constrained environment.

The perspectives and future use of the tool will also be discussed, as for example: include advanced signal processing, to extent the tool application to more use cases (for example design of new GNSS signals), enhance the validation methodology to assess the representativeness of propagation channel models, to study the propagation effects in urban environement, and to use GUEST to draw multipath error maps as function of environment type to aid bounding the multipath effect on pseudorange in constraints areas; and also the use of the GUEST tool observables to assess the PPP performance in urban scenarios.

An Experimental Evaluation of Galileo Wideband Signals

Dr. Melania Susi[1], Dr Daniele Borio[1], Dr Joaquim Fortuny-Guasch[1]
[1]*European Commission, Joint Research Centre, Ispra, Italy*

In December 2016, Galileo Initial Services were declared. This declaration implies that the Galileo space and ground infrastructures are now operationally ready (European Union, 2016). With its 18 operational satellites, Galileo is now able to provide positioning services with high availability. Moreover, Galileo is leading the race for populating the E5/L5 frequency band. Indeed all the Galileo satellites broadcast on three frequency bands providing a unique opportunity in terms of accuracy and signal redundancy.

The Global Navigation Satellite System (GNSS) receiver industry is evolving in parallel with the new opportunities provided by the Galileo system and several manufacturers are now developing and deploying devices able to exploit the Galileo dual frequency capabilities even in the mass market segment (Cozzens, 2017).
In addition to the aforementioned E5 signal, Galileo will also provide a High Accuracy (HA) service that will be broadcast on the E6 frequency, on the data channel that was previously allocated to the Commercial Service (CS). While the name CS is still used to denote the Galileo E6 signals, the HA service will be provided for free and will bring accuracies in the order of few decimetres.
In order to fully exploit the benefits brought by the Galileo system, it is important to characterize the performance achievable using the different Galileo signals. While several studies (Zaminpardaz and Teunissen, 2017) have analysed the performance of the Galileo signals in the measurement and position domain, it is also important to determine the related data dissemination performance. Indeed the ability to correctly demodulate the navigation message is fundamental for receiving and correctly using the corrections that, for instance, will be broadcast by the Galileo HA service.
The goal of this paper is thus to characterize the performance achievable using wideband Galileo signals under different propagation conditions. The paper considers different key performance indicators and complements traditional analysis in the position and measurement domains with an experimental evaluation of the data dissemination performance.
In this study, all the Open Service (OS) and CS signals are considered. The analysis focuses on the different signal combinations including E1, E5 and E6 frequencies. In the E5 case, the E5a and E5b components are analysed independently and as a whole, i.e. considering the full AltBOC modulation. The CS signal in E6 is studied considering different possibilities, either assuming the availability of the data component alone or considering the pilot component to assist signal tracking and help data demodulation.
The analysis in the position domain is performed considering the Galileo constellation alone or in a multi-constellation framework in combination with GPS signals.
Different scenarios were considered. At first tests were performed using a Spirent GSS9000 simulator capable of generating all Galileo signals in all Galileo frequency bands. The scenario considered in the simulations assumed static, open-sky conditions with the Carrier-to-Noise Power Spectral density ratio (C/N0) of all signals progressively decreasing. This test was performed in order to assess the sensitivity limits of the different receivers used for the analysis. In addition to this, it was possible to determine the relative performance achievable using the different Galileo signals.
Simulation analysis was complemented with data from real-live scenarios that included open-sky conditions, partially obstructed environments with multipath effects from nearby buildings and fading from trees and dynamic tests in rural and urban conditions. Open-sky conditions were obtained considering an antenna placed on the roof-top of the European Microwave Signature Lab (EMSL) of the Joint Research Centre (JRC) in Ispra, Italy. The location of the antenna was carefully surveyed and allowed the assessment of the position accuracy. The antenna used in the test was a high-end geodetic antenna capable of receiving all Galileo frequencies. The rural environment is considered of primary interest for the HA service for its strategic impact in the precise agriculture sector.
Different metrics were considered for the analysis. The C/N0 was analysed as a function of the satellite elevation in order to determine which signal provides the highest received power under the same reception conditions. The code noise on the different signals were determined combining pseudoranges and carrier phase measurements. The observation availability was determined as percentage of time during which measurements were available.
Figures of merits such as the presence of data gaps and the number of cycle slips were computed for the different signals. These performance indicators have a direct impact on the quality of carrier phase measurements.
Two approaches were used for the computation of the Bit Error Rate (BER). In the E6 case, a dummy message is currently broadcast. Thus, it is possible to compare directly the received bits with the values in the dummy message that is known a-priori. In this way, it was possible to directly count the number of

erroneous bits. For scenarios such as the rural and the urban, the analysis was performed satellite by satellite. This choice was motivated by the fact that signals come from different directions and can be affected by different local phenomena.
For the other Galileo signals, a reference receiver operating under open-sky condition was used to obtain a reference data bit sequence. The number of errors caused by the reference receiver was assumed significantly lower than that caused by the rover receiver.
Finally, positioning accuracy for different signal combinations was determined using an RTK commercial software.
The tests were conducted using several commercial receivers capable of acquiring and tracking all Galileo signals.
From the analysis, it emerges that the AltBOC modulation, threated as a whole signal, provide the best performance in terms of sensitivity and code noise. The E6 signal provides the second best performance outperforming the E5a and E5b modulations.

REFERENCES

European GNSS (Galileo) Open Service Definition Document (OS-SDD), Issue 1.0, European Union, December 2016.

Cozzens T. (2017),"Broadcom releases Dual-Frequency GNSS Receiver with Centimeter Accuracy for Consumer LBS Applications", GPS World September, 2017, http://gpsworld.com/broadcom-launches-dual-frequency-gnss-receiver-for-mass-market/

Zaminpardaz S. and Teunissen P. J. G. (2017), "Analysis of Galileo IOV + FOC signals and E5 RTK performance", GPS Solutions, 2017, Vol. 21, pp. 1855-1870

Autonomous Time Synchronization Using Beidou Inter-satellite Link Ranging

Mr. Wende Huang[1], Mr. Leyuan Sun[1], Mr. Yifan Zhou[1]

[1]*National University Of Defense Technology, Changsha, China*

The autonomous navigation means generating navigation messages and maintaining configuration by satellite constellation without the support from ground stations. The satellite constellation modifies its forecasting ephemeris and clock parameters through dual ranging, data exchange, and filtering online. Autonomous navigation reduces the dependence on ground stations of satellite constellations. In the mode of autonomous navigation, satellite constellation should establish and maintain an autonomous time scale, combining all the satellite atomic clocks by inter-satellite links. All the satellite clocks in the constellation keep in pace with the autonomous time reference to support precise positioning service. And the time reference is traced to Universal Time Coordinated (UTC), what is necessary to precise timing service. The time scale establishment is the kernel of the autonomous time reference. Inter-satellite clock error measurements and clock weights are necessary inputs of weighted average time scale algorithm. To establish a time scale, the constellation satellites must complete autonomous time comparison at first as a time measurement and positioning system. Furthermore, clock weights are steered based on the frequency stability of all the on-board clocks. To take advantage of the inherent property of atomic clocks, it is necessary to identify the noise characteristic of time synchronization links and design proper filters to filter out the corresponding noise introduced by time synchronization links and algorithm. So the autonomous time synchronization using a synchronism inter-satellite link ranging and the analysis of inter-satellite clock errors are preliminarily presented in this work.

In the mode of autonomous navigation, the time reference of atomic clocks is maintained and provided for satellite navigation system by autonomous time synchronization using inter-satellite links. The experimental satellites of Beidou navigation satellite system (BDS) are equipped with ISLs in Ka-band for autonomous navigation experiment. Based on the time divided system of BDS, the dual one-way ranging is completed in two contiguous timeslots. Systematic errors including hardware delays, relativistic effects and phase center offset of satellite antennas are corrected from the original dual one-way pseudorange measurements by steering or modeling and a pair of corrected pseudorange are got. Reduce the corrected pseudorange to a reference epoch and the relative clock error is resolved. The inter-satellite relative clock errors of three Beidou experimental satellites, on which Rb clocks are used, are separated from the ISL ranging data using the time synchronization algorithm above. The clock error results have shown there is always frequency drift in Rb clocks. Fit the clock errors with second-order polynomial models and analyze the fitting residual errors. Because of the influence from the space environment, the residual clock errors, corrected with initial time deviation, frequency deviation and frequency drift, have demonstrated periodic regularity.

Due to the restriction of observation arc, only the frequency stability in short term of the satellite clocks is analyzed. Select a continuous observation arc and correct the error data with a periodic term. The property of new residual errors is analyzed. The standard deviation of the residual errors is 0.1 ns. The standard deviation will increase with a larger arc. The modified Allan deviation of clock error is further used to evaluate the property and variety of the clock error noise. The inter-satellite clock error has represented only one type of primary noise, white frequency noises (WFM), because the slope of $\log(\sigma_y) \sim \log(\tau)$ is minus 0.5. The Rb clock is mainly influenced by white frequency noise and random walk frequency noise. And the later one hardly appears in the short term. According to the analysis, noise introduced by inter-satellite links and time synchronization algorithm does not submerge the inherent noise character of the atomic clock in a short term. But the noise type of time synchronization links is indeterminate. Precise clock errors and mathematical simulation are necessary for more exact conclusion. On the other hand, the influence of the time synchronization noise in medium and long term should be analyzed relying on more inter-satellite ranging measurements.

The first two networking satellites of Beidou global navigation satellite system have been launched into the orbit recently, indicating the BDS has been entering into the age of global networking. Because of the restriction of ground station distribution, autonomous navigation of BDS is necessary to maintain its system operation and reliability. In the mode of autonomous operation, the satellite navigation system should complete orbit determination and time synchronization autonomously using inter-satellite ranging measurements, and support precise positioning and timing service for users uninterruptedly. Establishment and maintain an autonomous time reference is a fundamental and core technology for autonomous operation. Time comparison, time scale establishment and time scale steering are involved. Satellite atomic clocks are the pivotal instruments, providing reference time and frequency. To take advantage it inherent property, the inter-satellite link and Time Synchronization noise should be identified and filtered out from the time comparison results. Preliminary analysis of time comparison is completed and a deep research work is carried out.

High Altitude Pseudo Satellites (HAPS) to Enable Performance Based Navigation (PBN) of Alternative Positioning Navigation and Timing (APNT) Systems

Dr. Boubeker Belabbas[1], Omar Garcia Crespillo[1]
[1]*DLR- Institute of Communications and Navigation, Wessling, Germany*

High Altitude Pseudo Satellites (HAPS) started being investigated during the mid-90's with the NASA's Pathfinder demonstrating a flight above 50,000 ft followed by the Pathfinder Plus in 1998 flying at 80,000 ft. Since then, different industrial companies have developed their own HAPS and demonstrated many hours of flight in the stratosphere. Examples of those projects are the Airbus' Zephyr [1], the Thales' Stratobus [2], and the Google Loom project [3]. The advantages of HAPS compared to the use of satellites are significant, especially for local services.. Among others, the capacity to provide higher signal power and better link budget, the easier and faster deployment capability and the lower costs in production and maintenance than satellites, and the possibility to adapt the payload to very specific needs.
The use of HAPS can be also considered as a new segment to provide navigation functions for aviation. Within the context of navigation, the civil aviation community is investigating ground based Alternative Position Navigation and Timing (APNT) options to make use of existing navaids systems, like DME (Distance Measuring Equipment) and to make use of the future ranging sources like the aeronautical communication system LDACS (L-band Digital Aeronautical Communication System). However, one problem associated with ground based APNT is the lack of accuracy in the vertical domain as most of the stations are distributed in the horizon. Additionally, the ranging stations need to be synchronized to enable the use of pseudo ranging rather than ranging in order to avoid user service capacity limitations. Finally for aircraft flying at low altitude during final approach for example, only very few stations are visible to the aircraft and an airborne autonomous integrity monitoring (AAIM) purely based on redundancy of ranges would therefore not be able to provide integrity monitoring during a critical phase of flight.
In this paper we proposed to use HAPS to overcome the limitations of a stand-alone ground APNT system. In [1], an analysis of the HAPS position and time error propagation used in an APNT context were investigated. The sensitivity equation of the user position error to the HAPS position error was derived. The "pseudo lite" service of HAPS provides clearly advantages for APNT as for example to fill in the ground ranging gaps (in areas not covered by enough DMEs for example) and also to provide observability in the vertical domain (Lower Vertical Dilution of Precision) especially in areas where vertical guidance is necessary (like in final approach regions).
Additionally HAPS can be used to enable time synchronization of a local ground station network. The HAPS being at 20 km altitude, a large number of stations are visible simultaneously and the clock corrections with respect to a local system time for each ground pseudo ranging station can be generated at a high data rate. The fact that the ground stations can be seen permanently by the HAPS avoids the need to install long term stable clocks.

A concept study with different classes of clocks will be investigated and the performance will be assessed. A quantitative analysis will be conducted using a realistic scenario using existing distribution of DME stations and simulated locations of LDACS stations. The DME error model will be taken from the literature and the LDACS error model will be derived from measurements during flight trials. This paper will demonstrate that both the positioning and time services of APNT will improve significantly by the use of HAPS.
As we want to explore the possibility to use these services for safety critical application providing Performance Based Navigation (PBN)
services, an integrity assessment will be investigated comprising the derivation of the fault free integrity bounds (protection levels) in both horizontal and vertical direction and a fault detection and exclusion service. For the fault free integrity bound, a ground network of stations will be defined and different user scenarios will be investigated. Depending on the way to derive the pseudo range/range observations and later the position solution, an error characterization will be conducted and an over-bound of the error distribution that fulfills a required integrity risk will be derived. For this step, it is foreseen to use for LDACS the measurements derived from past flight trials.
For the fault detection and exclusion service, a self-consistency check based algorithm to detect multiple erroneous ground ranging sources will be investigated and a possible integrity monitoring architecture will be suggested.
We will conclude the paper suggesting different directions of investigation for the use of HAPS to enable even more stringent requirements for APNT like precision approach and auto taxiing during low visibility conditions.

References:
[1] http://www.airbus.com/defence/uav/zephyr.html
[2] https://www.thalesgroup.com/fr/worldwide/espace/magazine/space-qa-stratobus
[3] https://x.company/loon/

Mega-Constellations: An Opportunity for Alternative Positioning, Navigation and Timing Services

Francis Soualle

Recent years have been especially rich in announcements regarding the development of so-called “Mega-Constellations” composed of several hundreds of spacecrafts, if not thousands for the most ambitious forecasts. The OneWeb constellation comprising 720 Low Earth Orbit (LEO) satellites, or the Starlink constellation developed by SpaceX, with more than 4400 spacecrafts, are first examples for such large space systems whose list will certainly continue growing according to declarations and filings. If initially designed to provide communication services, following the path of the forerunners Iridium and Globalstar systems developed in the late 90’s, the attributes of this new kind of constellations could also be well suited to offer Position, Navigation and Timing (PNT) Services, as this presentation will strive to demonstrate.

First, the orbital characteristics and coverage for such new space systems will be presented, together with the fully re-thought conception and industrialization processes that led to a drastic reduction of the cost per spacecraft-unit. Then, three main approaches will be introduced to exploit this new kind of space systems in a PNT context. The first one considers a dedicated constellation fully optimized for a PNT service over a given service area. The second, and less demanding one, proposes to equip each LEO satellite with a hosted PNT payload. Finally, the third one examines the symbiosis between communication and navigation signals, when transmitted by the same payload. In a subsequent part, it is proposed to derive the main “constellation scaling factors”, applied to both the number of satellites and required transmitted RF power, to offer the same positioning performances, either with a typical Global Navigation Satellite System (GNSS), or with a Mega-Constellation system. After this benchmarking exercise, alternative ranging techniques to the ones commonly used by GNSS receivers will be presented, with the aim to highlight the attractiveness of LEO-PNT for positioning performances. This concerns the Two-Way Ranging (TWR) and Doppler-based techniques, which both exploit the particularities of LEO satellites, with their inherent communication capabilities and their high velocity.

Based on those introductive assessments, the role of a LEO-based PNT system within the "GNSS landscape" will be addressed, considering either the possible complementarity or independency of services provided by both system types. With this respect, the case of the newly introduced Satellite Time & Location (STL) system, based on the Iridium constellation, and offering a global and resilient Timing and Position service will help supporting this discussion.
In a final part, the main architectures for LEO-PNT systems will be described with special focus on the primary and ancillary payload units, but also on the supporting ground segment infrastructures.

P6. Evaluation of Multipath Detection and Mitigation Techniques for SBAS Receivers

Dr. Mariano Wis[1], Antonio Fernandez[1], Rui Nunes[4], Maria Coimbra[4], Gianluca Franzoni[2], Letizia Scaciga[2], Dr. Andrea Emanuele[2], David Jimenez[3]
[1]Elecnor Deimos, Tres Cantos, Spain, [2]Thales Alenia Space Italia, , Italy, [3]ESA/ESTEC, Noordwijk, Netherland, [4]Deimos Engenharia, Lisbon, Portugal

It is widely known the importance of multipath effect in the reception of GNSS signals. The constructive/destructive interference effect and the induced delay error in complex visibility and reflective scenarios make the tracking of signals very hard when not impossible to achieve. Besides that, the importance of multipath effect has to be taken into account in receivers that are designed for operating with SBAS support. The purpose of SBAS in these receivers is dual, by one side it is expected that the accuracy of the navigation solution is increased thanks to the differential corrections transmitted. Moreover, it is also requested that the receiver has a high level integrity in terms of reliability, availability and accuracy of the service. This is very important in Safety of Life or transport of passengers applications as it is necessary to guarantee a minimum level of integrity. By those reasons the integration of Multipath detection and mitigation techniques have become a necessary requirement in the design and development of GNSS receivers, overall if they are aimed for urban scenarios and also require a minimum level of integrity supported by an SBAS or a RAIM algorithm.

In the close past, Elecnor Deimos worked in the evaluation of a series of advanced techniques aimed for multipath mitigation in the frame of ESA project ARTEMISA (Advanced Receiver Techniques: Multiprocessing Algorithms) in the frame of TRP program. This analysis required the implementation of these techniques in an evaluation platform and the implementation of a series of Multipath Models that were used to generate the scenarios that validated the techniques. Finally, MEDLL (Multipath Estimator DLL), VTL (Vector Tracking Loop) and DPE (Direct Positioning Estimator) techniques were implemented and tested in the ARTEMISA platform. In addition to this, two Multipath Stochastic models, the CSCM (Controlled statistical channel model) and the DLR LMCMM (Land Mobile channel Multipath model), were created or adapted for the generation of a series of MP scenarios that allowed evaluating these techniques under different levels of multipath environment.
Presently, Elecnor Deimos is participating in project EGNOS TUR (Test User Receiver), under ESA contract in the frame of H2020 Programme. In this project, leaded by Thales Alenia Space Italia and coordinated by ESA/ESTEC, a prototype receiver that is required to meet the features of EGNOS V3 and further evolutions is being developed. In this project, it is required to test the performance of the receiver for three kinds of applications (aviation, maritime and rail) in different scenarios. In addition to this, it is also requested to evaluate the effect of multipath in these scenarios and to implement a series of techniques that are capable

of detecting and mitigating Multipath in these scenarios. That is one of the tasks of Elecnor Deimos in EGNOS TUR project. Using the experience acquired and the platform developed in ARTEMISA project, a design of the multipath techniques integrated in the prototype receiver have been performed and implemented in the development platform.

Techniques tested in ARTEMISA showed a good ranging/positioning performance but at the compromise of having a great number of correlators per channel (between 30-40 for MEDLL and DPE) and high processing capabilities, or the necessity of generating a navigation solution for each integration epoch (for VTL). Given that requirements in EGNOS TUR implies the utilization of a more conventional HW architecture, it was necessary to use a set of different mitigation techniques that show a balance between the solution performance and a practical implementation. Because of that, after a survey of available techniques, it was decided to develop and integrate the HRC (High Resolution Correlator) and the IELS (Improved Early-Late Slope). The reason for its utilization in the project is that it is proven that they are very efficient and are simpler to implement. Both techniques require only 5 correlators and the algorithms practically do not affect the performance of the receiver.

In addition to this, these techniques need to be evaluated with some representative multipath scenarios that meet the requirements of the applications given above. For this, it has been necessary to implement some new scenario generators (for aviation and maritime applications) and combine them with the output of the DLR LMCM multipath model generator to reproduce some specific scenarios. For the train application, it has been assumed that DLR LMCM multipath model already fits the requirement of this kind of application.

This paper presents an overview of ARTEMISA platform and the modifications that have been necessary to implement to adapt to the requirements of EGNOS TUR. An overview of the selected techniques and how they have been integrated in the platform will also be shown. In addition to this, some comparative results obtained with these techniques in the frame of the platform will be also presented.

The work reported in this paper has been performed under a contract of the European Space Agency in the frame of the Horizon 2020 Framework Programme for Research and Innovation in Satellite Navigation. The views presented in the paper represent solely the opinion of the authors.

Positioning and Timing for 5G

Newton 1, December 6, 2018, 09:00 - 10:40

5G positioning in 3GPP

Positioning Based on OFDM Signals through Phase Measurements

Mr. Han Dun[1], Dr. Chrsitian Tiberius[1], Ms. Farnaz Chamanzadeh[2], Mr. Tarik kazaz[2], Dr. Gerard Janssen[2]
[1]Geoscience and Remote Sensing, Delft University of Technology , Delft, The Netherlands , [2]Circuits and Systems, Delft University of Technology, Delft, The Netherlands

Today our society heavily relies on Global Navigation Satellite System (GNSS) for positioning and navigation. GNSS has an excellent proven track record and a very high economic value, but it also has a number of limitations. Its positioning performance is especially sensitive to atmospheric errors. Due to a relatively narrow signal bandwidth, the receiver can also not distinguish the direct light-of-sight (LoS) path signal from reflections (multipath) very well, when the arrival time of these signals are close together. This leads to limited positioning accuracies. Compared to GNSS signals, some existing wireless communication signals have relatively wider signal bandwidths and larger signal power. Although these signals are not designed for positioning, they still contain certain features that can be exploited for positioning, for example, time delay measurements and carrier phase measurements. For instance, orthogonal frequency division multiplexing (OFDM) signals, which can be found in various telecommunication systems, such as Wireless LAN (WLAN), terrestrial digital video broadcast (DVB-T), long-term evolution (LTE) and the future 5G new radio (5G NR). These signals can be referred to as signals-of-opportunity (SOP) for positioning and navigation [1, 2].
Time delay measurements, as pseudo-range measurements in GNSS, are obtained through cross-correlation of received signals and locally generated reference signals, or super-resolution methods (e.g., ESPRIT [3]) based on channel measurements from multiple sub-carriers. However, its accuracy largely depends on the signal bandwidth.
Alternatively, considering a signal with a fixed and possibly narrow bandwidth, this wireless signal is modulated on a carrier which has a relatively high frequency (GHz-level) and can provide accurate phase measurements due to its short carrier wavelength. Thus, tracking the carrier phase of OFDM signals can potentially lead to a more accurate positioning performance. The Doppler effect results in a change of carrier phase, which can also be referred to as the integrated Doppler carrier phase. Therefore, positioning based on purely carrier phase measurements requires continuously transmitted signals and a change of transmitter-receiver geometry.
Generally, in a transmitter, data are modulated on pilot sub-carriers and these data are also known a priori to the receiver. They allow us to estimate and track the channel, and also provide an opportunity to estimate the carrier phase for positioning. However, in practice, the carrier frequency offset (CFO), the sampling clock frequency offset (SCO), and the imperfect OFDM timing synchronization will cause time variant phase errors in carrier phase measurements. In this paper, all these effects have been included in a mathematical measurement model.
For a single subcarrier, these offsets will cause difficulties in unwrapping the ambiguous phase measurements. For example, if there is a one OFDM sample timing synchronization error within a 10 MHz bandwidth, then it will introduce a carrier phase error much larger than one cycle if the carrier frequency is at GHz-level. Thus in an open-loop system or with snap-shot carrier phase measurements, relatively large phase errors can impair the phase unwrapping.
As in GNSS, in order to compute the coordinates of the receiver, phase ambiguities of corresponding transmitters remain constant over the entire observation period (as long as signal reception is un-interrupted). Instead of estimating and compensating the aforementioned offsets prior to measuring the carrier phase, we combined the measured phases from two symmetrically located pilot sub-carriers to eliminate the SCO and the timing synchronization error. Moreover, the phase combination of two

symmetrically located sub-carriers also interpolates the phase of the DC component. Though part of the SCO still exists in the carrier phase measurement based on the phase combination, its impact is negligible. In this paper, we considered an OFDM based IEEE802.11p system, which is designed for the Vehicle-to-Vehicle communication and the Vehicle-to-Infrastructure communication, as a potential system for positioning and navigation, in simulation. But this can be extended to any other OFDM system, as long as inter-carrier interference due to the CFO is insignificant for such a system.
Although we also introduced the SCO in the simulation, its impact can partially be eliminated from the combination of two symmetrically located pilot sub-carriers, and the residual part that remains in the carrier phase measurements can still be ignored. Due to the sampling clock offset, a timing synchronization offset may also occur. But this offset can be cancelled out based on the same phase combination.
For a large signal-to-noise (SNR) case, estimation of the sub-carrier phase is unbiased, and the probability density function of the phase measurement can be approximated as a Gaussian distribution with a variance of 1/2SNR. In practice, in a multipath channel, the SNR of each sub-carrier might be different. Thus, the variance of the combination phase measurements can be derived through the error propagation law.
Considering, for instance, a case with a 50ppm SCO and a 25 dB SNR in simulation, the positioning through carrier phase measurements achieved decimetre level accuracy for 99% of the cases.
Though positioning by means of carrier phase measurements requires a change of geometry of the positioning scenario (so the receiver has to change its position), and continuously transmitted signals, it can achieve more accurate positioning results compared to those based on time delay measurements. Because time delay measurements are mainly derived from cross-correlation or a super-resolution method (e.g., ESPRIT), their accuracies are limited by the signal bandwidth. Thus, given a continuously transmitted OFDM signal with a relatively narrow bandwidth (e.g., 10-20MHz), positioning based on carrier phase measurements is a promising approach to improve on positioning accuracy.

[1]. A. Makki, A. Siddig, M. Saad, J. R. Cavallaro, and C. J. Bleakley, “Indoor localization using 802.11 time differences of arrival,” IEEE Transactions on Instrumentation and Measurement, vol. 65, no. 3, pp. 614–623, 2016.
[2]. C. Yang, L. Chen, O. Julien, A. Soloviev, and R. Chen, “Carrier phase tracking of OFDM-based DVB-T signals for precision ranging,” in ION GNSS+ 2017, pp. 736-748, 2017.
[3]. B. Yang, K. B. Letaief, R. S. Cheng, and Z. Cao, “Channel estimation for OFDM transmission in multipath fading channels based on parametric channel modeling,” IEEE transactions on communications, vol. 49, no. 3, pp. 467–479, 2001.

Positioning and Timing in the MIMO-GNSS Framework

Mr. Jose Antonio Garcia-Molina[1], Mr Juan Antonio Fernandez-Rubio[2]
[1]ESA, Noordwijk, Netherlands, [2]UPC, Barcelona, Spain

This paper discusses about GNSS-based positioning and timing in challenging propagation conditions for receivers featuring an array of antennas with an arbitrary distribution. In particular, the positioning and timing problems are treated as multiple-input multiple-output (MIMO) estimation problems in which all the GNSS signals received by the array of antennas are jointly exploited in the corresponding domain. The MIMO-GNSS processing approach is targeting the derivation of robust solutions in the presence of realistic signal impairments introduced by the propagation channel or any other external interference. The maximum likelihood estimator (MLE) in the MIMO-GNSS framework is reviewed, and simulation results in realistic challenging scenarios are presented, showing the benefits introduced by the exploitation of arrays of antennas in both positioning and timing.

The Role of GNSS in 5G Wireless Networks

Roberto Prieto Cerdeira[1], Lionel Ries[1], Florin Grec[1], Stefano Cioni[1], Riccardo de Gaudenzi[1], Miguel Manteiga Bautista[1]
[1]*European Space Agency ESA/ESTEC, 2201AZ, Netherlands*

5G wireless networks stands for fifth generation and refers to the next and newest mobile wireless standard yet to be set. 5G technology is expected to be a new mobile revolution in wireless market combining different wireless technologies (4G LTE, WiFi and 5G newly defined air interfaces, a.k.a. 5G NR – New Radio) to cover new use cases and exploiting new frequency bands. 5G will be addressing many new types of users, ranging from low data-rate for narrowband Internet of Things (IoT) to ultrafast enhanced broadband exploiting technologies such as millimetre waves, small cells, massive MIMO among others.

Demand for localisation is increasing in different market segments, defined as verticals in 5G landscape, with diverse requirements. Positioning, Navigation and Timing (PNT) is increasingly considered as a utility, with a high level of expectations from the users and it is expected to be an integral feature in 5G, either provided by 5G-internal technologies (Cell-ID, OTDOA, UTDOA) or external technologies (GNSS, inertial sensors, terrestrial beacon systems, …) or most likely, through an hybrid solution exploiting different technologies. 5G network based positioning in three – dimensional space should be supported, with accuracy from 10 m to < 1 at 80%, and better than 0.5-1 m for indoor deployments. These figures are completely aligned to nowadays users' expectations and are linked to a number of 5G use cases mentioned in 3GPP. Critical Communications, eV2X, and massive IoT are recognised as the main drivers to 5G positioning capabilities and they would be supported by technological enablers in NR (high bandwidth, massive MIMO, etc.).

Use cases may be grouped in at least two categories (one more if relative positioning high accuracy is accounted separately), according to their horizontal accuracy targets:

- Coarse Accuracy Use cases: in the range of 10m to 50m, with flagship being regulatory requirements as E911.
- High Accuracy Use cases: better than 1m to 3m range, targeting verticals like autonomous vehicles, factories, etc.

Hybrid positioning (i.e. sensor fusion) combines all raw signals and sensors data in a true hybrid location calculation with superior output compared to a single-sensor positioning scheme alone. Additionally, it allows for a fall-back location technology in case one or more radio technologies fail due to the UE operating environment (no Line-Of-Sight to satellites, insufficient network coverage, and so on). Furthermore, it eases the transition from one environment to another, enabling seamless navigation provision to the end user.

Other key aspects of positioning are to be considered, such as power consumption, or energy per position fix for receiver not continuously operating (e.g device tracking and asset management) as well as reliability. The generalisation of the positioning and its growing integration in security and safety applications is indeed expected to raise positioning reliability as a key aspect of the service.
High accuracy positioning, will enable a new range of services and operators may want to provide these features within 5G. Nonetheless, implementing high accuracy positioning capabilities within the network may come along with significant additional complexity and constraints (higher network density, very tight synchronisation and additional operations to ensure high fidelity measurements for positioning). This is particularly true when the services call for positioning reliability, safe and trustworthy, power-efficient positioning like in many 5G use cases.

It seems indeed desirable to fulfil 5G high-accuracy use cases by maximising the use of existing technologies complementing new features available in the system. This draws additional perspectives for 5G in support of hybrid positioning for high accuracy use cases, which are at least twofold:

- Provide high accuracy and reliable positioning capabilities in areas and environments where existing technologies cannot fulfil the expectations of the 5G use cases
- Leverage existing technologies and become a key enabler to hybrid positioning for high accuracy use cases, at least through added value data enhancing the performances/functionalities (accuracy, reliability, security, etc.).

In the frame of 3GPP Release 16, further activities on 5G positioning use cases and requirements may leverage 5G as enabler to seamless and ubiquitous added-value positioning for outdoor needs. On this sense, a 3GPP SA (Service and System Aspects) Study Item named 5G_HYPOS, has been completed to fulfil this goal, and pave the way for a future Work Item to update the specification for all positioning use cases, with the following specific achievements:

- Identify positioning use cases, validating, clarifying and harmonising KPI, assumptions on applicable environments of use.
- Study performance targets in support of identified use cases, providing initial apportionment between existing technologies (e.g. GNSS) and 3GPP new technologies (e.g. New Radio NR-based).
- Identify potential requirements for 5G positioning services to be fulfilled with 3GPP technologies or with a combination of 3GPP and non-3GPP technologies.

Several use cases have been proposed by various 3GPP stakeholders.

Apart from positioning performance, additional design targets for commercial positioning in 5G include the support for difference device categories and a range of accuracy and latency level, reduced network complexity, terminal cost and power consumption, scalability and security.

In addition, a 3GPP RAN Work Item on dissemination of high accuracy corrections (RTK / PPP) through 4G LTE network has been completed, including broadcast mode, including RTK and PPP corrections based on ASN.1 encoding for all global GNSS systems.

In the future, the Study Item related to 5G New Radio positioning still to be started with GNSS considered as a complementary technology.

Furthermore, GNSS may also be an enabler of 5G, for example in aspects related to potentially challenging 5G network synchronisation needs. The discussions about network synchronisation on ITU-T Study Group 15 (SG15) include the fact that GNSS is observed as the fundamental stone for high quality time source in the network, yet its susceptibility to jamming/interference/spoofing raises concerns. The use of GNSS for accurate positioning for optimal angle-of-arrival in massive MIMO with narrow directional beam-forming in new mm-wave frequency bands has been also suggested as a 5G enabler by GNSS.

The paper will present the ongoing initiatives and latest results on positioning technologies with emphasis on the role of GNSS in 5G.

Cloud/Cooperative Navigation - The ICON Concept Demonstrator

Dr. Luis Enrique Aguado[1], Mr Ben Wales[1], Mr Davide Guerrini[1], Mr Jose Antonio Garcia-Molina[2]
[1]Nottingham Scientific Limited (NSL), Nottingham, United Kingdom, [2]European Space Agency (ESA), Noordwijk, The Netherlands

Location information and location awareness have quickly become a commodity in many aspects of our everyday life. Location-based services (LBS) and Internet-of-things (IoT) applications in particular are driving a constant push for improved low-cost/low-power mass-market navigation in most places of human and industrial activity. This is especially the case in terms of accuracy and availability in urban and indoor environments. Social networking, health monitoring, retail, navigation or safety applications, to name a few, are being mostly enabled by the omnipresent smartphones, with the support of other consumer devices such as wearable sensors, fitness bracelets or personal tracking devices. GNSS alone is often not enough to achieve the requirements of these applications in the more challenging settings. GNSS receivers are often assisted with navigation data, and increasingly being combined with IMU and other sensors in the receiver platform. However, with poor GNSS availability to calibrate the sensors drift, the quality of the IMU sensors still makes inertial navigation on mass market receivers a challenge. GNSS positioning is also frequently supplemented with location solutions derived from any wireless signals received by the device. This can take different approaches from simply using propagation models, fingerprint databases using bespoke infrastructure or signals of opportunity, to WiFi round-trip-time measurements introduced with IEEE802.11mc. Combinations of these technologies can be found in the research literature and commercial state of the art. Crowd-sourcing is used in some cases to build-up local data supporting those signals of opportunity measurements that would be too much effort to independently harvest and maintain for most companies.

Presenting significantly different use cases, IoT applications are also pushing related technology developments and often require location awareness. Many IoT applications have requirements in terms of long-range, long-term operation, remote deployment locations and largely autonomous operation. These requirements place the receiver design focus on low duty cycle operation and ubiquitous positioning while prioritising constraints on low power consumption, cost, and complexity of the user equipment.

Ubiquitous and affordable wireless connectivity, sensor miniaturisation and the popularisation of cloud computing have opened up new approaches for positioning addressing some of the requirements above. The Innovative Cloud-based coOperative Navigation (ICON) project aims to study, develop and assess the performance of innovative positioning and navigation techniques relying on the exploitation of crowd-sourced data and GNSS signal snapshots from low-end/cost/power devices/sensors connected to the Internet and based on the cloud processing of the data and signals. To this purpose, a mature, flexible concept demonstrator will be delivered relying on a commercial cloud computing platform and precise data products, third party applications and services, based on existing wireless communications infrastructures and multiple receiver platforms and supporting relevant use cases, including the described IoT and LBS users/applications.

Cloud-based snapshot receivers enable flexible, high-performance processing, offloading the local device or miniaturised low-power field terminals from the full GNSS processing. Cloud services offer on-demand processing and storage capabilities with advantages in terms of scalability and pooling of resources and resulting in economical propositions where internet access is available and there is a growing user population. Snapshot GNSS receivers deliver instant, low-duty cycle measurements, but at the same time COTS GNSS receivers have evolved hugely, and continue to do so, and in most scenarios and use cases will still be the best PVT source. We will investigate whether the combination of cloud-based snapshot receivers and conventional (in-field) GNSS chipsets is able to improve the overall performance in difficult scenarios where satellite signal tracking is difficult. The joint processing of both sources of GNSS measurements at the cloud platform will enable for close aiding in the signal processing and measurements hybridisation. The recent availability of GNSS raw measurements and RTT measurements for mobile phones on Android operating systems opens the door for innovative combinations of measurements from the embedded chipset and snapshot GNSS captures. This will enable new practical solutions to improve the available positioning techniques in mobile devices.

Cooperative signal processing and positioning algorithms integrating measurements across multiple users operating in geographical proximity may also be used to compensate for temporary or partial unavailability of GNSS signals. Cloud processing enables the combination of connected resources, heavy assistance from enhanced error modelling data, crowd-sourced fingerprints or geo-reference maps for signals of opportunity measurements, different sensors and positioning information and centralised collaborative positioning algorithms across local user groups.

The ICON concept demonstrator will be built integrating NSL pre-developments, off-the-shelf hardware and third party services which will considerably reduce the effort of the system implementation and enable us to meet aggressive targets to evaluate cloud/cooperative technology concepts. The figures of merit that will be considered when evaluating a technology for integration in the ICON Concept Demonstrator and, thereafter, when evaluating the developed system are:

- Implementation availability and suitability to the overall concept demonstrator platform (COTS or pre-existing), enabling timely integration in the receiver terminals and/or CCPM.
- Representativeness of the current state of the art.
- Cost and power consumption of the receiver platforms.
- Potential improvements of the overall system performance with acceptable complexity and processing load, and the associated cloud computing processing requirements and cost.
- Feasibility of use for the envisaged tests and experimentation to be conducted with the ICON Concept Demonstrator.

The concept demonstrator design will address challenges introduced by the distributed and heterogeneous architecture of the multiple system components, including synchronisation of receiver platforms measurements and data transport latencies, the diversity of sources and types of location information being combined at the fusion navigation solution and the different architectural and processing parallelisation choices required at the collaborative cloud processing module to meet ambitious performance targets.

ESA, the European Space Agency, through the Navigation Innovation and Support Programme (NAVISP) Element 1, is funding the ICON project, with Nottingham Scientific Ltd. (NSL), a UK-based company, as the sole contractor. The main objective of NAVISP is to facilitate the generation of innovative Space-Based PNT (Positioning, Navigation and Timing) propositions with Participating States and their industry, in coordination with the EU and its institutions. The ICON project duration is 12 months, aiming to complete in early 2019.

Atmospheric Monitoring

Newton 2, December 6, 2018, 09:00 - 10:40

Space Weather Forecast Services for GNSS Users

Dr. Filippo Rodriguez[1], Roberto Ronchini[1], Stefano Di Rollo[1], Eric Guyader[2], Angela Aragon-Angel[3], Sreeja Vadakke Veettil[5], Marcio Aquino[5], Claudio Cesaroni[4], Luca Spogli[4], Giorgiana De Franceschi[4], Alice Cristaldi[6], Dario Del Moro[6], Francesco Berrilli[6], Osman Kalden[7], Michael Hutchinson[8]

[1]Telespazio, Rome, Italy, [2]European Commission, , , [3]Joint Research Centre, , , [4]Istituto Nazionale di Geofisica e Vulcanologia, , , [5]University of Nottingham, , , [6]University of Tor Vergata, , , [7]Telespazio VEGA Deutschland, , , [8]Nottingham Scientific Ltd, ,

The Ionosphere Prediction Service (IPS) project has the aim to design, implement and operate a prototype for the monitoring and the prediction of ionosphere-related disturbances affecting GNSS user communities. It monitors and forecasts the solar and ionospheric activity and its well-known effect on GNSS signals and on the final performances of user applications. Aviation users, electricity and energy grids, professional users requiring stable precise positioning accuracy for their operations can be heavily impacted by insufficient GNSS performance. The IPS provides GNSS users a mean to anticipate such degradation of performance and therefore allows operators to put in place mitigation measures in a timely manner.
The project is developed in the framework of the Galileo Programme. It is funded by the European Union's R&D programme Horizon 2020. The project team is composed of Telespazio (coordinator), Nottingham Scientific Ltd, Telespazio Vega DE, The University of Nottingham, The University of Rome Tor Vergata and the National Institute of Geophysics and Volcanology.
The IPS service prototype is conceived with a 4-layer architecture:

- The external sensors which provide the input to the processors that run the algorithms;
- The processors, called RPFs, Remote Processing Facilities, that are in charge to run the forecasting and nowcasting algorithms;
- The Central Storage and Processing Facility (CSPF), that manages the output of the chain of processors;
- The Web Portal that is the final user interface

The prediction models of IPS are based on the results of the research activity carried out during the project. It represents the scientific backbone of IPS.
A whole class of products translates the observation of the atmospheric behavior and perturbations into predictions of GNSS performance figures at user level.
The monitoring and prediction of the Solar events (like CME, Flares and SEP (linked to CME)) is managed by the RPF-1. The input data are provided by several sensors and scientific payloads like among the others, GOES X, SOHO, MOTH telescope etc.
The Ionosphere monitoring is managed by RPF-2, ensuring that TEC and scintillation estimation are nowcasted and forecasted at Regional and Global level. It takes as input several GNSS reference station data (e.g. IGS) and scintillation data (e.g. RING network). For Regional and global products scintillation is provided through the ROTI (rate of TEC index) parameter, but direct output of scintillation values are monitored in specific stations.
The RPF 3 and the RPF 4 take as input the ionosphere estimation provided by the RPF 2, and monitor and predict of the GNSS related performance at local and global level. In particular the RPF 3, developed by the University of Nottingham, is dedicated to high accuracy users while RPF 4, developed by Telespazio, provides, among the others, nowcasting and forecasting of aviation related performance figures (from ABAS to SBAS) at regional and global level.
The products generated by each RPFs are then stored and forwarded to the front end represented by a web site.
The main driver for the IPS design was to provide an operational tool to the users for real time observation and prediction. The web pages offer a selection of products for each targeted user community (aviation,

high accuracy, solar and ionosphere scientific communities) and the user can also access to his personal page on which only his own selected products are displayed.
Products are then refreshed in real-time, thereby allowing regular checks without having to reload the computation. In this sense, the web page is conceived as an operator's console.
The user is also free to define alerts on specific quantities and Alarm notification (via email) can be configured when the monitored quantity overcomes a user-specified threshold.
Much attention has been devoted to the assessment of the performances of the products, through an extensive validation campaign. Two different adopted validation strategies are described in the paper:
[1] The first validation approach builds on the statistical characterization of the good fit of the prediction to the reality, using the “retro-validation” function of the platform. The "retro-validation" function measures the discrepancy between the predicted value and the corresponding actual value of a given parameter at a given location. The retro-validation maps are stored together with all the other products generated by IPS, allowing a trend analysis of the performance of the service. The retro-validation is available to the final users to provide them with a measure of the goodness of the predictions.

[2] The second validation strategy is based on the direct comparison of the IPS forecasting and nowcasting products against external ones (i.e. coming from other services).
The paper will present the main results of the validation activities carried out for each RPF algorithm.

After the validation task the IPS platform will be put in operations; from July 2018 the IPS will be freely accessible and the project team will operate the prototype for a 6-month period.
During this period the users will be invited to register to the service and use it in order to provide useful feedbacks for enrich the service itself and include any further improvement in the future evolution. The results of the operational period will be also described in the paper.

Statistical Characterization of Ionospheric Scintillation using a Phase-screen Model

Dr. Fernando Nunes[1], Dr. Fernando Sousa[2], Mr. Jose Marcal[1]
[1]Instituto de Telecomunicacoes and IST, Lisboa, Portugal, [2]Instituto de Telecomunicacoes and ISEL, Lisboa, Portugal

A fast technique to simulate the effect of equatorial ionospheric scintillation on GNSS signals was proposed by the authors in a previous work. The algorithm uses a single-layer phase-screen model of the ionosphere and the scintillation is expressed by the Huygens-Fresnel (HF) integral which can be determined analytically. Herein, we characterize statistically the amplitude and phase obtained with the HF integral for different values of the scintillation index S4. A phase unwrapper is also developed to determine the phase from the modulo-2π version provided by the argument of the HF integral.

State-space Estimation of Ionospheric Scintillation Processes with a Static GNSS Receiver

Dr. Fernando M. G. Sousa[1], Dr. Fernando D. Nunes[2]
[1]Instituto de Telecomunicacoes and ISEL, Lisboa, Portugal, [2]Instituto de Telecomunicacoes and IST, Lisboa, Portugal

The determination of the ionospheric scintillation processes that affect the reception of Global Navigation Satellite System (GNSS) signals is an important issue as it permits to monitor the ionosphere for practical and scientific applications and optimize the receiver performance in scintillation-prone scenarios using, for instance, a differential GNSS configuration. We propose an hybrid architecture for the receiver being constituted by a vector tracking block that estimates the receiver’s clock drift coupled with an ensemble of

extended Kalman filters driven by the prompt correlators that estimate the amplitude and phase of the fading processes. Those processes include as an important case the ionospheric scintillation.

Effects of Interference Mitigation Methods on Scintillation Detection

Mr. Wenjian Qin[1], Prof. Fabio Dovis[1]
[1]*Politecnico di Torino, Torino, Italy*

The use of Global Navigation Satellite Systems (GNSS) signals as signal of opportunity for ionospheric technology is becoming quite popular. In particular, for scintillation monitoring, it is essential that the affected GNSS signal must be clean of other artificial interference.

However, the Ionospheric Scintillation Monitoring Receiver (ISMR) used to observe scintillation activities could operate in scenarios where communication systems or even jammers are present. Such sources can provide scintillation-like performance in signal processing stage, leading to misconceptions about the behavior of actual scintillation activities. This paper investigates the estimation of S4 index under five types of anthropogenic interference, including continuous wave, narrow band, wide band, chirp and pulsed interference.

Furthermore, the study also addresses the use of notch filtering and wavelet packet decomposition to mitigate the anthropogenic interference from a scenario in which both scintillation and artificial interference are present, and the S4 is estimated on the mitigated data.

An Advanced Residual Tropospheric Error Model for Safety-of-Life GNSS Applications

Mile Mate, P.B. Ober[2], Rózsa Szabolcs[1], Ambrus Bence[1], Juni Ildikó[1]
[1]*Budapest University of Technology and Economics, , ,* [2]*IntegriCOM.NL, , ,* [3]*Hungarian Meteorological Service, ,*

In safety-of-life navigation applications of GNSS the major concern of the user is not only the accuracy but the integrity of the positioning service. To assess the integrity, the protection level is calculated by overestimating the positioning error even at very rare probability levels. Recent studies shows that - by the emerging multiple frequency civilian signals - the tropospheric delay becomes the most significant error source especially at low elevation angles. The RTCA MOPS (minimum operational performance standard) for GNSS systems in aeronautics specifies a global constant for the maximum tropospheric residual error in the zenith direction. Recent studies suggest that this value is too conservative in many regions of the globe leading to lower availability and continuity of the positioning service. To overcome this limitation, a new residual tropospheric error model has to be formulated, that considers both the geographical and the seasonal variations of the tropospheric delay model performances. Our study focuses on the development of an advanced residual tropospheric delay error model (ARTE) using the methodology of extreme value analysis for the RTCA troposphere model. The developed ARTE model was validated with IGS ZTD estimates, radiosonde observations and numerical weather models obtained in a case study of extreme weather in Central-Europe. The results show that the proposed model maintained the conservatism of the original model, nevertheless it provided a significantly lower residual error estimate in many regions of the globe.

GNSS for Cloud, IOT and LBS

Newton 1, December 6, 2018, 11:20 - 13:00

Assessment of GNSS Performance on First Dual-Frequency Smartphone

Mr. Moises Navarro-Gallardo[1], Mr. Ignacio Viciano Semper[1], Mr. Christophe Braun[1], Mr. Michael Kirchner[1]
[1]*Airbus Defence and Space, Taufkirchen, Germany*

Last year Google announced the availability of GNSS raw measurements in smartphones with Android 7.0 and beyond, giving access to smartphone users to code and/or carrier phase measurements for the first time in mass market devices. Since this milestone, the GNSS community (researchers and also companies) have been working in order to develop a variety of solutions and ideas that boost the GNSS mass market in the following years. RTK and PPP solutions are the most promising techniques to be adopted, but also optimization of multi-constellation solutions in urban environments and GIS developments are being investigated.

The first steps after the raw measurements availability were to create synergies between the GNSS experts and Android programmers, taking the form of basic mobile applications able to log the raw measurements in the smartphone memory. The next step was to convert those measurements to common formats used by the GNSS community such as RINEX or NMEA with which existing tools could work, or adapt those existing analysis tools to make them able to work with the new raw measurements format. Finally, from this point, research and development of new functionalities, applications and ideas followed. In this framework, the GSA released the White Paper "Using GNSS Raw measurements on Android devices", a guide on the understanding and usage of raw measurements in order to make easier and faster for new developers the use of these measurements.

On May 31st 2018 the first dual-frequency smartphone was launched, the Xiaomi Mi 8, that will enlarge widely the GNSS applications to be developed in the future. The chipset manufacturer claims that the chipset is capable of centimeter-level accuracy. The GNSS chipset, developed by Broadcom, is able to operate with E1/L1 + E5/L5 bands giving the possibility to estimate and compensate the ionospheric delay. Moreover, the signals on E5/L5 band have many advantages in single frequency mode thanks to their better multipath rejection compared to the E1/L1 signals. The higher chipping rate (10.23 MHz vs. 1.023 MHz of E1) makes E5/L5 signals more robust against multipath, which is usually one of the main error sources in harsh environments such as urban canyons. In this kind of environments, in fact, the removal of the ionosphere error has much less relevance than the possibility of removing multipath. Also, E5 signal is be transmitted with a higher power, hence making possible to have higher C/N0 values than with E1/L1 signals, making the tracking of those satellites better.

However, not many satellites transmit in the E5 frequency yet, where Galileo constellation takes the lead nowadays. Hence, Galileo users all over the world can already take profit of this chipset progress. It should be noted that with the upcoming Galileo and the GPS III satellites to be launched the users will experience a better performance.

Airbus together with GSA is conducting a testing activity to prove, describe and analyze the performance of dual frequency in smartphones, performing different type of tests under real conditions. For this purpose, Airbus has developed an Android app able to log the dual frequency raw measurements, storing them into a .csv file with a similar format to the one used by Google. Later on, those files can be post processed with Matlab, or similar tools, to obtain observation and navigation RINEX.

Using the logger tool, the testing phase can take place. Different kind tests are performed, trying to cover different environments and users, such as static and dynamic scenarios. Different phones will be used, both the new ones dual-frequency capable and the previous versions with only E1/L1.

Finally, after the different tests cases are performed, results are analyzed in order to assess their quality and to compare the new dual-frequency features with the previous E1/L1 single-frequency devices.

Understanding how the chipset makes use of the second frequency measurements is also important, as the manufacturer has an important restriction when trying to improve the accuracy: battery consumption.

When having ensured the E5/L5 readiness of the devices, several comparisons will be done, taking into account different constellations and frequency bands.
PVT solutions is computed using different configurations, though getting long-enough solution with Galileo is challenging due to the low availability of enough satellites in view and fully operational, at least until the Galileo satellites of Launch 10 are declared operational. In this context, the performance of the different configurations is assessed. PVT computation is computed after the testing period through dedicated Matlab functions.
This analysis can be seen as the starting point to many others developers and experts than want to profit the dual-frequency capability in smartphones to create new solutions and applications based on it. This performance assessment of the dual frequency in smartphones in order to understand the possibilities and limitations of possible applications is essential to understand the Galileo and dual frequency capabilities in smartphones.

Server-based Galileo PRS Processing to Ensure Secure Position and Time Information

Mr. Alexander Rügamer[1], Mr. Daniel Rubino[1], Mr. Xabier Zubizarreta[1], Mr. Daniel Meister[1], Dr. Fabio Garzia[1], Dr. Felber Wolfgang[1]
[1]*Fraunhofer IIS, Nuremberg, Germany*

Galileo Public Regulated Service (PRS) is a special, cryptographically protected satellite navigation service intended for governmental authorized users. The access to PRS is regulated by decision No 1104/2011/EU of the European Parliament and of the Council and controlled by each member state.

Thanks to the cryptographically protected Galileo PRS, the manipulation of a PRS obtained time and position is hardly possible. This enables the realization of many demanding or security critical applications that could not be operated using conventional GPS or Galileo open services (OS).

However, in general, PRS receivers will never be as inexpensive as mass-market OS receivers: PRS receivers require a security module (SM) that implements the cryptographic functionalities as well as key management. Especially keying and accountability of the PRS receivers make the user handling more complex. Lastly, PRS receivers are per definition not mass-market products since they are only available for selected, governmental authorized users.

An alternative to these conventional PRS receivers with integrated SM are server-based or remote processing PRS receivers: The general idea is to “outsource” the PRS signal processing to a secure server environment, in compliance with the existing regulatory framework. The user terminal itself samples only raw data from the signal-in-space (SIS) and forwards it to the server, where the PRS information included in the raw samples is processed. Since only a few milliseconds per measurement are used for a PRS PVT calculation, these measurements are also referred to as “snapshots”.

Consequently, the PRS is only used in a “passive”, non-real-time way. Under the jurisdiction of the responsible competent PRS authority (CPA), the service provider running the PRS server decides if and which information is returned to the governmental authorized user. This leads to certain advantages over conventional Galileo PRS receivers within integrated SM: Firstly, end users do not have to care about any PRS security requirement since their user receiver or terminal does not include any PRS assets. Only the service provider is concerned with them. Secondly, the Galileo PRS security cannot be breached by the user since the user terminal does not contain any PRS relevant methods or information. Lastly, as the end user device is a plain data grabber without SM, low size, weight, power, and costs (SWaP-C) devices in selected “mass”-markets can be realized.

This paper describes the architecture and proof-of-concept implementation with real-world experiments of a PRS server and its user terminal. Three measurement campaigns are outlined in which the Galileo OS information serves as the reference time to enable a PRS snapshot PVT.

The user terminal consists of a PRS-capable antenna and an in-house developed data recorder. This so-called "Flexiband" simultaneously samples the Galileo E1 and E6 signal bands with over 40 MHz of bandwidth and incorporates a commercial uBlox receiver module for an instantaneous reference. The uBlox UBX protocol data output is embedded in the recorded raw E1/E6 data stream in a way that the uBlox GNSS synchronized pulse-per-second (PPS) signal can be used as a time reference within the stream.

The PRS server is installed in a secure laboratory at Fraunhofer IIS, Germany. It consists of a modified PRS receiver, keyed with operational PRS keys, receiving and processing the PRS GNAV messages in parallel to the recording campaigns. For example, it provides the PRS secured ephemeris data for the PRS PVT computation. The second element of the PRS server is a so called "Security Module (SM) Token" connected via a PCIe adapter to the server. This SM Token implements the PRS NAVSEC and is used to provide PRS Pseudo Random Noise (PRN) codes for a specific satellite and time.

Using the OS time information of the recordings, the PRS server requests the PRS PRN codes from the SM Token and the secure GNAV ephemerides from the modified PRS receiver. Then, a snapshot PRS PVT is generated from the raw samples: Depending on the configuration of the data recorder, a dual-band E1/E6 full-BOC, a single band full-BOC or a single side-band only acquisition is carried out with certain refinement steps to derive precise pseudorange information. Thanks to the non-repeating PRS PRN codes with absolute time reference, the time of transmission is directly known with unambiguous code phase, in contrast to OS snapshot positioning where one has to resolve them first. Consequently, at least four satellites are required for a 3D PRS PVT snapshot fix, instead of five for an OS snapshot 3D PVT. The PRS PVT can then be compared to a reference OS PVT, e.g. to detect potential spoofing or to PRS approve the OS PVT.

The first measurements were taken from a static roof antenna on the building of Fraunhofer IIS, Germany. With a very high sampling rate (81 MHz), the full accuracy potential of snapshot-based PRS PVT is demonstrated. The second measurements are Galileo OS/PRS SIS snapshots from a car measurement drive in a dynamic scenario. With the emulation of different front-end bandwidth/sampling rates/resolutions, the dependency of the accuracy and availability on the front-end parameters can be demonstrated. Finally, SIS data recorded in a measurement campaign in Hanoi, Vietnam, is used for PRS positioning, demonstrating the huge potential of server-based PRS processing, enabling a secure PRS PVT from areas where PRS receivers would usually not be placed.

The paper concludes with the outline of possible applications for server-based Galileo PRS snapshot positioning, e.g. for privacy protected localization and authentication of position and time of measurements, both using Galileo PRS and the next steps towards an autonomous PRS snapshot PVT service. The results show the real-world proof-of-concept of both the PRS sampling and processing method as well as the PRS server environment setup at Fraunhofer IIS.

Acknowledgment:
Parts of this work has been carried out within the DIRACU project, funding code 50NP1601, sponsored by the national program for PRS of the Federal Ministry of Transport and Digital Infrastructure (BMVi). The test and measurement campaign at the NAVIS centre in Hanoi, Vietnam, has been co-funded by the H2020 BELS project.

Performance Analysis of Low-Power GNSS Positioning in IoT

Mr. Vicente Lucas Sabola[1], Dr. José Antonio López Salcedo[1], Dr. Gonzalo Seco Granados[1], Mr. Jose Antonio García Molina[2]
[1]Universitat Autònoma de Barcelona (UAB), Bellaterra, Spain, [2]European Space Agency (ESA), Noordwijk , The Netherlands

During the recent years, we have seen that positing information has become of paramount importance in a wide range of applications such as location-based services (LBS) or in internet of things (IoT) applications. The main idea of IoT is to connect physical objects (e.g., urban furniture, wearables, etc.) within a wireless low-end sensor network with the objective of collecting data for a given purpose (e.g., efficient resource management) with long duty cycles (usually from hours up to days). In this sense, the amount of IoT sensors is growing exponentially in the recent years, therefore requiring scalable solutions.
Global Navigation Satellite System (GNSS) technology is a widespread solution for positioning in IoT sensor networks. Nevertheless, the cost and power consumption of conventional mass market (MM) GNSS receivers collide with the stringent constraints of low-end IoT sensors (i.e., low-cost and low-power consumption), and the achieved location accuracy decreases in urban and soft-indoor environments, where IoT sensors are typically deployed. Following this tide, MM vendors are focusing in the development of low-powered GNSS modules without compromising the accuracy of their positioning solutions. This is achieved mainly by the constant evolution of semiconductor technologies and by the use of operation modes oriented for low-power positioning. However, the use of such low-power operation modes jeopardizes the position, velocity and time (PVT) solution, and whereas the duty cycle of the GNSS module is diminished, and hence its average power consumption, the position error tends to increase.
An analysis of the state of the art MM GNSS modules (i.e., u-blox, Télit, STM, Broadcom) will be performed in this work, together with a brief comparison of the different available technologies, and their claimed power consumption and positioning accuracy. In this context, we will mainly focus on low-power GNSS modules from u-blox, as it will be the receiver under test. The architecture, the algorithms used for obtaining the PVT, and the operation modes of a u-blox GNSS module will be analyzed. Current u-blox GNSS modules provide different operation modes: continuous mode (CM), cyclic tracking power save mode (PSMCT) for short update periods (i.e., 1-10 seconds) and on/off power save mode (PSMOO) for long update periods (i.e., longer than 10 seconds). Indeed, working with any of these two power save modes (PSMs) allows shortening the duty cycle and hence reducing the average energy required per position fix. Results provided by vendors demonstrate that the use of PSMOO significantly reduces the positioning accuracy.
In previous works carried out by the authors, the employment of a GNSS cloud-based solution has been proposed in order to tackle the typical constrains of MM GNSS modules. Such solution, the cloud GNSS receiver, is designed with the main objective of reducing the energy per position fix. To do so, the GNSS signal processing tasks are carried in cloud servers instead of in the sensor itself, thus offloading the power-demanding tasks of the sensor. Theoretical results have shown that the use of a GNSS cloud-based solution requires less energy than MM GNSS modules without compromising its accuracy, mainly due to the amount of time the sensor has to be on active mode in order to obtain a position fix. For instance, a MM GNSS module must be on active mode for approximately 1 and 30 seconds (depending on the signal conditions) in cold and hot start, respectively. In this regard, MM vendors provide assisted-GNSS (A-GNSS) services to their GNSS modules at a system start-up to minimize the time-to-first-fix (TTFF). However, this service requires of a fast down-link connection, which collides with typical IoT radio technologies such as narrowband IoT (NB-IoT) or LoRa, among others. On the other hand, the sensor used in the cloud GNSS receiver or cloud sensor only needs to be on active mode for a few milliseconds, enough to capture the desired GNSS signal for some milliseconds and transfer it to the cloud servers.
In this paper we will carry out an analysis of the positioning performance and availability of a MM GNSS module (i.e., u-blox M8T) and the cloud GNSS receiver in a real scenario at the European Space Research and Technology Centre (ESTEC) laboratories. In this test, we will compare the PVT fix accuracy of two u-blox M8T, one of them in CM and the other one in PSMOO with a duty cycle of 60 seconds. At the same time, a

universal software radio peripheral (USRP) N210 software defined radio (SDR) will be used to capture the same real signal for further processing at the cloud GNSS receiver. A MM GNSS antenna will be placed near the window inside the laboratory to perform the test under soft-indoor conditions. Preliminary results show that using the PSMOO instead of the CM significantly decreases the PVT accuracy.
Finally, some conclusions will be drawn with respect to the performance of MM GNSS modules when using low-power operational modes. It is expected that as the duty cycle of a MM GNSS module is shortened, the accuracy error increases. However, with extremely short duty cycles, the accuracy performance of the cloud GNSS receiver should not get jeopardized.

The Variometric Approach Applied to the Carrier-Phases of a Multi-Constellation Chipset for Smartphone and LBS Applications

Eng. Gabriele Pirazzi[1], Dr. Augusto Mazzoni[1], Prof. Mattia Crespi[1]
[1]"La Sapienza" University Of Rome, Roma, Italy

In the past, the possibility to access to dual frequency GNSS was achievable only with expensive and high quality receivers, in environment and conditions that are different from the everyday lifestyle. The use of dual-frequency is relevant because it allows increasing the accuracy and the reliability on the user's position estimation.
The technological evolution has brought today the possibility to extend the advantages of the high accuracy positioning to a larger number of users and applications. The way of providing these benefits goes through GNSS receiver devices designed to enhance the Location Based Services (LBS) applications for smartphones, clothes, tablets and watches. These solutions open the door to a large number of high-accuracy applications including lane-level navigation, mobile augmented reality (AR), autonomous driving, navigation of visually impaired and physically disabled people, micro geo-fencing, extremely precise analyses of the athletes' performance in various sports and smart city asset management.
The main objective of this work is to investigate on precise positioning with a GPS and Galileo enabled chipset embedded in a smartphone. Sapienza research team, as member of the GSA GNSS Raw Measurements Task Force, with contribution by Politecnico di Milano, is investigating the area of real time precise positioning with single frequency, focusing on the benefits of multi-constellation GNSS and raw data quality provided by a smartphone. The analysis is carried out with code- and carrier-based algorithms in different scenarios. Currently the smartphones use only one frequency (L1): this is an important constraint in the design of the precise positioning algorithm mainly due to ionospheric effect. Hence, the work is based in two main algorithms: the first uses the carrier phase differential approach (Static or Kinematic) in conjunction of a reference GNSS networks; the second is based on the variometric approach using the VADASE algorithm, using the carrier phase but without external data. Modern GNSS chipsets are multi-constellations (GPS, GLONASS, Galileo, Beidou) and after the release of the N version of the Android operating system, the raw data are obtainable from a phone or tablet. However, from a technical point of view, the raw data, especially the carrier-phase, are not directly available in standard format and must be properly parsed. Moreover, based on these parsed data, the work analyses the main errors. The primary error source on smartphones lies not in the GNSS chipset, which actually offers great performance in terms of tracking availability and code-based accuracy, but in the antenna, whose chief failing is its poor multipath suppression. High accuracy positioning requires a stable antenna position for referring the position. However, moving smartphones are constantly changing attitude (which affects the antenna gain also), altitude (e.g. when the smartphone is kept in hand along the body or in front of the face for reading) and obstruction conditions. In order to quantify the impact of these scenarios, tests have been conducted. The use of multi-constellation smartphone allows to increase the accuracy and the availability of the solution. In particular, the smartphone can reach decimetre accuracy in static condition and sub-metre when used in urban vehicle scenario; furthermore, the variometric approach is able to track the smartphone displacement with cm/sec velocity accuracy.

New dual-frequency GNSS receiver devices, designed to enhance Location Based Services (LBS) applications, use L1\E1 and L5\E5 GPS and Galileo frequencies to compute the position more accurately in both urban and open area environments. These receivers offer several benefits: the measurements from the two frequency can combined obtaining a new a iono-free measurement that completely remove the ionospheric effect; thanks to the narrower BOC (Binary Offset Carrier) modulation and to the higher chipping rate of L5\E5 signals, the code- and carrier-phases from L5\E5 frequency are less noisy than those in L1\E1, they are more robust against multipath reflections, and, more in general, they increase the quality of the satellites' tracking and the detection of cycle slips. The use of two frequencies allows to decrease the time the resolve the carrier-phases' ambiguities, speeding up the transition from positioning based on code-phase tracking to positioning based on carrier-phase tracking. Finally, the signals transmitted in L5\E5 are easier to track due the higher transmitting power, allowing an higher sensitivity that can be useful different scenarios such as urban canyon, presence of foliage and light indoor environment. In this context, the article presents also some preliminary results, in terms of accuracy and availability, of precise positioning' algorithms applied to a dual-frequency multi-constellation GNSS chipset designed for LBS.

GNSS Compare: A novel software framework for processing raw GNSS measurements on an Android smartphone

Mr. Mateusz Krainski[1], Eng. Sebastian Ciuban[1], Ms. Dominika Perz[1], Ms. Mareike Burba[1]
[1]*European Space Research and Technology Centre, Noordwijk, Netherlands*

GNSS Compare is an open source Android application, purpose of which is to ease the efforts of researchers that are interested in smartphone Global Navigation Satellite Systems (GNSS) raw observables processing. It is an easy to use and easy to extend Android-based framework for calculating the Position, Velocity, and Time (PVT) based on raw GNSS measurements.

With the release of Android API 24 in August 2016, Android application developers have gained access to the smartphone's raw measurements of GNSS signals. With that, every modern smartphone can be easily turned into a low-cost, mobile GNSS signal processing laboratory. Even further, in 2018 one of the major phone manufacturers has announced to start using dual-frequency GNSS receivers in their mass-market products. Other manufacturers and the Android system libraries are expected to follow this trend. It is also worth noting, that it is more and more common for Unmanned Aerial Vehicles (UAVs) and other robotic systems to be using Android as their Operating System (OS). GNSS Compare can be used as a development and test framework for GNSS related problems in those new emerging areas.

As it is well known in the GNSS scientific community, the GNSS raw observables (code-based pseudoranges, doppler measurements, carrier phase pseudoranges, etc.) have to be converted into pseudoranges. These pseudoranges are subject to multiple error sources (e.g., ionosphere, troposphere, relativistic effects, etc.) which have to be accounted for in the form of corrections. Finally, a PVT estimation algorithm is used to calculate receiver's position, velocity, and time. GNSS Compare defines easy to use programming interfaces for each of those steps. By the use of Object Oriented Programming (OOP) principles, such as polymorphism and inheritance, the detailed implementation of those steps can be changed, without the necessity to change the rest of the application's code. This allows the developer focus on his or her goals, instead of fixing unrelated system-level issues. GNSS Compare also implements an intuitive User Interface (UI), which allows the user to display the results of performed calculations in real time and change the chosen method for each of the aforementioned steps. One of the most valued features of the UI is a newly implemented ability to display internal state of the algorithms, in a form of plots or values (e.g., residual vectors from the Weighted Least Squares or innovation vectors from the Extended Kalman Filter), and change parameters by using sliders and switches, on application runtime.

The proposed application allows the user to display the results in real-time and compare multiple processing schemes. For example, the user can select that for scheme A they want to calculate the PVT based on GPS measurements, using their new algorithms, and for scheme B to use Galileo measurements and the same algorithm. Using GNSS Compare's User Interface, the user can quickly assess the quality of the calculated results. Using the data logging functions (estimated position, satellite signal strength, etc.), the user can log both processed results and raw measurements in the exactly same format as Google's GNSS Logger application for further post processing and detailed analysis. Therefore, with GNSS Compare the interested persons have full flexibility in terms of testing and analysis both in real-time and post-processing.

Since GNNS Compare is released as open source, it can be easily extended to include algorithms defined by its users. It must be added, that no knowledge about the Android system is required from the user to start working on the algorithms and define simple displays. Such knowledge is required only if the user wishes to make advanced changes to the UI. There is an online guide describing the details of implementation for GNSS experts, as well as the basics of OOP, the Android OS, and GNSS signal processing, for students interested in GNSS or software engineering.

The main purpose of this paper is to describe the software engineering principles implemented in the GNSS Compare framework. This description shall come in aid to the researchers or students interested in adaptation of GNSS Compare towards their needs (e.g., low-cost sensor fusion in Android smartphones, code framework porting on the microprocessor of an UAV, etc). Another paper proposed for the same conference is describing test results in the terms of PVT and raw GNSS measurement quality.

GNSS Compare has already received interest of multiple research institutions around Europe. Furthermore, it has been chosen as a winner of European Space Agency's internal challenge for smartphone application using the Galileo system. The competition was supported by the European Commission, European GNSS Agency (GSA), and Google.

Ongoing work focuses on extending the list of implemented algorithms, which are to serve as a starting point for everyone who would be willing to use GNSS Compare. Efforts also are to be taken to simplify the framework. Our goal is to provide this as a tool for any GNSS researcher to use, without the necessity to learn about the Android system or details of OOP. We are also increasing the robustness of the application, increasing code quality, and automated test coverage.

Precise Positioning

Newton 2, December 6, 2018, 11:20 - 13:00

Kalman Filter Optimization for RTK- Positioning using Android GNSS Raw Data

Mr. Himanshu sharma, Andreas Schütz, Prof. Thomas Pany
[1]Universtät Der Bundeswehr, Munich, Munich, Germany

With the release of Android N, Google announced the availability of GNSS Raw data from the mobile phone. This opens up to the broader perspective for research, analysis, and enhancement of the positioning quality in mobile phones.

Modern mobile phones offer a positioning accuracy up to 6 meters with best environmental conditions Figure 1. With the release of the Broadcom BCM4557 dual frequency GNSS chip for mass market receivers, the mobile phones are capable of performing decimeter-level position accuracy. With increasing applications based on augmented reality, e-banking, e-health, etc., there is a rapid increase in the demand for precise positioning (cm level accuracy) using the existing architecture of mobile devices. Error sources such as the ionosphere and multipath tend to degrade the quality of precise positioning in mobile phones. Cycle slip introduced by a weaker carrier-phase signal makes the positioning in mobile phone code-phase dependent only. Now with the availability of GNSS raw data, researchers are getting the opportunity to re-analyze and develop new concepts to enhance the carrier-phase positioning into a mobile phone. Optimized error models and development of new multipath mitigation techniques can enhance the feasibility of carrier-phase positioning in a mobile phone.

At the Institute of Space Technology and Space Applications, we are working on the development of error models which improve the quality of positioning in mobile phones using the carrier-phase technique. The approach presented in the paper showcases the quality of GNSS raw data, feasibility of RTK positioning in mobile phones, development of the error models for RTK positioning and finally demonstrating the quality of RTK solutions in post-processing.

For the analysis of GNSS raw data, a zero baseline setup has been performed in Figure 2. The Rover GNSS data is recorded by a Nexus 9 tablet. Whereas, the reference data stems from the Software Receiver developed at the institute. For the preliminary phase, un-differenced and differenced analysis were performed on the GNSS raw data set. Sustainable Carrier to Noise Ratio, satisfactory code minus carrier value within the range of 8-10 meters, centimeters level carrier phase residual indicates the feasibility of RTK positioning in the mobile phone under a very good signal strength.

The carrier phase based positioning technique requires the ambiguity to be an integer value before the resolved ambiguity can trusted. Constraining the solution to integer gives better accuracy and improved convergence time. The ambiguity fixing was performed using multiple techniques such as instantaneous (calculate the phase bias estimate on every epoch), continuous (estimate is done continuously over many epochs) and fix and hold (estimate from one epoch is passed to another epoch). This analysis leads us to the greater requirement of optimizing the Kalman filter (navigation filter).

The Kalman filter is a Bayesian estimation algorithm. Precise modelling of process and measurement noise is a must for better estimation of states. The Kalman tuning is a covariance estimation problem and the Kalman gain is based on the estimation of covariance. The papers' work is based upon the implementation of a Kalman filter tuning algorithm through covariance estimation technique. In the later part of the research, RTK positioning will be performed on a static scenario to analyze the quality of the RTK fix using the software receiver.

The software receiver developed at the institute of Space Technology and Space Applications supports a wide variety of operations including support for multi-frequency and multi constellation. The configuration parameter in the software receiver can be used for modeling the smartphone chipset type GNSS raw measurements.

The paper also discusses the various other approaches investigated for the development of the tuning algorithm. The reader will have an insight into the limitations related to precise positioning using mobile phones. The testing environment including testing procedure, results and comparison between standalone and RTK positioning with/without error models will be discussed in detail. The paper will conclude the future possibilities and the extension of the work.

High precision GNSS-inclinable surveying pole with low-cost IMUs

Mr. David Calero[1], Mr Enric Fernández[1], Mrs Eulalia Parés[1]
[1]*CTTC, Castelldefels, Spain*

Surveying poles are topographic instruments used to measure with a certain precision and exactitude a ground point position. GNSS surveying poles obtain the GNSS antenna position (top of the pole) through a geodetic GNSS receiver and later on project the point to the ground (bottom of the pole). The classical surveying poles operate in a vertical mode and the projection is obtained by subtracting the pole length distance into the height component of the measured GNSS point. This operation requires the user to level the pole perpendicular to ground plane.

Nowadays some surveying poles can operate in an obliquus mode by adding sensing systems and measuring the inclination. Most of the current GNSS-inclinable surveying pole systems rely on magnetometer sensors such as the Trimble R10. The use of this sensor imply a performance degradation when operating near magnetic fields making the results unreliable. In addition, magnetometer based tilted poles require a complex calibration methodology consisting on rotating the system over the three different axis. Other GNSS-inclinable surveying pole systems use an expensive high-grade IMU.

The main objective of the research presented on this paper is to propose an alternative approach to ranging pole systems, able to provide requested performance even when working near magnetic fields at a low price. The proposed solution relies on a GNSS receiver with RTK capability and a low-cost INS (MEMS IMU). Recently some of the big surveying companies are starting to launch their GNSS-inclinable surveying pole products based on low-cost IMU sensors, such as Leica GS18 T. We present here an alternative approach.

The advantages of using inclinable poles systems include measuring coordinates in difficult environments, considered inaccessible until now such as corners of buildings, walls, areas that are steep, dangerous, hidden or difficult to access, to mention a few. In addition, this procedure achieves better accurate results subtracting the human component error on the measurements due to a non perfect pole level (verticality). Furthermore, the fact that users do not need to level the pole for measuring GNSS coordinates leads into a faster acquisition procedure, increasing the campaign productivity.

In order to properly perform the ground point projection, the orientation of the pole needs to be determined. The orientation of the surveying pole is defined by three rotating angles named heading (or north-finding), pitch and roll (inclination angles). In order to determine these parameters and to calibrate the low-cost IMU a custom initialization procedure is executed.

The key point of the proposed research is based on the IMU initialization procedure, patented on 2015 with the international application number PCT/EP2015/081433. The main objective is to estimate the bias of the accelerometers and gyroscopes each time the surveying pole is turned on. Pitch and roll angles can be easily estimated with a static acquisition by relating the accelerometer values to the gravity force equal to 9.8m/s2. The challenging orientation parameter to estimate is the heading angle. The initialization procedure consists on maintaining the tip of the pole on a single point in the ground while inclining the pole into different angles, at least in three different inclinations. Considering that the ground coordinate is the same at the different pole inclinations, the heading, pitch and roll orientation angles of the pole are estimated using least squares method. The set of equations relate the RTK GNSS receiver coordinates to the ground coordinate with the pole length and orientation. By determining the pole orientation angles, the accelerometer and gyroscope biases can be obtained. In comparison with the existent solutions, the proposed initialization procedure is simple, fast and effective and it does not require the user to move to another ground coordinate.

Once the system is initialized the user can perform point projection as a normal GNSS-inclinable surveying pole by using the loosely coupling mechanization equations.

The IMU initialization procedure needs to be performed every time the system is powered on due to the bias repeatability. Furthermore, the bias stability changes the initial estimated biases due to time drifts so the system needs to be periodically recalibrated to ensure the accuracy of the system.

The projection error that is added by tilting the pole depends on the pole height, on the tilt angle and on the IMU performace. For example, by using a 2 meters pole, a maximum tilt angle of 20 degrees and a low-cost IMU (Invensense MPU9250) the reprojection error is about 2 cm.

The main conclusion reached is that using this methodology it is possible to use a GNSS-inclinable surveying pole with a low-cost inertial sensor within the GNSS RTK accuracy specifications. Using a fast and simple initialization procedure it is possible to estimate the IMU biases and the pole absolute orientation to guarantee the surveying pole performance. This new technology and methodology adds the tilt capabilities to the current surveying poles at a low price by implementing a consumer grade IMU and taking profit of the GNSS RTK position. In addition, this method is robust in any outdoor environment even with magnetic fields disturbances. This new challenging surveying system is capable to measure GNSS coordinates in places that previously was inaccessible.

Advantages and Limits of Using a Passive Hydrogen Maser in Kinematic Precise Point Positioning

Mr. Thomas Krawinkel[1], Mr. Steffen Schön[1]
[1]*Leibniz Universitaet Hannover, Hannover, Germany*

Absolute positioning and navigation based on GNSS (Global Navigation Satellite System) measurements always requires the synchronization of satellite and receiver timescales. This is usually done by using a third timescale, that is GNSS system time by introducing so-called satellite and receiver clock biases into the parameter estimation. Satellite clock corrections are computed from the broadcast navigation message or applied as IGS (International GNSS Service) clock products (Dow et al., 2009). Since the latter are significantly more accurate, they are a prerequisite for precise point positioning (PPP). The user has to take care of the receiver clock bias, which is usually accomplished by estimating an additional parameter together with the user coordinates. However, due to the poor accuracy and limited long-term stability of the internal quartz oscillator of the receiver, this error source has to be estimated on an epoch-wise basis. This changes the whole observation geometry in three ways: (a) at least four satellites must be observed simultaneously, (b) the up-component is estimated less precisely than the horizontal ones, and (c) significant correlations between the receiver clock bias, the up-coordinate and other elevation-dependent errors such as the tropospheric delay arise (Rothacher and Beutler, 1998). Replacing the internal oscillator by a much more stable external clock allows for introducing the knowledge about the superior frequency stability of such a clock into the estimation process, and enables receiver clock modeling (RCM) in a physically meaningful way over intervals in which the clock noise is well below the receiver noise, which is dominated by the noise of the observation type in use.

This approach already proved to be especially beneficial in GNSS-based navigation using code and Doppler observations by applying RCM over intervals of several minutes for a chip-scale atomic clock (CSAC) connected to a GNSS receiver. Extensive investigations regarding the performance improvements in accuracy, precision, reliability, continuity and availability as well as the application of CSACs in spoofing detection have been carried out in recent years by the authors (Krawinkel and Schön, 2015). Our algorithm of RCM is real-time applicable and also enables positioning with only three satellites in view, which is especially beneficial in urban environments as shown in Krawinkel and Schön (2016).

Ongoing developments of this technique now involve the transfer of RCM to approaches based on carrier phase observations such as kinematic PPP. Due to the approximately one hundred times higher precision of phase observations, physically meaningful RCM is not feasible when using a CSAC. However, the theoretically required frequency stability can be provided by a transportable passive hydrogen maser (PHM), for example the Vremya VCH-1006. Furthermore, it can be assumed that advancements in clock and miniaturization technology make high-precision clocks reality for use in kinematic applications in the near future.

In our contribution, we will briefly present the results of a simulation study on the potential of clock modeling in kinematic PPP (Krawinkel and Schön, 2018). All analysis scenarios lead to similar results when applying receiver clock modeling: we find an improvement of 70% to 80% in precision of the up-coordinates, and 60% to 80% in precision up-velocities. In order to validate the insights gained from the simulation study, a true kinematic experiment was carried out using a PHM onboard a van, where the maser was connected to a Javad Delta TRE-G3T receiver. Thus, the main part of our paper will discuss the corresponding analyses in a Kalman filter and a sequential least-squares approach. This includes investigations on how to determine an optimal reference trajectory, since for this the same observations, i.e. carrier phase observations are used as for the test trajectories. Here, we have three possibilities: (a) using a nearby reference station for relative positioning, (b) using GNSS and IMU measurements in absolute positioning, (c) a combination of (a) and (b). Furthermore, we will present investigations on the impact of RCM in different challenging environments, i.e. urban areas and open sky scenarios. First results already indicate that RCM based on carrier phase observations when using a hydrogen maser offers similar advantages as already shown in our simulation study. More precisely, the precision of the vertical coordinates and velocities are improved by approximately 65%. The ambiguity and troposphere estimates, on the other hand, are almost unaffected by RCM.

References:

Dow J, Neilan R, Rizos C (2009): The International GNSS Service in a changing landscape of Global Navigation Satellite Systems. Journal of Geodesy 83.

Krawinkel T, Schön S (2015): Benefits of Chip Scale Atomic Clocks in GNSS Applications. Proceedings of the 28th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2015). Tampa, FL, USA.

Krawinkel T, Schön S (2016): Enhanced Multi-GNSS PVT Solution When Using Chip Scale Atomic Clocks. Proceedings of the 29th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2016). Portland, OR, USA.

Krawinkel T, Schön S (2018): On the potential of Receiver Clock Modeling in Kinematic Precise Point Positioning. Currently under review for proceedings of the 31st International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2018). Miami, FL, USA.

Rothacher M, Beutler G (1998): The Role of GPS in the Study of Global Change. Physics and Chemistry of the Earth, 23(9-10).
Weinbach U (2013): Feasibility and impact of receiver clock modeling in precise GPS data analysis. Wissenschaftliche Arbeiten der Fachrichtung Geodäsie und Geoinformatik der Leibniz Universität Hannover, no. 303, PhD thesis.

Steering a GNSS Low-cost Receiver with a Chip Scale Atomic Clock and its Impact on PVT

Mr. Mohamed Bochkati[1], Mr. Steffen Schön[1]
[1]*Leibniz Universität Hannover/ Institute für Erdmessung , Hannover, Europe*

During the last decade the field of PNT has been dominated by low-cost GNSS devices and their, almost, unlimited applications such as autonomous driving, robotics, Unmanned Arial Vehicles (UAVs) or precision farming. But their full capability seems to be not exhausted yet, for instance in term of performance of the receiver clock and its stochastic characteristics.
Usually, such devices comprise a conventional TCXO (Temperature Compensated Crystal Oscillator) oscillator which has a poor accuracy and limited long-term stability. Theoretically, this drawback can be drastically improved by simply replacing the quartz oscillator with other oscillator of higher precision and stability which, in turn, should undergo, for example, Kalman Filtering technique to explore the full capability of Receiver Clock Modeling (RCM). This benefits of approach, i.e. connecting an atomic clock, e.g. Chip Atomic Scale (CSAC), to a GNSS receiver and modeling its stochastic behavior in a physically meaningful way has been already validated by Krawinkel et al. (2016). RCM was applied in a multi GNSS PVT solution based on GPS and GLONASS using code and Doppler observations. The achieved results indicate a significant improvement in the precision of the height and the vertical velocity by 84% and 50%, respectively. Furthermore, it was shown that this method is capable of coasting through periods of partial satellite outages with only three satellite in view. In these experiments, the receiver clock modeling has been performed with high-end geodetic receivers, which accept by default external frequency input as 5 or 10 MHz.
In this contribution, we would like to explore to which extent it is possible to feed external frequency signals into low cost receivers and how the technique of clock modeling could improve both the accuracy and the availability when applied to low-cost GNSS devices. To this end, we conducted a zero-baseline experiment where four GNSS receivers, two high-end JAVAD TRE-G3T Delta and two low-cost u-blox NEO M8T, have been employed to assess the improvement of both hardware and mathematical adjustment of only one low-cost devices.
The core of our experiment consists of modifying one of the u-blox GNSS modules to run on an external oscillator of higher stability instead of the built-in TCXO clock. Here, the main challenge was to feed the GNSS module with approx. 26 MHz frequency as provided originally from the TCXO device. This signal was generated by a 80 MHz Function/Arbitrary Waveform Generator, Agilent 33250A, where the behavior of its internal oscillator is steered by a SRS PRS 10 Rubidium frequency standard.
Similarly, the second 10 MHz output of this highly stable oscillator provided one JAVAD receiver to regularize the corresponding internal time reference. The remaining hardware, i.e. one JAVAD as well as one u-blox module, were free running based on their own internal quartz clocks. Finally, all the GNSS receivers were sharing the same Antenna, a Novatel 703 GGG, via an active signal splitter.
Multiple datasets were collected for approx. three hours which have been afterwards post-processed in code-based Single Point Positioning (SPP) mode with our IfE GNSS Matlab Toolbox. Considering the stochastic proprieties of the Rubidium oscillator, the clock modeling was applied for, only, the modified u-blox and one of the JAVAD receivers. Here, a Linearized Kalman Filter strategy has been chosen to estimate 8 states including three states for position, three states for velocity and two clock states, i.e. time offset and frequency offset.

Before applying RCM, our developed hardware concept should be first validated. In other words, we investigated the behavior of the receiver clock residuals from the SPP process in comparison to the other used GNSS receivers. We will show that as expected, the estimated clock residuals from the modified u-blox device have a very stable and flat curve. On the other hand, the residuals of the conventional u-blox receiver reflects the effect of clock steering due to the typical 1 ms clock jumps in such device. Similarly, both JAVAD receiver with and without external oscillator exhibit the expected curve progression. i.e. stable flat curve when using the Rubidium signal and the sawtooth behavior if the JAVAD receiver when running on its internal TCXO oscillator. These observations have been also validated using the Allan Variance technique in the time domain.
The evaluations of the SPP routine using RCM shows a promising result, where an improvement for both the precision of the up-coordinate and up-velocities between 50% and 60% w.r.t. SPP without RCM could be easily achieved. Finally, in order to show the capability of clock coasting when only three satellite data from a static scenario in urban canyon with a lot of obstructions will be analyzed. To obtain precise information about the environment geometry and thus the potential areas where the GPS signal can be fully blocked or reflected, we employ a 3D building model with Level of Detail 2 (LoD2). The obtained results will be discussed w.r.t. the satellite geometry and reacquisition times of the receiver.

Estimation of the Base Station Position Error in a RTK Receiver Using State Augmentation in a Kalman Filter

Dr. Paul Thevenon[1], Dr. Jérémy Vezinet[1], Mr. Patrick Estrade[2]
[1]Enac, Toulouse, France, [2]Sterela, Pins-Justaret, France

Low-cost single frequency Real-Time Kinematics (RTK) modules have recently been released by several manufacturers. This type of receivers allows to obtain much better accuracy, reaching decimeter-level accuracy, than traditional low-cost receivers, thus opening the world of precise GNSS positioning to a new sector. However, while this type of system will provide very good relative positioning accuracy, the absolute positioning accuracy might be degraded if the position of the RTK base station is not estimated with sufficient accuracy. Any bias on the RTK base station position will introduce the same bias on the RTK rover position. This paper proposes a modification to the position estimation algorithm that includes the estimation of the RTK base station position error, by combining both the Single Point Positioning Solution and the RTK solution. The algorithm is illustrated using 2 types of real data: first, for a fixed reference station using GNSS observations only, then for a moving vehicle using a sensor fusion algorithm between GNSS, inertial and odometer observations. Performance analysis shows that the bias affecting the absolute position of the RTK rover can be estimated using the proposed algorithm, decreasing the horizontal bias from a few meters to a few decimeters.

Early-Late Discriminator Performance of CDMA: Limitations of the Spectral Separation Coefficient

Mr. Christoph Enneking[1], Prof. Felix Antreich[2], André L.F. de Almeida[3]
[1]German Aerospace Center, Weßling, Germany, [2]Instituto Tecnológico de Aeronáutica (ITA), , Brazil, [3]Federal University of Ceará (UFC), , Brazil

Satellite navigation systems rely on asynchronous code-division multiple access (CDMA) to allow simultaneous broadcast of multiple signals in a common frequency band. Other than orthogonal multiple access strategies, asynchronous CDMA involves a controlled level of multiple access interference (MAI) received by the user. This leads to a slight degradation of the estimation and detection of key raw observables, which are code-phase, carrier-phase and navigation data. While the effect of MAI is much more subtle than perturbances such as multipath propagation and ionospheric effects, it is a form of nominal, always present nuisance much like noise. As such, MAI is an important contributor to a navigation service's nominal performance, and should be considered accurately during the design of navigation signals and the dimensioning of navigation systems.

Most satellite navigation services have been (and continue to be) noise-limited rather than interference-limited, which is why accurate performance models in the presence of MAI are not as sophisticated as they are, for instance, in terrestrial communications. However, as transmit powers are raised by system operators and more satellites and services are deployed, MAI can be observed to approach typical thermal noise levels in some frequency bands. As next-generation satellite navigation systems may be limited by interference rather than noise, it is worthwile to review and refine the performance models that have been used for the assessment and coordination of MAI. An accurate, conservative performance analysis of satellite navigation in the presence of MAI is also of interest for integrity assessment of safety-critical services such as ground-based augmentation systems.

The currently used standard for assessment of MAI in satellite navigation is ITU-R M 1831, which is based on the concept of the spectral separation coefficient (SSC). The SSC, given as the inner product of the power spectral densities (PSDs) of the desired CDMA signal (X) and the interfering CDMA signal (Y), is a measure for the average power of (Y) contributing to the matched filter output for (X). In the literature, there are basically three versions of the SSC, ordered here according to the level of detail with which they model the PSDs of signals (X) and (Y): a) the aperiodic SSC, which considers only the PSD of a transmit pulse modulated by perfectly aperiodic spreading code and data; b) the periodic SSC, which considers the PSD of a transmit pulse modulated by perfectly random spreading codes of finite length N and data; c) the pseudorandom SSC, which considers the PSD of a transmit pulse modulated by the actual pseudorandom spreading code and data. It is well-known that the SSC model a) does not correctly reflect the dependence of MAI on the relative Doppler between (X) and (Y), which leads to particularly erroneous results if (X) and (Y) have data rates which are small compared with the repetition rate of the spreading code.

The problem with all three versions of the SSC is that they are proportional to the average variance measured at the matched filter output of signal (X) caused by signal (Y), but most of the time not to the instantaneous variance. This means that the actual performance of the navigation system may be much better, or much worse, than predicted by the SSC. While the SSC models b) and c) at least take into account the instantaneous relative Doppler, they represent still just an average over all possible relative code-phases and carrier-phases. In particular, they neglect the non-uniformity of the odd cross-correlation between the spreading codes of (X) and (Y). Short spreading codes or spreading codes of certain code families have extremely non-uniform odd cross-correlation – which means that their performance is less accurately modeled by an average measure such as the SSCs.

In this work, we derive the variance of MAI conditioned on the instantaneous relative carrier-phase, code-phase and Doppler from first principles. The only source of randomness, according to our model, are the random data bits that modulate the pseudorandom spreading waveform. We further argue that MAI, conditioned on all relative synchronization parameters but with random data, is actually a Gaussian random variable for moderate to large coherent integration times, thus putting the frequent Gaussian approximation for MAI on a solid theoretical basis. We also demonstrate that the Gaussian approximation is, in general, wrong if relative code-/carrier-phase are unconditional, i.e., random, as assumed by the SSC. For our numerical results, we compute the conditional variance of MAI for GPS and Galileo for each constellation state over time with a resolution of 6.5 Hz. The histogram of the conditional variance serves as a numerical estimate for the probability density function of MAI. Comparable works have only considered the much simpler aperiodic SSC (i.e., the average MAI rather than its distribution) computed with a resolution of 0.3 per minute. Our results demonstrate that the methodology of SSCs leads to overly optimistic assessment of MAI not only for legacy signals (such as GPS L1 C/A) but even for modernized signals with moderate to large spreading code length. In particular, the SSC underestimates the tails of the distribution of MAI by 4-8 dB. We also discuss the impact of MAI on coherent code-/carrier-phase discriminators and data demodulation.

Analysis and Evaluation of Modulation Techniques for a Component incorporating Spreading Code Authentication

Mr. Elias Gkougkas[1], Mr. Thomas Pany[1], Mr. Bernd Eissfeller[1]
[1]Universität der Bundeswehr München, Neubiberg, Germany

The paper assess the performance of different modulation schemes adopted for authentication schemes which could be taken into account in the design of new satellite navigation signals offering increased robustness against spoofing attacks. The modulation techniques under evaluation are based on the concept of Spreading Code Authentication (SCA), where chips are encrypted partially or fully, and an a posteriori despreading is applied as soon as the key is received through for example a data component, where Navigation Message Authentication (NMA) is applied. These modulation techniques in conjunction with techniques applied at user level can increase the robustness against spoofing threats substantially.
To evaluate the performance of the proposed modulation techniques, different spoofing attacks are simulated and the probability of detection is assessed. Particular emphasis is given to estimation and replay attacks, where the encrypted chips are on-the-fly estimated and retransmitted, and to meaconing attacks, where GNSS signals are rebroadcasted with a delay (repeater). To illustrate the performance of the authentication techniques, a variety of signal spoofing scenarios are considered ranging from poorly phase/code aligned signals with large pseudorange rate differences to perfectly aligned with small pseudorange rate differences.
The primary goal of the current paper is to analyze and assess the impact of the modulation technique for the component incorporating spreading code authentication features in terms of authentication performance, and particularly, of the achieved robustness against the aforementioned attack types. For this reason, three main modulation techniques have been selected and compared for the different spoofing scenarios.
The first technique is based on the simple BPSK modulation. To demonstrate the robustness improvement in terms of higher chip rates, two specific scenarios are investigated: a low bandwidth signal comprised by a BPSK(1) modulation and a higher bandwidth version with higher chip rate, a BPSK(10) modulation. With a higher chip rate adopted for authentication, the receiver is able to restrain meaconing attacks in a smaller uncertainty region because of the narrower autocorrelation function. On the other side, in case of a Security Code Estimation and Replay (SCER) attack, the complexity on the estimation of the particular underlying chip is increased due the shorter chip length which offers an increased protection. This in addition with lower power, would even further increase the robustness of the authentication signal and avoid potential attacks.

The second family of modulation schemes under assessment are the Binary Offset Carrier (BOC) signals. These modulation schemes depending on the subcarrier and chip rate, can offer increased robustness by narrowing down the width of the autocorrelation function as it happens with higher chip rate BPSK signals. On the other side, they display the disadvantage of having secondary peaks which are introduced due to the subcarrier. These secondary peaks impact the detection statistic at the receiver side and could actually lead to a decreased authentication performance, particularly in urban scenarios, in which secondary peaks (including the ones originating from reflections) are difficult to separate.
The third and last family of signals considered for SCA are multi-carrier signals. For the current paper two different multi-carrier implementations have been considered displaying bandwidths equivalent to the BPSK(10) case. The first implementation relies on multiple BPSK(1) components separated by an offset frequency. The accumulated power of that signal equals the power of a nominal navigation signal (i.e., -160 dBW). The second implementation assumes as well the same power but the signal is based on a varying BPSK(1) component in time. Both implementations are high bandwidth signals and thus offer narrow autocorrelation functions, which could increase the robustness against replay (meaconing) attacks. In this case, a meaconer has to be located near the receiver antenna (10-20 meters) to deteriorate the PVT solution.
To demonstrate the advantages and disadvantage of each modulation a BPSK(10), BOC(10) and a multi-carrier signal offering the same bandwidth are compared. For simulation and demonstration purposes, both components, the authentication and navigation signal, on which the actual PVT computation is based upon, are multiplexed on the same frequency neglecting in the case of the multi-carrier the constant envelope constraint.
The scope of the paper is to illustrate and demonstrate whether encryption featured signals in the form of spreading code authentication for Open Service (OS) satellite navigation signals are feasible at user level and whether these features provide significant benefits worth to be incorporated in future satellite navigation signals. Furthermore, the paper assesses and quantifies the benefits of spreading code authentication for different spoofing scenarios and highlights the best modulation scheme for a potential authentication component.

Using Future GNSS Multi-Tone Signals for Increased Success in Carrier Phase Integer Abiguity Resolution

Dominik Doetterboeck[1], Thomas Pany
[1]*University of the Federal Armed Forces Munich, Munich, Germany*

A multi-tone GNSS signal is a single GNSS signal consisting of multiple carriers within one frequency band. A BOC signal can be seen as a dual-tone BPSK signal but future GNSS may utilize signals that consist of more than two carriers. For example, one may add an additional component to an existing open service signals (e.g. to the Galileo E1 signal) with a certain frequency offset. Within the Beidou system the multi-component constant envelop (MCC) signals have been discussed. Also OFDM signals (consisting of many carriers) have already been considered for the use within GNSS.
Multi-tone signals have certain advantages. Typically the multiple carriers increase the bandwidth, resulting in lower code noise due to the f^2 weighting when computing the Gabor bandwidth. Furthermore, they allow selective access to the components (e.g. a user who pays a fee can be allowed to use encrypted outer signals) and provide a flexible response to jamming as the receiver can choose to track only jamming free signal bands.
Multi-tone signals can be tracked as a wideband signal (sometimes called meta-signal concept) or the components can be combined noncoherently. In case of wideband tracking, the autocorrelation function exhibits multiple peaks and the tracking algorithms needs to ensure that the correct central peak is tracked (so-called BOC ambiguity resolution). One method to achieve this is to use the LAMBDA method (Teunissen et al.) by treating the BOC-ambiguity as an integer value and combining signals from multiple signals. The

method was proposed by J. Wendel and showed reliable BOC ambiguity resolution results especially if many satellites are tracked. The method did not consider the carrier ambiguity.
In our work, we want to assess the impact of splitting up a single-tone signal into a multi-tone signal for carrier phase ambiguity resolution. To achieve this we process the different components of a multi-tone signal individually to give code and carrier ranges for each tone. In order to improve the performance weaker signal components can be tracked as slaves ofa stronger master signal component. This way additional correlation between the measurements has to be considered. The measurements are then used for RTK positioning with the well known LAMBDA method, which by decorrelating the ambiguity states forms implicitly the optimal wide- and narrow lanes.
Our methodology to analyze the technique consists of observation simulation for a grid of user positions covering the Earth's surface and a given satellite constellation. The covariance of the simulated observations is passed to the Ps-LAMBDA module (Verhagen, Li, Teunissen) which computes the probability of correct carrier integer ambiguity resolution (success-rate). The success-rate is then calculated as a function of latitude/longitude and the average is the test metric.
The interesting question is now, if the splitting of a single tone signal into multiple tones (with reduced power and thus increase code/carrier noise) increases the success rate. Our initial trials show promising result if for example a Galileo E1/E5 solution is compared with an E1/E1D/E5 solution (E1D is new signal component on E1 with a frequency offset of 2-30 MHz). The investigations will also include results from OFDM-like signals. The Ps-Lambda module allows success rate calculation in AWGN channels and in multipath channels.
This investigation is an important finding if multi-tone signals are a viable mean to increase the robustness of carrier phase based positioning, which is the method of choice if utmost accuracy is sought.

Navigation Message Authentication for Next Generation GNSS

Riccardo Andreotti[1], Ottavio Maria Picchi[2], Marco Luise[2], Salvatore Corvo[1], Mr. Francesco Paggi[1], Vittorio Valle[1]
[1]Thales Alenia Space, , Italy, [2]Wireless Systems Engineering and Research, , Italy

Since the early days of GNSS, one of the main issues has been the need to protect the final user from attackers trying to emulate the data sent by the real system, the so-called spoofers. This can be done in particular adding the system the function of navigation message authentication, that represents the subject of this paper.

The paper introduces a general approach to the problem, to come to a detailed real-world in-orbit case, that is the Galileo Navigation System. This kind of authentication feature is in fact foreseen for the evolution of the system towards its own second generation, evolution that is currently ongoing.

Recent research (performed by Wiser and TASI in the frame of internal R&D activities) within the GNSS evolution study for Galileo Second Generation as well as GPS evolution, are investigating the possibility to have a more robust and reliable signal through the broadcasting of navigation message authentication bits. The paper describes a possible solution to the problems wherein the authentication bits are included in a dedicated channel that is added on top of the current signal-in-space format using IBOC multiplexing. This represents an alternative solution to the standard idea of reserving some bits of the current navigation message for authentication. The advantage of the dedicated channel is relatively clear: the bit-rate dedicated to authentication is considerably larger than that resulting from the reserved bits in the current message, thus providing a higher security level, and lower time to first authenticated fix (TTFA)/time between authentication (TBA). This allows in particular to easily meet the latest recommendations stating that (at least) a security equivalent to a symmetric algorithm with 128-bit key is needed.

Concerning the authentication algorithm, the present study proposes a combination of the TESLA protocol with a public-key protocol (such as ECDSA). This allows to improve on a weakness of TESLA that requires time synchronization: albeit loos, it cannot guaranteed at receiver start-up, and in addition the TESLA root key shall be authenticated anyway. The optimal combination is found based on a trade-off between security strength, bandwidth overhead, authentication error rate, and time between authentication.
Our proposal may pave the way towards an Open Service Navigation Message Authentication (NMA) solution to be broadcast on future GNSS signal channel using IBOC multiplexing solution. The proposed NMA criteria are based on the mutual combination of Elliptic Curve Digital Signature Algorithm (ECDSA) and TESLA authentication protocol.

The solution foresee the use of ECDSA in a first phase when time synchronization between the sender and the recipient is not available, to switch afterwards TESLA when time synchronization is achieved.
The paper concentrates on a specific solution wherein iBOC multiplexing on the E1 channels is supplemented with NMEA. This feasibility assessment is just a case study to show the generality of the approach and does not preclude any other implementation for future GNSS signals.
The paper is organized as follows: first a summary of the authentication protocols are provided, focusing on the TESLA one, and the IBOC multiplexing scheme for GNSS evolution signals. Then a proposed solution is detailed, together with associated performance, and finally the conclusions are drawn.

A Virtual Receiver Concept for continuous GNSS-based Navigation of Inland Vessels

Dr. Tobias Kersten[1], Dipl.-Ing. Le Ren[1], Prof. Dr. Steffen Schön[1]
[1]*Leibniz Universität Hannover, Hannover, Germany*

Transport on waterways is an extreme reliable and the safest possibility for transportation of different kind of goods that reduces traffic stress on roads and motorways. Motor freight ships are profoundly effective as a single vessel with general dimensions of 110 m length and 10 m width can carry the goods of approx. one hundred trucks. Some waterways allow push tugs of up to 270 m. To ensure and improve the safety and usability on waterways and to reduce in addition further costs due to accidents or similar scenarios, a robust and reliable navigation on waterways is required and under investigation. Driver-assisting concepts by means of GNSS in real-time kinematic mode (RTK) are topics of current research projects of several groups. However, the majority of those approaches mainly rely on RTK infrastructure, which is challenging in several cases.

The Institut für Erdmessung performed different studies to improve navigation of a vessel. To this end, we could use the motor freight ship "MS Jenny" which is modified to an event and exhibition vessel named “MS Science”, as a vessel-based navigation platform. Interestingly, passages of bridges or similar infrastructures that cross the waterway have two main effects: whether they completely interrupt the signal acquisition or they significantly diffract and disturb the incoming electro-magnetic GNSS signal. For both cases, this results in disturbances, discontinuities and jumps in the position estimates, which are extremely critical in safety-relevant applications and have to be reduced to a minimum. Generally, a complete loss of lock could be bridged by coupling GNSS with other units such as Inertial Navigation system (INS). However, our approach aims to be cost effective since an INS of good quality is generally not a standard infrastructure on present inland vessels. But a simple addition of more GNSS receiver-antenna-units and their optimal installation on a vessel is highly effective since they are required for other applications like, e.g. the guidance in entry locks or for the assistance to find the correct docking position in harbours.

In this contribution, the authors will apply the Virtual Receiver concept to acquire precise and continuous position estimates. This concept is a modular mathematical approach to combine whether code-phase only or code-/carrier phase combined observations of multiple antenna receiver combinations mounted on a single navigation platform into one unique platform solution. As successfully demonstrated for safety-relevant flight approaches, this concept is robust and provides necessary assistance for a proper and safe navigation with improved reliability, continuity and precision, cf. Kube et al. (GPS Solution, 22:41, 2018, doi: 10.1007/s10291-018-0709-y). In addition, the attitude information of the vessel can be determined.

In this paper, we are focussing on passages of bridges. We will show that a significant improvement of up to 70% for the position estimates is obtained with the proposed approach. The recorded dataset contains a trajectory of two and a half hours with up to 30 bridges and different infrastructures that cross the Mittelland-Kanal between Hannover and Wunstorf. To evaluate the required and correct setup we studied several modifications of the proposed approach. Finally, we show that a broader field of view for the virtual antenna increases the number of usable observables, which are helpful to provide continuous position estimates even for challenging passages. In addition, as the common field of view of the antennas is enlarged the corresponding quality parameters, like the dilution of precision (DOP) values, improve significantly as the geometry of visible satellites is strengthened.

Carrier-to-Noise (C/N0) values portray diffraction and scattering in those moments where the motor freight ship passes bridges, which degrades the GNSS signal quality. However, the bridge and corresponding infrastructure provides characteristic signatures, which lead to a useful information, e.g. the appearance of a bridge or similar elements.In order to evaluate the detailed information of the signal interruptions a 10 Hz data rate was used . As different receiver handle the internal processing of the GNSS signal and corresponding C/N0 values individually, we show and discuss how to interpret and classify these signal interruptions with respect to the infrastructure on and at the waterway.

Finally, with respect to attitude detremination, we studied the usability of the carrier phase and the impact of the multipath signal for the carrier-phase observations in the mode of a kinematic baseline. A baseline length along the vessel of approximate 56 m seems to be optimal with respect to the investigation of bridge passages, but significant disturbances occur due to local effects which have to be considered accordingly.

Receiver System Calibration for Multi-GNSS Multi-Signal Raw Observation Processing

Mr. Florian Reckeweg[1], Mr. Erik Schönemann[2], Mr. Florian Dilssner[3], Mr. Tim Springer[3], Mr. Matthias Becker[4], Mr. Werner Enderle[2]

[1]TU Darmstadt @ ESA/ESOC, Darmstadt, Germany, [2]ESA/ESOC, Darmstadt, Germany, [3]PosiTim @ ESA/ESOC, Darmstadt, Germany, [4]TU Darmstadt, Darmstadt, Germany

In the last decade the satellite navigation environment has changed from GPS-only dual-signal to multi-GNSS multi-signal (MGMS). Still most of the operational global GNSS processing strategies rely on dual-signal measurements only. In the dual-signal environment, signal biases played a subordinate role since estimated and applied clock offsets were specific to the only used ionosphere-free combination. With more GNSS, frequencies and signals, the handling of biases becomes more crucial and apparent in form of inter-system time offsets (ISTO) and biases between different signals or combinations, as can be seen for Galileo INAV/FNAV. The joint usage of multiple GNSS and multiple signals therefore requires a proper handling of all biases, with the benefits of amongst others estimating a single properly defined clock for all signals and absolute ionospheric delays. The most prominent sources for signal biases are the hardware in space and on ground, the atmosphere and the receiver software settings. The sum of the uncalibrated delays attributed to a certain signal and to either a satellite or an antenna-receiver chain is the so-called uncalibrated signal delay (USD), or more specific, the uncalibrated code (UCD) and phase delay (UPD). Due to limitations in the common GNSS analyses it is general practice to estimate differential code biases (DCB).
In order to benefit from the MGMS environment available today, this contribution presents the calibration of the EGON (ESA's GNSS Observation Network) receivers and results achieved with the Raw Processing Approach [1], which is used to jointly process measurements from multiple GNSS and multiple signals on 6 different frequencies in one single adjustment. In this approach no differences or linear combinations of GNSS observations are formed.
Different GNSS receiver models have been calibrated with an MGMS Simulator and relative to an absolute calibrated receiver chain with real data.
The goal of MGMS processing with the Raw Approach is to increase the flexibility and number of applications on the user side with respect to classical PVT solutions. This is primarily achieved by the capability of the Raw Approach to consistently process all available code and phase observations on multiple frequencies to benefit from their individual signal characteristics and to estimate additional parameters, like ionospheric delays jointly with the classical PVT solution.
In addition, the Raw Approach is used to emphasize the true physics of estimated parameters, for example by ignoring any zero mean conditions which are commonly applied to resolve a rank deficiency in the normal equation matrix for ionosphere and DCB estimation.

With the Raw Approach in combination with calibrated antenna-receiver chains, an unbiased and common receiver clock offset for all signals can be estimated. This allows for direct analysis and monitoring of the inter-system time offsets (ISTO) between available GNSS, which is fundamental to present and future multi-GNSS multi-signal processing strategies. The absolute ionospheric delay in form of one common total electron content (TEC) level for all signal paths between a GNSS satellite and receiver can be estimated with the Raw Approach to facilitate atmospheric research with a single GNSS receiver.
The calibration of signal code delays of antenna-receiver chains allows to estimate the true (without zero mean condition applied) Galileo FOC Differential Code Biases (DCB), which have not yet been published on the GSA website. In addition, the published Galileo IOV DCBs will be verified, including signal combination E1/E6 and the estimated DCBs of all Galileo satellites will be compared to the broadcast BGD values and to existing DCB products from IGS.
In addition to signal code delays, the MGMS Simulator has also been used to analyse uncalibrated carrier phase delays (UPD) of different GNSS receiver models to facilitate undifferenced raw observation carrier phase ambiguity resolution. The channel dependency of carrier phase biases will be assessed and a method is described to resolve the undifferenced raw observation carrier phase ambiguities at the receiver side, linking this fundamental problem to the correct estimation of an absolute ionospheric delay.

[1] Schönemann, E. (2013): Analysis of GNSS Raw Observations in PPP Solutions, Ph.D. Thesis, TU Darmstadt, 2013.

Performance of an Adaptive Partitioned Vector Tracking Algorithm with Real Scintillation Data

Eng. José Marçal[1,2], Dr. Fernando Nunes[1,2], Dr. Fernando Sousa[2,3]
[1]University Of Lisbon, Lisboa, Portugal, [2]Instituto de Telecomunicações, Lisboa, Portugal, [3]ISEL, Lisboa, POrtugal

Vector tracking algorithms have been used in both frequency and code tracking of GNSS signals in the last years with success. Vector phase tracking algorithms still present a challenge due to the order of magnitude of the errors when compared to the wavelength of the carrier wave, especially in situations where strong disturbances are present in one or more satellites.
Partitioned vector tracking for carrier phase signals has been used in simulation scenarios with good results. In this work the performance with real scintillation data is shown. Furthermore, an adaptive method with dynamic optimization of the weights in the partitioned vector tracking is included, in order to adjust the tracking structure to the variation of environmental parameters.

Kepler – Our Proposal for a Future Satellite Navigation System

Prof. Christoph Günther[1]
[1]DLR and TUM, Weßling, Germany

Positioning in the second generation satellite systems GPS, GLONASS, Galileo and Beidou is based on pseudorange measurements, which requires that the orbits and the clock offsets of all satellites are accurately estimated by control centers. Today, the estimation of the latter parameters is achieved using highly stable satellite clocks and an extensive network of ground reference stations.
Satellite clocks are a limiting factor in three respects: firstly, they are the most fragile component and limit the lifetime of the satellites. Secondly, their stability is critical to the accuracy with which orbits and clocks can be separated and also to the maximum time lap between updates of the navigation messages. Finally, atomic clocks are prone to rare exceptional events, such as frequency jumps. Under certain conditions such events are threats that need to be addressed in expensive augmentation systems. Ground networks are another limiting factor to current systems. GPS had to expand its original network by NIMA stations, Galileo included a large number of ground stations, and GLONASS as well as Beidou had and are still struggling with

the extent of their networks. The costs of maintaining the network of Galileo reference stations are substantial and Brexit is causing worries about the coverage in the South Atlantic.
Kepler circumvents these problems. It is a system without atomic clocks and with a ground network that could be reduced to a single station. Furthermore, initial simulations of the GFZ-Potsdam indicate that the signal in space accuracy could be improved by more than a factor of 10. Kepler achieves satellite synchronization by using cavity stabilized lasers as time references as well as two-way inter-satellite laser links. Furthermore, the observability of Kepler navigation signals is tremendously improved by placing the references stations on LEO satellites above the atmosphere. The synchronization to UTC is achieved either from the ground or by placing a small number of ultra-stable clocks on selected satellites. The use of LEO satellites leads to the most cost effective upgrade capability but is more limited by the knowledge of the gravitational field.
The Kepler system consists of 24 MEO satellites, which reuse the current orbital positions of the Galileo satellites, and another 4 additional LEO satellites. All satellites carry cavity stabilized lasers, which have an Allan deviation of roughly 10-15 for □ up to 10 seconds. These lasers are synchronized by two-way optical links, which have an Allen deviation that is much smaller. In order to keep optical transceiver terminals simple, the associated links only connect MEO satellites within one orbital plane. A third MEO terminal is oriented more freely to any LEO satellites, in order to connect the respective MEO plane with a LEO satellite. Each LEO satellite carries a number of terminals to simultaneously connect to at least two orbital MEO planes. The LEO satellites thus act as synchronization relays between the orbital planes. The accumulated delay to propagate information from an arbitrary satellite to any other one is below one second, i.e. well in the range of stability of the cavity stabilized lasers. Using spread spectrum optical signals and the optical carrier itself leads to a synchronized constellation with very little uncertainty by combining all time and frequency offsets in a multi-layer composite clock algo-rithm. The laser links are additionally used for data communications at a data rate of 50 Mbps and to measure inter-satellite ranges with an accuracy of a few tens of a micrometer. The accuracy is thus not limited by measurements but rather by vibration modes of the satellite.
A frequency comb transforms the synchronized optical signals into a radio frequency signal of equal stability, which is used to drive generators for the modulation of the optical signals, as well as for the L-band navigation signals transmitted towards earth by a nadir pointing antenna. The latter signals are compatible with the latest specification of Galileo. They are observed by Kepler's LEO satellites using zenith pointing antennas. Since the latter satellites are flying above the ionosphere, these navigation signals only experience distortions due to the transmit and receive equipment, which allows for a characterization of the associated antenna patterns and biases. All measurements performed on LEO and MEO satellites are easily transported throughout the constellation and processed in one or several places to obtain orbits, biases, and the mentioned time and frequency offsets. The clock corrections and biases are corrected directly during the generation of the navigation signals. The orbital parameters and antenna patterns on the other hand are integrated into the navigation messages. In order to prevent a drift of the satellite based orbits with respect to an earth fixed reference frame at least one ground receiver need to be included. This is confirmed by extensive simulations carried out by GFZ-Potsdam. For robustness, a small number of receivers will typically be used. There are no a priori requirements on their location.
Cavity stabilized lasers are robust: lasers have been characterized for space and cavities are made of low expansion glass. Frequency combs have been characterized for space and one was flown on a sounding rocket. Optical transceiver terminals have been built and flown in LEO and GEO orbits. Thus the system described so far seems suited for a long life-time in a space environment. The MEO space environment is, however, even more demanding than the GEO environment, for example, and thus a careful qualification program needs to be carried out in a pre-development program.
The approach discussed in this abstract is attractive to other regions of the world as well, in particular with respect to its low requirements on ground infrastructures. Europe can and should take the lead on the approach.

*) The project is supported by the Helmholtz-Gemeinschaft Deutscher Forschungszentren e.V. under grant numbers ZT-0007 (ADVANTAGE, Advanced Technologies for Navigation and Geodesy).
**) The project ADVANTAGE is a joint project of DLR and the GFZ German Research Centre for Geosciences. It aims at defining a future system for navigation, geodesy and metrology.

Advanced co-design of message structure and channel coding scheme to reduce the time to CED and to improve the resilience for a Galileo 2nd Generation new signal

Eng. Lorenzo Ortega[1], Pro. Charly Poulliat[2], Pro. Marie-Laure Boucheret[2], Dr. Marion Aubault[3], Dr. Hanaa Al-Bitar[4]
[1]Tésa, Toulouse, France, [2]INP Toulouse, Toulouse, France, [3]CNES, Toulouse, France, [4]Thales Alenia Space, Toulouse, France

The design of new GNSS signals represents always a trade-off between improving performance and keeping an reasonable complexity of the system. Recent research [1] has shown the interest of improving the current GNSS system performance through both the reduction of the Time-To-First-Fix (TTFF) and the enhancement of the resilience of the broadcast data, in particular the Clock and Ephemeris Data (CED). The advanced scheme for co-designing the message structure along with a structured channel coding proposed throughout this paper can jointly reach these usually conflicting objectives.

In previous works, co-designs of message structure and channel coding scheme where presented in order to reduce the time to retrieve the CED, also called Time-To-Data (TTD), without losing resilience of the CED under low C/N0 environments. In particular, a new model of message based on block fading channel model along with a channel coding scheme based on Root-LDPC codes [2] of rate one-half was proposed. Those Root-LDPC codes are capable to provide desired coding properties such as Maximum Distance Separable (MDS) [2] or full diversity under the well-known Belief-Propagation (BP) decoding algorithm, providing fast CED retrieving under good channel conditions and good resilience under low C/N0 environments. This scheme is combined with a Cyclic Redundancy Check (CRC) in order to provide data integrity [1].

In this paper, two new advanced techniques to co-design jointly the message structure and the channel coding scheme are proposed.

The first advanced technique consists in increasing the design constraints of the Root-LDPC parity check matrix structure in order to provide a reduction of the TTD (compared with the previous works based on a co-design message structure with a Root-LDPC code channel scheme of rate ½). This is achieved by introducing an independent erasure decoding algorithm. The new Root-LDPC code structure is modeled in n=4 independent blocks of information (2 blocks of systematic CED blocks and 2 data redundant blocks). Thanks to the erasure decoding algorithm, the retrieval of the systematic information is possible once k=2 error free blocks are retrieved. Moreover, since these codes belong to the Root-LDPC codes family:

- Firstly, in some cases the retrieval of the systematic information can be directly obtained by running the BP decoding algorithm instead of the erasure decoding algorithm.
- Secondly, the good error correcting performances under low C/N0 environments are kept.

A second advanced technique is proposed in order to increase the resilience of the GNSS system (for instance, to enhance the CED Error Rate (CEDER) performances) in parallel to the reduction of the TTD. This technique changes the methodology to co-design the structure of the message and the channel coding scheme proposed in previous works. In order to enhance the resilience of the system, the new methodology looks for a channel coding scheme with a coding rate lower than ½. Of course, the fact of decreasing the coding rate could involve an increase of the time to retrieve the CED. Therefore, the new message structure has to be adapted to this new channel coding rate in order to avoid increasing the TTD.

In order to address the new co-design requirements, a family of codes inspired from in Rate-compatible-Root-LDPC codes [3], is considered. This family of code has the following properties:

- The MDS property, which allows to retrieve k data units of systematic information from any k free error information units (no matter if it is systematic or redundant information).
- The full diversity, which allows creating error correction code structure with good error correction capabilities.
- Last property derives from rate compatibility. Assuming a Root-LDPC code of rate 1/n, with just k blocks of information (no matter if it is systematic or redundant information) we can achieve the error correction capabilities of a Root-LDPC code of rate 1/k. As example, if we have a Root-LDPC code of rate 1/3 with k = 2 blocks of information we can retrieve the error correction capabilities of a Root-LDPC code of rate 1/2.

In order to evaluate the reduction of TTD, an analysis of the time to retrieve the CED based on the calculation of the cumulative distribution function is implemented. Simulation results show a reduction of 50 % of TTD for at least 50 % of the time under high C/N0 channel conditions compared to the current GPS L1C signal thanks to the first advanced technique. In case of the second technique, the same performances of the former Root-LDPC scheme under high C/N0 channel conditions are observed, however a huge increment of the error correction capabilities can be accomplished.

In order to evaluate the error correcting algorithms capabilities of the second advanced technique, CED Error Rate (CEDER), which is equivalent to the evaluation of the probability of retrieving the CED under one specific C/N0 value is calculated under AWGN channel.

CEDER simulation results from the second technique codes (of rate 1/3 after retrieving 2 blocks of data) illustrate a demodulation threshold almost equal to the Root-LDPC code of rate ½ (gap of 0.15 dBHz) for a targeted error probability of 10^{-2}.

CEDER simulation results from the second technique codes of rate 1/3 after retrieving 3 blocks of data illustrate a demodulation threshold gain of 1.6 dBHz and 1.2 dBHz compared to the Root-LDPC code of rate ½ and GPS L1C for a targeted error probability of 10^{-2}.

References:

[1] Birgit E. Schotsch, Marco Anghileri, Thomas Burger, Mahamoudou Ouedraogo, “Joint Time-to-CED Reduction and Improvement of CED Robustness in the Galileo I/NAV Message”. "Proceedings of the 30th International Technical Meeting of The Satellite Division of the Institute of Navigation (ION GNSS+ 2017), Portland, Oregon, September 2017.

[2] J. Boutros A. Guillen i Fabregas E. Biglieri G. Zemor "Low-density parity-check codes for Nonergodic Block-Fading Channels” IEEE Trans. Inf. Theory vol. 56 no. 9 pp. 4286-4300 Sep. 2010.

[3] Y. Fang Y. L. Guan G. Bi L. Wang F. C.M. Lau "Rate-compatible root-protograph LDPC codes for quasi-static fading relay channels" IEEE Trans. Veh. Technol vol. 65 no. 4 pp. 2741-2747 Apr. 2016.

Ultra-Sparse Binary LDPC Codes with CSK Signals for Increased Data Rates in Future GNSS

Dr. Rémi Chauvat[1], Dr. Axel Garcia Peña[1], Dr. Marco Anghileri[2], Dr. Jean-Jacques Floch[2], Dr. Matteo Paonni[3]
[1]Ecole Nationale de L'Aviation Civile, Toulouse, France, [2]Airbus Defence and Space, Munich, Germany, [3]European Commission (Joint Research Centre), Ispra, Italy

Data rate increase in global navigation satellite systems (GNSS) is necessary to provide new features (e.g. precise positioning, security code authentication (SCA) key management). In addition, the data transmission reliability in urban environments can be improved using an induced increase of temporal diversity; the latter being obtained by retransmitting data bits thanks to the data rate improvement. The code shift keying (CSK) modulation is a solution for augmenting data rates of direct-sequence spread-spectrum (DSSS) signals. In addition, last developed GNSS signals make use of modern channel codes in order to further improve the reliability of GNSS data recovery. Hence, this article aims at proposing new binary low-density parity-check (LDPC) codes constructed for the CSK modulation in a bit-interleaved coded modulation (BICM) context. Codes achieving good error rate performance for both BICM and BICM with iterative demapping/decoding (BICM-ID) are presented. The code construction methodology is detailed and the good performance achieved by the constructed codes is assessed in additive white Gaussian noise (AWGN) channel.

On the Use of CSK for GNSS Anti-Spoofing

Gianluca Caparra[1], Nicola Laurenti[1]
[1]University Of Padova, Padova, Italy

Many proposals for GNSS anti-spoofing have been presented by the research community in the past decade. Many operate at the receiver level, for instance by exploiting advanced signal processing algorithms or by making use of additional information such as that coming from inertial sensors for detect- ing, and possibly mitigating, interference and spoofing attacks. Another class of mechanisms instead foresee the introduction of new features on the GNSS signals in order to make it harder to mount spoofing attacks, and to make easier to detect them. This paper focuses on the possible use of CSK as an anti-spoofing mechanism, that was proposed for GNSS. The aim is to evaluate which are the benefits of this modulation from the GNSS security point of view, evaluating the increase in attack complexity, and showing results obtained by simulation through GNSS simulators and software receiver.

Reduced Clock and Ephemeris Data making use of equinoctial parameterization

Ms. Susanne Schlötzer[1], Dr. Matthias Söllner[1], Dr. Thomas Burger[2], Mr. Mahamoudou Ouedraogo[1], Dr. Marco Anghileri[1], Mr. Thomas Bey[1]
[1]Airbus Defence and Space, Taufkirchen, Germany, [2]ESTEC, Noordwijk, The Netherlands

Abstract— According to Galileo OS SIS ICD [3] altogether four I/NAV words (i.e. I/NAV words 1 to 4) need to be decoded successfully in order to retrieve the full-precision Clock and Ephemeris Data (CED) from the broadcast I/NAV message. Especially in challenging environments this can lead to long time-to-first-fixes. Recently I/NAV message improvements have been proposed to reduce the time-to-first-fix, where the introduction of Reduced Clock and Ephemeris Data (Reduced CED), replacing spare words, is one of them. The general concept of introducing Reduced CED in order to improve the time-to-first-fix has already been presented in [5]. Reduced CED provides coarse ephemeris and clock-minus-radial-error correction information within one single I/NAV word to Galileo users. It is sufficient to decode only one single Reduced CED word successfully in order to obtain an initial position fix. However, the broadcast of Reduced CED words is only attractive if the position accuracy degradation by processing Reduced CED instead of full-precision ephemeris and clock correction data is limited. Therefore, sensitivity analyses have been performed in order to come up with optimum bit allocations to different Reduced CED parameters. The total number of bits which is available for Reduced CED is limited to 122 bits, corresponding to the nominal I/NAV word length, i.e. 128 bits, minus 6 bits reserved for the word type. It has been found that broadcasting equinoctial orbit parameters instead of classical Keplerian orbit parameters results in less quantization errors facing severe constraints on the number of available bit for orbit elements' quantization.
Equinoctial orbit elements' representation is typically used for parameter fitting in case of close to circular orbits (zero eccentricities) and/or close to equatorial/polar orbits (zero/ninety degree elevations). It is shown in [1] and [2] that the singularity in the classical partial derivatives at zero eccentricities is removed by using a parameterization in terms of equinoctial orbit elements instead of Keplerian orbit elements. In terms of Galileo, where the orbital planes are nearly circular, but the reference inclination is 56°, it is sufficient to select an orbit elements' parameterization which merely removes the singularity at zero eccentricities instead of using a generalized equinoctial representation removing both the singularities at zero eccentricities and 0°/90° inclination angles for orbit parameter fitting.
In contrast to orbit parameter fitting problems, where partial derivatives for the orbit elements need to be computed, the inverse task of computing the satellites' positions from classical Keplerian orbit elements does not exhibit any singularity problems in case of eccentricities being close to zero. Both GPS and Galileo system are broadcasting orbit elements making use of the well-known Keplerian parameterization, e.g. see [3] and [4]: Semi-major axis, eccentricity, inclination, longitude of the ascending node, argument of perigee

and the mean anomaly. However, sensitivity analyses performed for Reduced CED, where the number of bits for broadcast is severely limited going down from altogether four I/NAV words for full-precision CED to only one single I/NAV word for Reduced CED, have revealed that sticking to the equinoctial parameterization even for message broadcast is beneficiary: the resulting satellite positions derived from discretized Reduced CED are more precise when discretizing the equinoctial elements instead of the Keplerian elements while keeping the total number of bits for orbit parameter quantization constant. Therefore it is proposed to replace the classical Keplerian parameters 'eccentricity', 'argument of perigee' and the 'mean anomaly' by the equinoctial eccentricity vector components x and y and the mean argument of latitude within the broadcast Reduced CED I/NAV word. The transformation from these three equinoctial parameters to the corresponding Keplerian parameters, which has to be performed by the user segment before applying the standard user algorithm for ephemeris determination from Keplerian orbit elements, is straight-forward. Previous work on Reduced CED, see [5], still makes use of the classical Keplerian parameterization for orbit elements' broadcast, which is considered to be less efficient.

Besides six orbit parameters the Reduced CED I/NAV word does also comprise two "clock correction coefficients". The proposed Reduced CED methodology does allow for compensating radial errors, resulting from the discretization of the orbit elements, by adjusting the clock correction coefficients respectively. Thus, Reduced CED does not convey true clock correction, but clock-minus-radial-error correction. This strategy is beneficiary, having only a total number of 122 bits for the broadcast of all CED parameters within the I/NAV word. It has to be noted that the clock-minus-radial-error compensation is (slightly) elevation dependent. A heuristic approach has shown that optimizing the clock-minus-radial-error compensation for elevation angles of approximately 30° provides the most promising results in terms of the overall Reduced CED Fitting Range Error (FRE).

The FRE is used as performance metrics. It is defined as the sum of the absolute value of the clock correction minus radial satellite position fitting error and the absolute value of the tangential satellite position fitting error. Both FRE summands are elevation dependent. The tangential satellite position fitting error strictly increases with decreasing elevation angles. Therefore it is suggested to optimize the clock-minus-radial-error compensation for ~30° elevation instead of 90° elevation in order to result in well-balanced FREs over the complete range of elevation angles.

The proposed Reduced CED approach has been tested by processing full-precision CED received from all operational Galileo satellites and deriving the corresponding Reduced CED from that data. The maximum observed FREs did not exceed 10 meters and the 95% percentile of the FREs is even below 5 meters having analyzed 3 months of data. Thus, the resulting horizontal positioning accuracy when using Reduced CED instead of full-precision CED will be far better than the originally targeted 40 meters (95%). Fast and reasonably accurate initial position fixes are enabled by introducing the proposed Reduced CED word layout into the I/NAV message sub-frame.

ACKNOWLEDGMENTS

This work has been performed in the frame of the Galileo System Support contract. We would like to acknowledge the support of the European Space Research and Technology Center (ESTEC), and especially Elisa Gallon for the insight on the navigation message fitting optimization for Galileo.

Augmentation Services

Newton 2, December 6, 2018, 16:00 - 17:40

Impact of Issue of Data Update Periods on Satellite-Based Augmentation Systems

Ivan Lapin[1], Jaron Samson[2], Stefan Wallner[3], Mikael Mabilleau[4], Pierre Durel[5]

[1]Vitrociset Belgium, Toulouse, France, [2]European Space Agency, Toulouse, France, [3]European Space Agency, Noordwijk, The Netherlands, [4]RHEA Group for European GNSS Agency, Toulouse, France, [5]European GNSS Agency, Prague, Czech Republic

The aim of the paper is to analyse the distribution of update periods of Issue of Data (IOD) parameters in Galileo F/NAV and Navstar Global Positioning System (GPS) LNAV messages. For this purpose, a new method aiming at the reconstruction of IOD update periods reported by a network of monitoring stations is proposed. Over one year of Galileo F/NAV and over three years of GPS LNAV data is processed and consolidated using the proposed method. A reconstruction rate of 99.66% is achieved for the Galileo F/NAV messages. To extract the information on the consecutive update periods of IOD parameters, two new metrics are proposed. It was observed that Galileo F/NAV messages can experience fast single and fast double updates. Double updates happen at worst over two subsequent Galileo F/NAV sub-frames. The obtained results suggest a possible impact on the drafted Dual Frequency Multi Constellation (DFMC) Standards And Recommended Practices (SARPs). In order to assess the impact, a Galileo F/NAV IOD selector whose task is to select a specific IOD for augmentation in a Satellite-Based Augmentation System (SBAS) is proposed and implemented. The design of the Galileo F/NAV IOD selector takes into account the observed IOD update periods as well as relevant requirement defined in the drafted DFMC SBAS Minimum Operational Performance Standards (MOPS). The selector aims at maximising the minimum time that the SBAS user has to decode the navigation message identified by the IOD before it is selected for augmentation. In addition, the maximum time that the SBAS would be using IOD which is no longer transmitted by the Satellite Vehicle (SV) is also over bounded by the design. According to the analysed data, it is identified that an optimal time to trigger the selection of new IOD for augmentation is 350s when maximising the minimum decoding time. The trigger time guarantees that the SBAS user would always have at least 200s available to decode the Galileo F/NAV message.

The GNSS Laboratory Tool Suite (gLAB) updates: SBAS, DGNSS and Global Monitoring System

Mr. Deimos Ibáñez Segura[1], Dr Adria Rovira Garcia[1], Dr Jaume Sanz Subirana[1], Dr José Miguel Juan Zornoza[1], Dr Guillermo González-Casado[1], Mr David Jimenez Baños[2], Mr Carlos López Echazarreta[3], Mr Ivan Lapin[3]

[1]Universitat Politècnica De Catalunya, Barcelona, Spain, [2]ESA/ESTEC - European Space Agency, Keplerlaan, The Netherlands, [3]ESA/EPO - European Space Agency, Toulouse, France

This work presents recent and ongoing updates to the free and open-source advanced interactive multi-purpose package for processing and analysing Global Navigation Satellite System (GNSS) data, named GNSS-Lab Tool suite (gLAB). The updates have been performed in the framework of two projects funded by the European Space Agency (ESA), namely, the “gLAB upgrade for European Geostationary Navigation Overlay System (EGNOS) Data processing” and “Upgrade of gLAB Tool for Double Frequency Multi-Constellation (DFMC)”.

We examine various sets of results obtained with actual data using the Satellite Based Augmentation System (SBAS) corrections and the Differential GNSS (DGNSS) mode. Specifically, we introduce the Global Monitoring System (GMS) that routinely assesses the performance of the SBAS and DGNSS solutions using multiple station networks. That is, the Stanford-ESA integrity diagram, the Worst Integrity Ratio (WIR) maps, continuity risk, among other types of performance monitoring.

Lastly, we present the ongoing update to the gLAB tool that focusses on the implementation of multi-frequency and multi-constellation data processing capabilities.

GNSS Performance Characterization Framework

Mr. Paolo Crosta[2], Dr. Joan Clua[1], Mr. Marc Solé[1], Mr. Rodrigo Romero[1], Ms. Lourdes Tavira[1], Prof. Gonzalo Seco-Granados[3], Mr. Antonio Tripiana[3]

[1]Indra, Barcelona, Spain, [2]European Space Agency, Noordwijk, The Netherlands, [3]SPCOMNAV (UAB), Barcelona, Spain

Introduction

With the advent of new constellations, signals and frequencies, the reference stations are expected to face a major evolution by incorporating multi-frequency capabilities and adopting the multi-constellation concept, while also including more demanding requirements in terms of robustness against signal deformations, spoofing, multipath and interferences.

The European Geostationary Navigation Overlay Service (EGNOS) is Europe's regional Satellite-Based Augmentation System (SBAS) that is used to improve the performance of GNSS such as GPS and Galileo. EGNOS will experiment a major evolution by 2020, EGNOS V3, including the fulfilment of the SBAS L1/L5 standard, expansion to dual-frequency and evolution towards a multi-constellation concept. Hence, the Ranging Integrity Monitoring Stations (RIMS) are expected to incorporate modernizing features.

In this context, ESA awarded the consortium Indra and SPCOMNAV (a research group from the Universitat Autonoma de Barcelona) with a contract for the development of an advanced GNSS reference station breadboard (a.k.a. R3B) in the frame of the General Support Technology Programme (GSPT 6.2).

The main objectives were:

- Development of a Reference Station Prototype/Breadboard integrating two state-of-the-art GNSS receivers, including

- Selection of multi-constellation/multi-frequency (MC/MF) receiver and COTS antenna candidates to become part of the reference station;

- Design and development of a reference station prototype;

- Assess the compliance of two MC/MF receivers against EGNOS requirements studied during V3 definition phase (Phase B).

Description

Indra has acquired during the last decades a large experience in the assessment of GNSS performances. This experience has led the company almost naturally to the compilation of previously developed well-tested tools, resulting in the GNSS Performance Characterization Framework (GPCF).

GPCF is a toolset that allows analysis of GNSS data collected from different receiver types (mass market, differential, precision, etc.) and systems (SBAS, GBAS and GNSS). It can then be easily integrated within any test environment allowing the assessment of performances such as:

- Position-Velocity-Time (PVT) solution accuracy and integrity.
- Code and carrier phase measurements accuracy, including estimation of effects such as inter-frequency biases, group delays, channel biases, noise errors, etc.
- Signal in Space acquisition and re-acquisition for GNSS and GEO satellites.
- Impact on the measurements and behaviour of the receiver under a wide variety of complex scenarios including
  - Multipath errors of different nature (diffuse, reflective, etc.)
  - Interfering signals of different types (narrowband or wideband, pulsed or continuous, inter-system or intra-system, etc.)
  - Ionospheric Scintillation (IS) errors of different nature (high or low latitude IS)
- Orbit estimation accuracy.

- Code-carrier measurements coherence
- Availability of GNSS systems or augmentation systems

The tools and methodologies provided by GPCF are well suited for the assessment of the performances and the validation of:

- Any kind of receiver, or
- An entire GNSS-based system.

Furthermore, the GPCF can also be used as a part of a system to detect potential threats (especially interferences) in real time.

General setup of the characterization framework

In the frame of R3B project, GPCF was used as the basis of the final characterization framework to assess performance of two COTS receivers and a selected COTS antenna on scenarios relevant to EGNOS V3 requirements (studied during V3 definition phase) and to assess the level of compliance against them.

Test Case 1: Code and carrier phase error due to reflective multipath

One of the metrics assessed was the code and carrier phase error due to reflective multipath versus satellite elevations. The test was performed with the following signals: GPS L1CA, L2PY, L2C, L5; GALILEO E1b, E5a; and SBAS L1, L5. In order to isolate the impact of reflective multipath, no extra sources of noise were added. The signal power was aligned with SIS-ICD power + 10dB (in order to minimize other sources of error such as thermal noise and assess the error due to multipath only). Reflective multipath depends on the satellite elevation and shall be represented for any multipath delay and any phase shift in the range [0,180°]. In order to do so, a channel of multipath for each visible PRN is manually selected. Each multipath channel Desired-to-Undesired (D/U) power ratio was controlled by a pattern file based on elevation and the delay of the undesired ray was controlled by a random multipath delay from 0 to 30 meters for each elevation and azimuth. Besides, the real antenna pattern was included for L1, L2 and L5 bands to do the simulation more realistic, and the results were computed in elevation windows. In order to derive the multipath effect, the data log from Spirent containing the real range data was used as reference.

Results for code and carrier phase error have shown that the receivers under test were mostly not compliant with ESA requirements due to the lack of an advanced antenna with multipath mitigation.

Test Case 2: Code phase error due to diffuse multipath

This test measured the code phase error caused by the diffuse multipath by comparing the real range of the satellites via the simulator log files with the pseudoranges affected with diffuse multipath. The test was performed with two GPS satellites [L1CA, L2PY, L2C, L5], two Galileo [E1, E5] and one EGNOS [L1, L5]. Galileo satellites were in the same orbit as those of GPS in order to simulate both intra-system and inter-system interferences. Performance was evaluated on the basis of a maximum error per signal and per elevation.

The results showed that both receivers were compliant for most of the signals except GPS L2C, which showed the largest errors among all signals. It is also observed that one of the receivers outperforms the other in terms of code phase error for all signals.

Conclusions

The outcomes of the project have reported benefits at multiple levels by means of:

- Recommendations to ESA for the consolidation of future EGNOS requirements;

- Recommendations to receiver manufacturers to improve their compliance to future EGNOS requirements;

- A prototype of an advanced multi-constellation and multi-frequency reference station candidate for future industrialization;

• An improved characterization framework, which now offers the possibility to assess receivers' performance against complex scenarios.

Galileo Characterisation as Input to Safety-of-Life Applications

Dr. Phillip Brieden[1], Dr. Oliver Baur[1], François Robert[1], Dr. Andre Nuckelt[1], Domenico Lauria[2], Michael Kirchner[1], Stefan Wallner[3], Fabrice Cosson[3], Enrico Spinelli[3]
[1]Airbus Defence And Space Gmbh, Taufkirchen, Germany, [2]Thales Alenia Space Italia S.p.A., Rome, Italy, [3]Galileo Project Office, European Space Agency, ESTEC, Noordwijk, The Netherlands

The Galileo characterisation results represent an essential input to Safety-of-Life applications like ARAIM (Advanced Receiver Autonomous Integrity Monitoring) and EGNOS V3 as basis for aviation, rail applications, reliable guidance and autonomous driving.
This paper provides insight into the Galileo feared event characterisation with the focus on the results in terms of feared event probabilities of occurrence, its comparison to Safety-of-Life needs and the extrapolation to future Galileo configurations.
In the scope of Safety-of-Life applications a set of monitors have been developed to identify feared events on each operational Galileo satellite. Feared events are defined to be anomalies in the satellites' signal-in-space that could impact the positioning integrity. The identification and characterisation of these events is the precondition to derive as-observed failure probabilities of the system in order to use the signals with the trust required by Safety-of-Life applications, in particular with regard to SBAS.
The current set of feared event monitors allows identifying different kinds of anomalies in the E1 and E5a signal-in-space, namely: the ranging signals (code and carrier phase measurements) and the F/NAV navigation message. Based on data streams from GSS stations, the core characterisation is performed independently for each satellite and frequency. In order to increase the robustness of the characterisation of the ranging signals, additional data streams of GESS and IGS stations have been used for the related monitors. The identification of feared events is done in a two-step approach starting with (i) an automatic identification of outliers in the monitor output time series followed by (ii) a detailed inspection of the outliers in order to discriminate between false detections and actual feared events. The feared event probabilities of occurrence are then derived for input to Safety-of-Life applications taking also into account the length of the observation period and confidence level. A specific feared event monitor is detailed in this paper.
An initial extrapolation of feared events probabilities of occurrence to Galileo full operational capability is also performed by excluding observed events which root causes are clearly linked to the non-fully deployed Galileo system.
The characterization results confirm the high quality of the physical ranging signals: the FE probabilities as input to Safety-of-Life applications are better than expected. For the message related errors including the broadcast orbit and clock prediction errors, the current results are limited due to a limited observation period, ongoing maintenance and system deployment. First results of an extrapolation to future Galileo configurations show important improvements and lead to a level of feared event probabilities as it is expected as input to the Safety-of-Life applications.

Note: Approval of this abstract has been requested from Galileo Project Office but is pending so far.

Optimal Smoothing Filter Configuration for Local GNSS Augmentation in Challenging Urban Environments

Mr. Daniel Gerbeth[1], Mr. Michael Felux[1], Ms. Simona Circiu[1], Ms. Maria Caamano[1]
[1]German Aerospace Center (DLR), Wessling, Germany

Within the last years, Ground Based Augmentation Systems (GBAS) were starting to get widely used in civil aviation. In GBAS a ground reference station at an airport provides differential corrections and integrity parameters to landing aircraft during approaches.

With the upcoming UAV (unpiloted aerial vehicle) market, a new potential case of application for local augmentation systems with considerably different requirements evolves. Numerous global companies already investigate the possibility of using unmanned aerial vehicles for service or delivery tasks. Furthermore, Personal Aerial Vehicles (PAVs) are foreseen to be a possible means of local transportation not only, but also in cities and urban areas. Therefore, it is likely that in a foreseeable future a considerable amount of unmanned (and/or autonomous) aerial vehicles will share the airspace, particular in low altitudes.
It has to be a major goal in designing those systems to guarantee safe applications in crowded urban environments, where collisions with other vehicles as well as obstacles can easily cause serious hazards. This becomes particularly difficult when considering the already deteriorated performance of satellite navigation in urban regions with tall buildings shading the sky or causing signal reflections.

While local augmentation systems cannot solve this issue alone, they surely can help in achieving the goal of safe and coordinated operation by proving UAVs in the service area with a reliable navigation. Given a reliable positioning, the task of avoiding obstacles and especially other vehicles in the airspace can presumably be achieved more easily and with higher reliability using cooperative approaches and monitoring or tracking systems.

Therefore, in this work, we contribute to the provision of precision navigation and guidance to UAVs using low-cost ground reference stations in urban environments. Based on a simulation environment we study different scenarios and simulate the achieved nominal performance. Residual differential position error overbounds (protection levels) are used to judge the feasibility of such systems in different environments.

In a city-scale scenario the major problems result from multipath as well as limited satellite visibility. In the simulation environment we set up, different types of urban environments are considered where these effects are of increasing severity. We mainly consider three cases in the simulations:

- Suburban surrounding with mainly small buildings and one family houses
- Urban areas and commercial areas with multistory buildings
- Downtown, central urban area with pronounced street canyons and skyscrapers

The main idea is to study whether the severe conditions for GNSS in urban environments could be compensated by the use of multiple constellations together with local corrections to minimize the ranging errors on the (potentially few) available ranges in an urban canyon. The trade-off that is foremost studied in this work is regarding the carrier smoothing of the code ranges using Hatch Filtering in the (airborne) user receiver.
While a longer smoothing of course minimizes the residual noise on the ranges and suppresses high frequency multipath effects, it also increases the time until a satellite can be first used after the tracking starts. This is due to the convergence time that has pass until a tracked and smoothed satellite range can be actually included into the position solution.
In a dynamic scenario with high buildings around, that might lead to barely any satellites usable if the smoothing time constant is chosen too big. In other words, there are either more but noisier (less precise) ranges to be used or fewer ranges with less residual noise. Depending on the urban scenario and the user trajectory another smoothing time is expected to minimize the user position error in the end. A ground reference network with enough bandwidth (on the datalink to the users) could consequently provide

corrections for a multitude of smoothing time constants to allow each user (i.e. UAV) to choose the currently optimal configuration at any moment.

One additional key aspect in this concept is masking parts of the sky that are obstructed by e.g. buildings to remove ranges that are only from non-line-of-sight signals. In the simulation framework we assume to know the current local horizon and base the masking on that knowledge. In an experimental implementation however this has to be provided by a vision/IR based system in the end which might need additional conservatism regarding the reliability of the detection.

Based on the simulative results the future steps would then involve actual measurements in different urban environments together with a city-based low-cost network of differential reference stations to validate the expected performance.

ESA activities and plans for experimentation and exploitation of Precise real-time On-board Orbit Determination (P2OD)

Mr. Pietro Giordano[1], Paolo Zoccarato[1], Roger Walker[1], Giuseppe Mandorlo[1], Abderrazak Bouridah[1], Massimo Crisci[1]

[1]*Esa, Noordwijk Zh, Netherlands*

Precise orbit determination using GNSS signals is a key aspect of today's Low Earth Orbit satellites, in multiple cases it is a critical part of the mission (e.g.: Sentinel 1, 2, 3, etc). The current, well established, approach foreseen the computation of the precise orbit in post processing on ground, based on raw measurements generated on-board and downloaded in the telemetry packages. The accuracy of the computation of the orbit determination has reached outstanding performances already years ago with missions such as GOCE and SWARM, and will further improve with the new Sentinel satellites planned for launch in the close future, however the delay in the availability of the information might be a limitation for future applications for which very precise on-board real-time knowledge of orbit and clock information is crucial.

Real-time Precise Onboard Orbit Determination (P2OD) has been proposed several years ago and aim to provide real-time sub-decimeter accuracy on-board. The approach is based on the use of precise GNSS satellite orbit and clock, in a similar way as for ground Precise Point Positioning (PPP), in conjunction with advanced real-time sequential orbital filter. The final target is to achieve centimeter level with integer ambiguity resolution in point positioning (PPP-RTK).

This contribution will provide an overview of the P2OD concept, including its challenges and opportunities, and will provide an overview of ESA effort to support the development of P2OD technologies and their demonstration in space .

Real Time Reduced-Dynamics POD for LEO Satellites from GNSS Measurements

Prof. Stefano Casotto[1], Dr. Massimo Bardella[1], Dr. Paolo Zoccarato[2], Dr. Pietro Giordano[2]

[1]*Università degli Studi di Padova, Padova, Italy,* [2]*ESA/ESTEC, Noordwijk, The Netherlands*

New computational hardware is becoming available for use on board satellites, which allows real-time data processing of large amounts of data. This technological advancement is going to make it possible to execute on board tasks which have been so far relegated to ground-based post-processing. In particular, the precise orbit determination (POD) task can be run on board in real time to support critical science operations. The concept of Precise Onboard Orbit Determination (P2OD), which has been floating around for some time, is now becoming a definite possibility and is currently supported by the European Space Agency (ESA) for application to future missions.

In this context, a preliminary step has been taken and a software tool has been developed to provide P2OD capability for testing real data processing within a Single-Board Computer (SBC) environment in the laboratory. The software tool is based on an Extended Kalman Filter (EKF) and implements an approach to POD known as reduced-dynamics. In practice, the fully dynamical approach commonly adopted for tracking data post-processing based on the numerical integration of the motion of the satellite using a force model as complete as possible, is here supplemented by a number of first-order Gauss-Markov processes to simulate through stochastic noise the shortcomings of the dynamical models and other processes like the behaviour of the onboard clock. The P2OD tool accepts dual frequency measurements, both pseudorange and carrier phases, is currently validated for GPS data types, but supports Galileo observables as well. The reference force model includes all relevant components to simulate orbital motion of a LEO satellite to a centimeter level accuracy using state of the art modelling for both gravitational and non-gravitational forces. It implements the IERS 2010 kinematic standards and the IAU 2000 reference frame definitions and algorithms.

The P2OD tool has been tested on a week worth of Sentinel 3a raw measurement data and has consistently shown a sub-decimeter fit to the data as well as to the official ESA precise ephemeris. Details of the software tool will be provided and the effects of several options as to the quality of the ancillary data stream necessary for its operation will be given. It is believed that the tool is a solid starting point for the development of a more advanced version fully compliant with the requirements of missions where real-time PNT is a critical aspect for mission success.

A Software Test Bench for Radio-occultation Performance Study

Dr. NABIL JARDAK[1], Dr. FRANCK BARBIERO[2], Dr. LAURENT LESTARQUIT[2], Dr. ELIE AMANI[1], Dr. Thierry ROBERT[2]
[1]M3 Systems, Lavernose-lacasse, France, [2]CNES, Toulouse, France

Since many years, the use of GNSS is extended to more applications such as scientific ones. Especially, GNSS signals could be used for remote sensing namely via receivers onboard LEO satellites in order to sound the earth atmosphere: this is GNSS-Radio-Occultation (GNSS-RO). GNSS-RO takes profit of the propagation property of radio signals through the Earth's atmosphere. In this case, when the GNSS signal propagates across the earth atmosphere, the signal is delayed and its path is bent by gradients in the refractivity field. This delay increases as long as the earth atmosphere interposes between the transmitter (GNSS satellite) and the receiver (in general GNSS receiver onboard a LEO satellite). The phase excess is related to the refraction angle, itself is related to the refractivity of the crossed field. As the latter can be expressed as a function of physical parameters (water vapor pressure, temperature, ionosphere density –depending upon the wave bending location altitude), the GNSS carrier phase excess can finally be converted into an atmospheric parameter.
The advantage of GNSS-RO is its complementarity to the other means of atmospheric sounding, namely the vertical information content from RO data is highly complementary to that from advanced infra-red sounders such as IASI.
With the emergence of GNSS (GPS and GLONASS) the RO has been applied to the Earth. In 1995, the UCAR launched the GPS/MET project. Other projects: the German satellite CHAMP(2000), the Argentine SAC-C(2004), in 2006 six Taiwan-US satellites were launched: FORMOSAT-3/COSMIC with next-generation RO-GNSS receivers[RD. 1].
This amount of experiments testifies the potential of GNSS systems in the terrestrial atmospheric sensing and demonstrates the importance of this application as a real support for the prediction of the weather and in the study of the Earth's climate.
It is to be noted that when the occultation occurs in the troposphere (height below of 10-15 km), the received GNSS signal experienced strong fading with highly random carrier phase dynamic [RD. 3][RD. 2]. And it is well known that COTS receivers are unable to track the carrier phase in such condition. This is because high noise and high dynamic carrier phase shrink the stability region of the carrier tracking loop (PLL) and it becomes difficult to satisfy the noise–dynamic tradeoff: indeed, filtering the noise is generating more dynamic error. The baseline tracking architecture for RO is the open loop tracking adopted in the advanced RO missions (Black Jack: a dedicated GPS-RO instrument [RD. 7]). Open loop tracking architecture in the literature is shown to be either "Open PLL + Open DLL" or "Open PLL + Close DLL". Both configurations should be aided in velocity. This aid is either geometry based or geometry and atmospheric based. The last aid being more relevant because reducing the post-correlation RO signal bandwidth which robustifies the carrier phase extraction (reduces cycle slips during phase extraction).
The challenge of RO signal tracking resides rather in the low troposphere occultations where fading becomes the predominant impairment effect [RD. 5][RD. 4].

This paper deals with the development of a software platform for GNSS-RO application. The platform is composed of:

- Synthetic I/Q GNSS signal generator with radio-occultation propagation modeling capability. The carrier phase excess and wave attenuation are being modeled based on the ECMWF Profiles. These ones are shown to be sufficiently representative of fading in low earth atmosphere (troposphere) to challenge the GNSS base band signal processing. In addition, propagation file formats have been standardized in order to take other atmospheric attenuation/excess phase models as input.
- Software GNSS Receiver which implements the dedicated RO base band signal processing. The open loop tracking architecture with external aiding capability has been developed and integrated into the GNSS-SDR. GNSS-SDR is an open source GNSS software defined receiver [RD. 6]. This powerful tool allows to observe intermediate tracking signals at all signal processing stages (correlation and discriminator outputs). It implements traditional GNSS tracking loops. In the frame of this work, this tool has been updated by the adding of velocity aiding. The RO processing has been implemented for GPS-L1C/A and L2CM and Galileo-E1B and E5a.
- A post-processing tool: extracts the RO signal carrier phase excess and the signal power. It is fed by the complex correlator outputs and raw measurements provided at the output of the GNSS-SDR receiver.

This software test bed has been developed and validated by comparing the extracted carrier phase excess and signal attenuation to those injected into the GNSS signal generator.
In the final version of the paper we will describe the test bench and show the RO processing design and performance.
The RO signal processing performance based on open-loop tracking has been optimized and assessed by using many RO excess phase/attenuation profiles from ECMWF model. The final paper will present such performance and validation results.
The developed test bench allows to predict the performance of RO signal amplitude and phase measurements for different GNSS signals, which allows to compare different GNSS components in terms of RO performance.
The perspectives and future use of the RO test bench will also be discussed as for example the adding of new capabilities and relevant supported use cases of the test bench.

[RD. 1] "GNSS Remote Sensing: Theory, Methods and Applications", Shuanggen et al
[RD. 2] "Use of the L2C signal for inversions of GPS radio occultation data in the neutral atmosphere" Sokolovskiy et al.
[RD. 3] "Tracking tropospheric radiooccultation signals from LEO", Radio Science Volume 36, pp 438-498, May/June2001, Sokolovskiy
[RD. 4] "Postprocessing of L1GPS radio occultation signals recorded in open-loop mode", Sokolovskiy et al
[RD. 5] "Modeling and inverting radiooccultation signals in the moist troposphere", Sokolovskiy Radio Sci., 441–458
[RD. 6] https://protect-eu.mimecast.com/s/VYelCZ4NuzVn2zTzylJD
[RD. 7] "RadioOccultation Activities At NASA", CGMS-39 White Paper, October 2011 Mannucci1 et al.

Space GNSS Receiver for In-Orbit Demonstration of Precise Real-Time On-board Orbit Determination (P2OD) for Cubesat Missions

Mr. José Maria Palomo[1], Mr. Paolo D'angelo[2], Mr. Antonio Fernández[1], Mr. Pedro Silva[3], Mr. Pietro Giordano[4], Mr. Paolo Zoccarato[4], Mr. Javier Tegedor[5], Mr. Ole Oerpen[5], Mr. Lasse Hansen[6], Mr. Chris Hill[7], Mr. Terry Moore[7]
[1]DEIMOS Space S.L.U., Tres Cantos, Spain, [2]DEIMOS Space UK Ltd. , , United Kingdom, [3]DEIMOS Engenharia S.A. , Lisbon, Portugal, [4]ESA-ESTEC, Noordwijk, The Netherlands, [5]Fugro Norway AS, , Norway, [6]GomSpace A/S, , Denmark, [7]The University of Nottingham, Nottingham, United Kingdom

The paper presents a low-cost Space GNSS receiver for Cubesats promoted by European Space Agency, with the aim of providing real-time precise on-board orbit determination (P2OD). The activity is oriented to a Low-Earth Orbit in-orbit demonstration of the concept in 2019-2020.
The GNSS Receiver is based on Deimos FPGA-based dual frequency GPS / Galileo receiver (L1/E1 and L5/E5a), integrated in a space qualified Software Defined Radio hardware platform produced by GomSpace, and a Precise Point Positioning software library provided by Fugro. The University of Nottingham will contribute to the validation.
The paper describes in detail the proposed system, the expected performances and the validation approach.

High Performance Single Frequency Navigation Receiver for LEO Missions

Mr. Christian Pommer[1], Mr. Franz Zangerl[1]
[1]*Ruag Space Gmbh, Vienna, Austria*

High-end dual-frequency Global Navigation Satellite System (GNSS) receivers have become an enabling technology for contemporary earth observation missions in Low-Earth Orbits (LEO). Such receivers deliver measurements for space vehicle Precise Orbit Determination (POD) with position accuracy of a few centimetres to geo-locate the measurements taken by other sensors. For such POD GNSS receivers real-time positioning, accurate within a few meters is a kind of by-product readily supporting the Attitude and Orbit Control Subsystem (AOCS) of the host Spacecraft (S/C).
For POD receivers dual frequency operation is considered mandatory. In order to support both GPS and Galileo the current deployment of the modernised GPS constellation – with L5 being not yet operational – requests a triple-frequency receiver (L1/E1, L2, and L5/E5a). As far as publicly available, to this day, all existing space-borne GNSS receivers apply variants of the super-heterodyne architecture with dedicated analogue down-conversion chains for individual signal bands of interest increasing the receiver's recurring costs. Further, the POD receivers require a high end multi-frequency antenna optimised for suppression of local multipath.
For LEO missions not needing cm-level orbit determination accuracy but still profiting from the real-time navigation capabilities as input to the AOCS, POD receivers are unattractively expensive. Single frequency receivers have established as cost-efficient but less performant alternative.
The most common LEO orbits are located within the Earth's ionosphere. The ionospheric plasma shows a high variability over latitude, time of day and seasons and is influenced by the solar activities. As a consequence accurate models of the ionosphere do not exist, especially for receivers in orbit being amidst and not underneath the ionosphere. For kinematic single-point navigation and dynamically filtered solutions the uncorrected ionospheric delays are recognised as the dominant source of error limiting the achievable position, velocity and time (PVT) accuracy of GNSS based navigation. This fact is often respected in the planning of space missions by trading receiver price versus performance and accepting position accuracies of 10m 3D rms or more. For orbits below about 600km even this moderate performance cannot be guaranteed during high solar activities.
Approaches for estimating the ionospheric delays have been proposed exploiting the fact that the group delay and phase of a signal are oppositely affected when it traverses a dispersive medium such as the ionosphere. One of these approaches is referred to as Group Delay And Phase Ionospheric Combination (GRAPHIC). While the GRAPHIC algorithm using code phase and carrier phase measurements allows for rather accurate estimation of the evolution of the pseudo-range over time, its absolute value is affected by the ambiguity of the carrier phase measurements. Dynamically filtered GNSS based navigation solutions in orbit make use of the fact that the movement of the spacecraft can be rather accurately modelled. Unknowns do not have to be estimated from a set of snapshot measurements but estimates can be refined by a sequence of measurements. Therefore, dynamically filtered navigation solutions are able to resolve the ambiguities of the GRAPHIC combinations and can achieve excellent single frequency navigation performance.

One of the main challenges when using the GRAPHIC algorithm is the sensitivity of the measured carrier phase to the receiver clock error (in contrast to code phase measurements). As the receiver clock error is not stable over time (e.g. due to relativistic effects, temperature variance over the orbit, aging of the receiver clock hardware, etc.) improper handling of this disturbance will directly influence the carrier phase measurements and hence lead to an uncompensated error of the resulting pseudo-range. This effect would compromise the achievable performance or even endanger the robustness of the GRAPHIC based navigation solution.
RUAG has developed a high-end multi frequency, multi constellation receiver (PODRIX), which is dedicated to demanding precise orbit determination of earth observation missions. A single frequency variant of PODRIX has been developed. This receiver - referred to as LEORIX – maintains the class 1 quality level of PODRIX. LEORIX can be offered for an attractive price due to reduced hardware complexity and a cost-optimised single frequency antenna developed by RUAG Space in Sweden.

To achieve the superior single frequency PVT performance, the PODRIX receiver software has been augmented by a single frequency extension of the high performance Kalman filter based navigation solution successfully applying the GRAPHIC combination for the generation of pseudo-range measurements and resolving the carrier phase ambiguities in a real hardware environment. Both LEORIX hardware and software have been flight qualified within an ESA mission, and thus, have reached the Technical Readiness Level (TRL) 8.
After a brief introduction of RUAG's spaceborne GNSS-receivers, the paper will describe the key features of the LEORIX electronic hardware, present physical properties and electrical performance of RUAG's single frequency antenna and highlight some software features. Most prominent of the latter is the achieved real-time navigation performance of about 1m 3D rms even under severe ionospheric conditions. The performance will be demonstrated with results of on-ground tests obtained with the LEORIX hardware and software.

Analysis of the Chimera Time-Binding Scheme for Authenticating GPS L1C

Anna Poltronieri[1], Gianluca Caparra[1], Nicola Laurenti[1]
[1]*University Of Padova, Padova, Italy*

This work analyzes the Chimera scheme, proposed for protecting the GPS L1C signal, focusing the investigation on the lookup table to evaluate whether this structure affects the security of the system or not. In particular, we describe a simplified version of Chimera that doesn't involve the presence of the lookup table and we compare the robustness of the two models against a collision attack. We proceed analyzing other attack strategies against Chimera, calculating their success probabilities and performing Monte Carlo simulations.

Multi-Tier Signal Authentication for next generation GNSS

Dr. Oscar Pozzobon, Dr Andrea Dalla Chiara, Mr Giacomo Da Broi, Mr Samuele Fantinato, Dr Giovanni Gamba
[1]*Qascom S.r.l., Bassano Del Grappa, Italy*

The authenticity of the PVT requires the trustworthiness of the ranging measurements performed on the satellites spreading codes. Maintaining the secrecy of the spreading code is one known approach to ensure the authenticity of the ranging measurements and therefore of the overall PVT. During various activities with ESA, two main approaches have been considered for spreading code authentication: The first one is an asymmetric approach, where the information required to re-generate the spreading code is sent with a delay and verified by a public key mechanism. This has the benefit of being public available to all users and does not require a security module. As a side effect, asymmetric mechanisms lack of fast authentication performances, which, depending on data bandwidth can be in the order to several seconds. In addition, they require the storage of signal samples and provide the authentication in a post-processing mode.

A second approach is the use of symmetric schemes: with this approach the satellite and the receiver share a common secret to generate the spreading code authentication information. A security module is required to protect the common secret, which is the main disadvantage of such solution. As benefits, symmetric key schemes reach performances than can be in the order of several milliseconds to authenticate the range. Inclusion of a security module in the receiver (e.g. a smart card) or delayed authentication. The first method foresees the inclusion of a module responsible for the generation of the secret spreading code used by the satellite. This allows the user to track the encrypted signal and to seamlessly obtain authentic range measurements in real-time. The delayed authentication approach has less impact into the receiver, since no security module is needed, but it requires the storage of signal samples and provides the authentication in post-processing.

The paper presents a hybrid approach that allows different services to be integrated in the signal, both for users willing to access the public asymmetric service and users willing to use the more advanced symmetric service, that requires special hardware with a security module.
The technique is called multi-tier because it provides authentication to different levels of users.
The protocol therefore enables both real-time and delayed authentication within the same system.
Specifically, it foresees the design of a new signal component, which can be processed by all the receivers either in post processing mode or that embed a security module to generate the local replica of the encrypted sequence.

The performance of the protocol are assessed both for the symmetric and asymmetric users, in order to show the applicability of such a hybrid approach. The simulations are be carried out using the Qascom QA707 Software Defined Radio (SDR) signal simulator, with fully software simulations. The performance of the technique are evaluated on several Key Performance Indicators KPIs such as time to first authentication (TTFA), transmitted overhead data size (digital signature, mac, keys, certificates, etc…), robustness and applicability of the technique in harsh environments (such as urban canyons), complexity of an attacker to threaten the protocol and complexity at the receiver side.

The final paper is structured in five sections. It starts from an overview of authentication in GNSS systems and it ends with the presentation of some results concerning the proposed protocol. The introduction gives an overview of the already proposed authentication techniques for GNSS. Secondly, the state of the art of spoofing threats that the proposed technique is aimed at counteracting.
Thirdly, the paper explains the implemented authentication techniques, describing the hybrid authentication approach: spreading code encryption symmetric component for users equipped with security modules and watermarking with delayed information disclosure for the remaining receivers.
Subsequently, scenarios for simulations are defined. Specifically, the section describes the simulated environments, in order to assess the performance also in harsh and realistic situations. Moreover, it follows the illustration of the authentication Key Performance Indicators (KPIs).
Finally, the paper describes the simulation results for both the authentication sides (symmetric and asymmetric), providing results and performance comparison of the different tiers and services.

Measured GPS performance under LTE-M in-device interference

Mr. Olli Apilo[1], Mr. Mikko Hiivala[1], Mr. Atte Kuosmonen[2], Mr. Jani Kallankari[3], Mr. Hamid Amin[4], Mr. Mika Lasanen[1], Dr. Markus Berg[4], Prof. Aarno Pärssinen[4]
[1]VTT Technical Research Centre Of Finland Ltd, Oulu, Finland, [2]Polar Electro Oy, Kempele, Finland, [3]Verkotan, Oulu, Finland, [4]Centre for Wireless Communications, University of Oulu, Oulu, Finland

In this paper we present the measurement results for time-to-fix, position accuracy, and carrier-to-noise ratio of commercial Global Positioning System (GPS) receivers under the in-device interference from an LTE-M transmitter. The laboratory measurement set-up is built using software-defined radio (SDR) platforms to conductively feed emulated GPS L1 signals and LTE-M interference signals to the antenna input of the GPS receivers. The LTE-M interference from second harmonics is accurately modelled taking into account the transmitter activity patterns in different coverage enhancement modes. According to measurements, there are large variations in interference tolerance between different GPS receivers. REC01 was able to tolerate high level of interference during tracking and also in acquisition as long as the interference pulse duration is not too long (tens of milliseconds). REC02 performed clearly worse and tolerated only low levels of LTE-M interference during both acquisition and tracking. The same measurement set-up can be used with any GPS receiver for designing proper isolation and filtering levels for co-existing LTE-M transmitters.

Finding Interference Threats

Ioana Gulie[1], Jan Wendel[1], Frank Schubert[1], César Roda Neve[2], Olivier Desenfans[2], Ruediger Weiler[3]
[1]Airbus DS GmbH, Taufkirchen, Germany, [2]M3 Systems Belgium, Wavre, Belgium, [3]ESA - European Space Agency (ESTEC), Noordwijk, Netherlands

Radio frequency interferences (RFI), whether intentional or unintentional, are affecting the performance of the navigation receivers.
The GNSS sensor stations (GSS) are key elements of satellite navigation systems. Located on ground, their primary scope is to continuously provide accurate ranging measurements and navigation data received from the satellites to the control centre. The control centre is responsible for the monitoring of the system

performance and the generation of the new navigation data that will be transmitted by the satellites (ODTS process). Like any other navigation receiver, also the GSS receivers are highly susceptible to radio frequency interference. The detection and localization of the interference sources affecting the GSS receivers are therefore very important.

While interference detection, characterization and mitigation have been objectives of numerous past studies and can be found implemented in state of the art reference receivers, the problem of localization of the interference sources deserves further investigation. The goal is to derive recommendations for the design of future GSS architectures and receivers.

The objective of the Finding Interference Threats (FIT) activity was to study and evaluate the performance of RFI detection and localization techniques in realistic GSS scenarios and to make recommendations for promising techniques. An end to end simulator was developed to allow experimentation.

The elements of the dedicated simulator are ranging from the generation and processing of GNSS signals, to the generation of the interference sources taking into account real world characteristics like potential dynamics, propagation effects and antenna characteristics. Over 16 RFI types can be simulated, including Continuous Wave, Noise like, Pulsed signals, Linear and Nonlinear Frequency Modulated, DME and TACAN, and Spread Spectrum interferences.

The simulator holds a very reliable detection and characterization module. The detection of interferences is done in frequency domain based on Welch power spectral density analysis. The RFI's are characterized first in terms in bandwidth and power. In the next step, they are isolated from the signal by bandpass filtering and are analysed in time domain for determining their pulse duty cycle.

In order to localize interferences, the specific characteristics of the interfering signals have to be exploited. Such characteristics can be the interference power level, the time of reception, the carrier frequency, or the angle of arrival of the interfering signal, to name a few. A realistic GSS scenario, in which 3 independent receiver chains are placed at an equal distance from each other and from a central point, imposes some constrains on the measurements to be used. Localization methods based on angle of arrival can have high performance, but they require specialized equipment, like directive antennas, or multi elements antennas. That is why the simulator focuses on measurements that can be obtain with a typical GSS setup, like Received Signal Strength Difference (RSSD), Time-Difference-of-Arrival (TDOA) and Frequency-Difference-of-Arrival (FDOA). For the determination of TDOA and FDOA, cross correlation techniques are implemented.

The simulator implements various localization techniques, from iterative ones, like Nonlinear Least Squares and Levenberg-Marquardt that can be implemented for any of the above mentioned measurements, to purely geometric methods for localization based on TDOA measurements.

The performance analysis module generates figures of merit for each of the RFI detection, measurements and localization modules.

As an additional mode, the simulator can process measurements that are generated artificially from statistics, here including also AOA. Monte-Carlo simulations are performed to asses the performance of various localization techniques.

Realistic interference simulation scenarios dedicated to GSS have been designed based on publically available information about existing GSS stations.

In order to asses the impact of the various RFI on the GSS receivers, Airbus PIPE SW GNSS signal generator and PIPE SW receiver are used. The input to the receiver is the GNSS signal mixed with the RFI. The PIPE Integrity Analysis Tool generates a report showing the receiver performance.

The project offers a first assessment of promising detection and localization algorithms to be implemented in GSS. It also offers a platform that can be used to further implement and test other RFI localization techniques.

Characterisation of Radio Frequency Interference for GNSS Maritime Applications

Dr. Andriy Konovaltsev[1], Emilio Pérez Marcos[1], Dr. Stefano Caizzone[1], Dr. Kazeem Yinusa[1], Dr. Prof. Michael Meurer[1,2]

[1]*German Aerospace Center (DLR), Wessling-Oberpfaffenhofen, Germany,* [2]*RWTH Aachen University, Aachen, Germany*

Global Navigation Satellite Systems (GNSS) such as American GPS and European Galileo have become the main technology to provide position and timing services worldwide. The increasing dependency on these services across many application fields has raised concerns about the vulnerability of GNSS. Distortion and operational outages of GNSS user receivers caused by radio frequency interference (RFI) is widely recognized as a real issue in this context. As a matter of fact, GNSS signals have very low power when they arrive at the user receiver. Such situation makes the GNSS services vulnerable to interfering signals. The power required for an in-band emitter in the neighborhood of the user to block the reception of satellite navigation signals start from a few milliwatts and therefore are not very demanding. The interference can be caused unintentionally, for example by a malfunctioning radio device or by an avionics radio system operating in the same frequency band, e.g. DME system in E5 band. However, a large number of events have been reported about deliberately produced interference, for example by using so called personal privacy devices (PPDs).

Unintentional and deliberate interference signals constitute a challenging problem in many Safety of Life applications and in Liability Critical applications, such as the use of GNSS in maritime domain. Several studies have demonstrated a high vulnerability of maritime navigation systems to deliberate GNSS interference, specifically jamming and spoofing attacks. The development of adequate countermeasures is one of the main topics addressed by the e-Navigation strategy launched by the International Maritime Organization (IMO). However, only little information is currently available about the RFI situation encountered in everyday practice which could support this development. Several RFI events have been reported harbors, but the information is far from offering a complete picture.

In order to provide some more insight into the topic, the Institute of Communications and Navigation of the German Aerospace Center (DLR) conducted a worldwide maritime RFI measurement campaign. The main objective of was to detect, observe and record radio frequency interference events in the GPS and Galileo Open Services frequency bands - L1/E1 and L5/E5a. Both L1 and L5 bands are strictly regulated, with L1 band being actually reserved for radio navigation services, while L5 band allows coexistence of several radio systems.

A multi-antenna interference detection and recording system was developed which is capable of detecting the presence of L1/E5a interfering signals and automatically recording data snapshots. Each of the data snapshots contains intermediate frequency digital samples recorded with a high bandwidth and sufficient length for characterization in post-processing. Additionally, a DLR GNSS multi-antenna navigation receiver prototype was used to provide reference position and time information as well as relevant logging capabilities. Both parts of the measurement system are simultaneously fed by a seven element conformal antenna array. The utilization of the antenna array allows characterizing interference in spatial domain and easier distinguishing between multiple overlaying signals by using their different angles of arrival. The hemispheric form of the antenna array enables to achieve a low gain drop-off and good signal reception at low elevation angles. Hence it is possible to gain information of signals arriving from all possible receiving directions.

In order to perform the measurement campaign, the DLR system was installed on a vessel from the company Hapag-Lloyd, specifically a large container ship, traveling in a route from Europe to Asia, covering very different regions and docking in several countries. The campaign started on April 20, 2017 in the port of Hamburg and finished on February 23, 2018 in the port of Singapore after the ship served the route several times.

Because of the significant duration of the measurement campaign and the big amount of collected measurements the processing and analysis of the data was performed in three runs, each time focusing on a portion of the campaign. Some of the corresponding results for each part of the measurement campaign either have been already presented to the public (see [1][2]) or are going to be presented (see [3]). The main purpose of this paper is to summarize the obtained results over the entire length of the campaign and to propose an interference threat model for GNSS applications in the maritime domain

This paper will contain a very brief description of the measurement systems, including antenna, subsystems and detection methodologies used (more system details can be found in [1][2]). The most significant interference results of the recorded data are going to be presented. The characterization of the observed interference events will be achieved by combining both the observables of the array receiver (GNSS position and time, C/N0 values for the satellites in track, pre-correlation array covariance matrix) produced in real time and the results of the post-processing of recorded data (pre-correlation DOA estimation for interference signal(s) and post-correlation DOA estimation for the GNSS signals, spectral and time-domain characteristics). Though not claiming to be an exhaustive analysis of all possible interference events in the maritime domain, the presented work will however show the results of the first, to the author's knowledge, worldwide and long-time interference measurement campaign. The authors believe this information will be a valuable input for the development of adequate countermeasures to the threat of radio frequency interference in maritime GNSS applications.

[1] A. Konovaltsev et al, "Interference Detection and Characterization with an Array based GNSS Receiver using Conformal Antennas in Maritime Environments", Proc. of ION GNSS+ 2017, Portland, OR, USA, Sept. 2017, pp. 2795-2811.

[2] E. Pérez Marcos et al, "Interference Awareness and Characterization for GNSS Maritime Applications", Proc. of IEEE/ION PLANS 2018, Monterey, CA, USA, 2018, pp. 908-919.

[3] E. Pérez Marcos et al, "Interference and Spoofing Detection for GNSS Maritime Applications using Direction of Arrival and Conformal Antenna Array", to be presented in ION GNSS+ 2018, Miami, Florida, USA.

NAVILEO - a COTS-based GNSS Receiver for Space Applications

Dr. Cyril Botteron[1], Mr. Michele Scotti[1], Dr. Paul Blunt[1], Mr. Mathieu Rico[1]
[1]SYDERAL SA, Gals, Switzerland

The use of small satellite platforms has significantly increased over the last years, and this trend is expected to continue in the future with the development of a number of LEO mega constellations announced by several companies for the coming years. In order to reduce operational costs for these mega constellations and provide additional benefits, GNSS-based navigation can without any doubts become a viable and attractive alternative, offering many advantages over present ground based methods, while at the same time providing other capabilities to the spacecraft and the operator including autonomous on-orbit commissioning and precise position, navigation, and timing services.

In the first part of this paper, we present the development status of NAVILEO, a multi-constellation multi-frequency receiver currently being developed within an ESA navisp element 2 project. In order to offer a high performance, autonomous, state-of-the-art positioning navigation and timing solution at an affordable price as well as serving as a basis platform to target further markets in the future, NAVILEO is built around some carefully selected COTS-EEE and radiation tolerant parts. It will thus offer a performing and affordable solution that can bridge the gap between today's available low cost, low performance, single-frequency COTS-EEE-based GNSS solutions (as typically used on cubesats projects) and the space-grade, high performance, multi-constellation, multi-frequency solutions. To provide state-of-the-art performance, NAVILEO will be able to receive the signals from multi-constellations (GPS and GALILEO in a first step), operate on multiple frequencies (L1/E1 and L5/E5 bands in a first step), accept more than one antenna inputs (both passive and active antennas being supported), and include an on-board orbital propagator for improved TTFF, position, velocity, timing performance, and reliability. Its architecture based on a high capability FPGA and processor will also enable on the ground and in-flight software upgradability, which will be particularly important in order to implement or adapt to some GNSS SIS ICD features that are currently under development (such as Galileo open services navigation signal authentication or Galileo commercial services). It is also foreseen that NAVILEO could be extended in the future to offer additional on-board computer (OBC) functionalities, thus removing the need for a separate OBC or allowing the integration of additional sensors.

In the second part of this paper, we present a preliminary performance assessment of NAVILEO, assuming a satellite orbiting at two different LEO altitudes, 450 km and 1200 km. For these tests, we considered a GPS/Galileo constellation of 30/30 satellites, as well as realistic GPS/GALILEO antenna patterns. First, we have obtained the complete kinematic state of the GNSS constellations, propagated by a full constellation simulator. In order to verify the receiver requirements, we have analyzed the experienced Doppler shifts and Doppler rates and received GNSS signal powers for the two assumed LEO orbits. For both orbits, we then report the number of satellites visible and geometric dilution of precision. To assess the navigation performance, we computed two solutions, one obtained with the Orbital Filter (OF) and one obtained with Least Squares (LS) estimation. While we will show that the expected achievable positioning accuracy of NAVILEO in LEO using only code-based measurements is already very good, thanks to the on-board OF (e.g., position error < 1 m 3D rms), we note that an even higher accuracy could be reached in the future by implementing additional precise orbit determination (POD) signal processing.

Autonomous, Low-Cost GNSS Positioning and Timing Function Under Electrical Propulsion Toward the Geostationary Orbit: a Novel Kalman Filtering Approach

Alessandro Ferrario[1], Alberto Zin[1], Stefano Zago[1], Andrea Piccolo[1], Cristina Pecchioni[1], S. Casotto[2], M. Bardella[2]
[1]Thales Alenia Space Italia, Gorgonzola, Italy, [2]University of Padova, Padua, Italy

The availability of an autonomous mean of positioning in a geostationary platform is essential in reducing the constraints on the ground control. This is even more true in the case of the transfer to the GEO orbit, where the current trend is to implement the low-thrust electrical propulsion and this transfer phase could have a duration of several months. In this case, an on-board GNSS function can autonomously feed the avionic systems in charge of controlling the trajectory and the attitude and schedule in this way the requested thrusters actuations and attitude variations.
In this scenario, the main issue is the acquisition and tracking of GNSS signals, within short time visibility periods and with low received signal power. For this purpose, navigation solution shall provide aiding information to the signal processing (e.g. tracking stages) of the receiver which, in turn, provides usable measurements to the navigation function. Previous studies showed that, even considering side-lobe availability of GNSS to the receiver, the visibility toward GNSS satellites could be very poor.
In particular, in case of geostationary receiver, GNSS signal tracking is possible only from GNSS satellites in opposition w.r.t. spacecraft orbit, resulting in low received power from a little number of satellites, with line-of-sight very close to Earth projection. During most of the time in this condition, the set of four measurements at the same time necessary for a complete classical Position-Velocity-Time (PVT) solution is rarely available and in general with a bad relative geometry.
On the other hand, in typical high eccentricity LEO-to-GEO transfer orbit profile, a period of several hours without the possibility of having GNSS measurements availability is not uncommon. The spacecraft frequently crosses the GNSS orbit altitude, dealing with acquisition and tracking of GNSS signals within relative geometries which are rapidly changing in time. In addition, continuous thrust imposes constraints in spacecraft attitude, limiting the tracking capability on receiving antennas. In example, GEO transfer mission profiles considered in the frame of ARTES program are characterized by periods of up to 22 hours without availability of any GNSS satellite, alternating with very short time periods around perigee with a high number of satellites in visibility at the same time.
Therefore, an Extended Kalman Filter approach that foresees propagation of the solution in complete absence of GNSS measurements and an update of PVT solution even with less than four available measurements is a suitable approach to optimally handle the problem and to keep the position/timing errors within reasonable bounds. A particular effort should be dedicated in developing of an accurate model of accelerations acting on the spacecraft, in order to minimize propagation errors.
The complexity of the Kalman Filter, and in particular of the dynamic propagation step, has to be balanced with the computational power available on board. To this end, an optimization activity has been carried out in order to limit the force (dynamic) model to be in line with the requested position and timing performance of the GEO orbit transfer phase. A similar approach has been followed for the numerical integrator.
In presence of electrical propulsion, the thrust acceleration is a significant contribution to the spacecraft dynamic and at least a-priori estimation of nominal thrust vector shall be included in dynamic propagation. This nominal thrust acceleration is considered to be always available (provided by the AOCS to the receiver function), but it is typically affected by errors in the order of 5%. A model of thrust acceleration correction w.r.t. nominal vector should be considered, based on a set of parameters to be included into the Kalman Filter state vector estimation process, along with the standard Position, Velocity and Clock states.
In order to achieve large availability of position and timing of the hosting platform, the tracking of the GNSS antenna side lobes feature is a critical aspect. Based on the recent experience of SGR GEO (a GPS receiver on board the MEO satellite GIOVE-A, the Galileo In-Orbit Validation Element), additional insights on the side-lobe levels were made available and this allows to better design a receiver architecture whose performance can be more precisely assessed for the study case. An optimization of two antennas visibility

has been conducted in order to guarantee wide measurement availability to the Kalman filter, with attention to the side-lobe visibility.
A SW simulator representative of navigation solution functionality of TASI receivers, including enhancement of Navigation Kalman Filter (NKF) solution, has been developed in TASI, with the collaboration of University of Padova, Italy. This tool enables evaluation of NKF performance during long time mission profiles (e.g. weeks), speeding-up the tuning process and providing support to its development. Then, the NKF algorithm has been successfully integrated within a TASI GNSS space-borne receiver prototype and tested using HW-in-the-loop RF Constellation Simulator (RFCS) in a reduced set of real-time scenarios (e.g. few days). The considered GNSS receiver is a single-frequency, dual-antenna receiver hosted in the avionic computer of Thales Alenia Space Geostationary platform.
This paper will present the Kalman filter simulation results in a set of GEO Transfer Orbits and final operative (Geostationary) orbit, corresponding to different launchers (Ariane 5, Falcon 9) injection. The above scenarios consider continuous and discontinuous application of thrust of different amplitude levels. In addition, results from HW-in-the-loop tests are presented, consolidating outcome from SW simulations. Good position and velocity accuracy are achieved with the new Kalman filter structure proposed, e.g. the estimation of thrust parameters together with the classical position, velocity and clock states. Moreover, it has been noticed that even without estimation of thrust parameters the positioning and time performance are already sufficient to sustain acquisition and tracking stages within long propagation periods and harsh geostationary environment. Note that this simplification is possible given that at least the a-priori information on nominal thrust vector is available at the receiver from AOCS.
This paper is based on a project currently carried out by Thales Alenia Space under an ARTES contract with ESA, funded by the Italian Space Agency.

Emerging Applications of Snapshot Navigation in Space

Mr. Samuele Fantinato[1], Mr Giacomo Da Broi[1], Mr Fabio Bernardi[1], Mr Oscar Pozzobon[1], Mr Andrea Dalla Chiara[1]
[1]*Qascom, Bassano del Grappa, Italy*

New terrestrial GNSS positioning applications and services are increasingly exploiting snapshot-based processing techniques. This trend is boosted by the evolution of always connected devices, cloud processing infrastructures and high data rate mobile networks, [RD1]. The use of snapshot positioning methods in space applications is currently very limited. Indeed, in these scenarios, batches of GNSS signal samples received by the satellite navigation antenna shall be collected on board the satellite, timestamped with an approximate time reference, when available in the satellite payload, and then transmitted to ground facilities where the GNSS processing routines are executed on a workstation where the position or orbit of the satellite can be determined. For example [RD2] describes a snapshot GNSS positioning concept and prototype for LEO satellites and [RD3] multiple snapshot signal processing architectures for GPS and Galileo signal batches acquired at very low CN0 in interplanetary missions or on the moon. There are well-known advantages of snapshot processing that could be beneficial also for space navigation. First of all, a simplified GNSS hardware can be mounted in the satellite as only an RF Front End is required to digitize the signals and provide them to the on-board computer; it is an energy efficient processing mode as the front end is switched on only on pre-defined intervals and the computationally demanding tasks are executed on ground servers. In addition, snapshot processing allows to increase the availability of GNSS positioning and timing data in particular for high orbit scenarios such as GEO or Interplanetary mission because more sophisticated processing techniques can be implemented on the ground processor to reduce the acquisition threshold, to demodulate modernized GNSS signals and to support multi-constellation ranging and navigation.
From a robustness and assurance perspective, while much attention has been given to ground applications, few requirements have been considered for protection and enhancement of robustness of space based

GNSS services, [RD4]. It is believed that an upcoming need in space is satellite positioning authentication as most of satellite constellation can be considered critical infrastructure assets.
The proposed solution of this work is to expand the capabilities of Ground Snapshot processing to enable security in space processing the Galileo encrypted signals (e.g. Galileo Commercial Service). With this approach the E1 and E6 signals shall be transmitted to the ground together where the encrypted local replica for E6 acquisition is generated by a security function on ground. This is one of the main innovations that is being introduced by Qascom in the next generation of ENSPACE GNSS Software Space Receiver.
The focus of this paper will be on the design and first experimental results of the on-Ground Snapshot processing mode implemented in the ENSPACE receiver.
The paper presents the architecture of the demonstrator that is being developed including:

- the GNSS Simulation Layer, used to simulate all the mission scenarios such as LEO, GEO, MEO, Launchers and Interplanetary spacecraft. The GNSS Simulation Layer is essentially based on a GNSS RF Constellation Simulator.
- the Space Application Layer that allows to capture of the GNSS signals in space for the snapshot processing mode. This layer is composed by a Software Defined Radio (SDR) platform embedding a state of art and powerful Zynq System on Chip (ARM/FPGA) board and a flexible Analog Device radio front end.
- the Link Emulation layer that emulates the transmission of IQ samples and other telemetry data link in S band through a real transponder.
- the Ground Emulation Layer that includes the ENSPACE ground software components supporting snapshot processing

The paper describes the on-ground snapshot processing architecture including the signal processing modules for the acquisition, the high-resolution code phase and doppler estimation and the adaptations introduced to ground-based snapshot positioning algorithms (e.g. millisecond ambiguity resolution) for the space scenarios.
One of the major complexity of on ground processing is the estimation of the exact time reference of the captured signal batch. Two specific solutions that exploit Galileo E1 OS and E6 CS features respectively have been implemented. The first approach uses the Galileo E1C pilot component for long coherent integration and Galileo E1B data component to correlate with a local replica modulated with the E1 navigation message symbols in order to determine the batch exact time reference. It is assumed that the ground servers can easily retrieve the Galileo navigation message as aiding data from the network. The time reference of the space board could be considerably unprecise (in the order of hundreds of ms) therefore, it may be necessary to check several combinations of symbols sequences to find the correct synchronization. However, when the receiver computes the accurate time estimation for one satellite, this can be applied to all the other Galileo satellites to be acquired and also to GPS. Simulation results for GEO scenarios mission analyses have already shown that it is possible to acquire in snapshot processing mode satellites with C/N0 down to 21 dBHz, assuming signal batches of 200 ms.
Positioning using E6 CS data is similar but provides as added value the authentication of E1 PVT. Time synchronization is achieved acquiring the E6 encrypted code that varies continuously, therefore an unambiguous time reference can be determined. The generation of the CS encrypted codes requires the access to the CS keys that could be available in the ground stations of satellite operators.
The paper will include also the design tradeoffs in terms of batch duration, positioning duty cycle, sampling frequency and number of bits depending on the mission needs and available resources.
Snapshot acquisition capability can provide a huge added value in particular for Position and Time availability of GEO missions and interplanetary mission, that typically have available communication bandwidth for the transmission of the signal batches.
The ENSPACE receiver development is capturing the need of security in space and developing an innovative software receiver. The aim is to become a reference product for low cost, secure and flexible space navigation, positioning and time, and to enable existing high-grade space applications to enhance GNSS security.

TDS-1 - Towards an Operational GNSS Reflectometry Service For Ocean Winds

Dr. Martin Unwin[1], Dr Phil Jales[1], Dr Christine Gommenginger[2], Giuseppe Foti[2], Josep Rosello[3]
[1]SSTL, Guildford, United Kingdom, [2]NOC, Southampton, United Kingdom, [3]ESA Estec, Noorwijk, The Netherlands

The SGR-ReSI instrument flying on UK TechDemoSat-1 since 2014, and exploitation of the instrument has been supported by ESA. It has demonstrated that GNSS signals can be used as a bistatic radar source for sensing the Earth's surface from space, and has also been used as the payload on the NASA CYGNSS small satellite hurricane sensing constellation. TDS-1 has been given a life extension, and the SGR-ReSI is now collecting data at a higher rate than before. Ocean wind measurements from TDS-1 are being released from the web-site MERRByS with a short delay to demonstrate the feasibility of the use of GNSS reflectometry for an operational wind and wave sensing service. Recent results from an ESA-sponsored study called TGSCATT have shown an agreement with the best weather knowledge of better than 2 m/s for lower wind speeds.

Furthermore, data from TDS-1 has allowed the development of new potential GNSS-Reflectometry applications for ice, snow, soil moisture and flood sensing, amongst others. Preliminary work is being undertaken into a constellation of small satellites called ORORO with an instrument that can collect both reflectometry and radio-occultation measurements simultaneously to provide new measurements for numerical weather prediction assimilation purposes with unprecedented spatial and temporal coverage of the ocean surface.

This presentation will show the latest results from TDS-1, and look to the potential for a future small satellite constellation dedicated to an operational service.

A Software-Defined Spaceborne GNSS Receiver

Dr. Carles Fernandez-Prades[1], Dr Javier Arribas[1], Mr. Marc Majoral[1], Mr. Antonio Ramos[1], Dr. Jordi Vilà-Valls[1], Dr. Pietro Giordano[2]
[1]CTTC, Castelldefels, Spain, [2]ESA/ESTEC, Noordwijk, The Netherlands

This paper reports the design, proof-of-concept implementation and preliminary performance assessment of a low-cost, software-defined spaceborne GNSS receiver. The presented approach takes advantage of the flexibility of software-defined radio technology and the forthcoming availability of radiation-hardened, space-certified Systems-on-Module to implement a fully customizable receiver with the capability to process GNSS signals in real-time and to deliver GNSS products in standard formats. The core GNSS engine is based on a free and open source software implementation of a multi-band, multi-system GNSS receiver released under the General Public License v3.0 and available in a public source code repository.

Multiple Jammer Localization and Characterization Based on Time-Frequency Analysis

Dr. Giacomo Pojani[1], Yazan Abdoush[2], Dr. Marco Bartolucci[3], Jose Antonio Garcia-Molina[4], Prof. Giovanni E. Corazza[2]
[1]u-blox, Sgonico, Italy, [2]University of Bologna, Bologna, Italy, [3]University of Barcelona (UAB), Barcelona, Spain, [4]European Space Agency (ESA), Noordwijk, The Netherlands

Interference, Spoofing and Authentication - continued, December 7, 2018, 11:20 - 13:00

Jammers commercialized to interfere with satellite navigation systems usually modulate narrowband waveforms over wide bandwidths. Time-frequency transforms are by definition mathematical tools meant for the analysis of waveforms of this kind. This paper describes a framework for estimating the modulation characteristics of multiple jammers and therewith the respective locations, by means of a novel use of the S-transform. The performance of the characterization is evaluated through extensive numerical simulations with two jammers. As shown for a case study in a square area of side of one kilometre, when the jamming waveforms are well characterized, the locations of the respective transmitters can be estimated by trilateration with accuracies below ten meters.

Modelling the Noise of GNSS Signals under Jamming Conditions

Dr. Christoph Lass[1], Dr. Ralf Ziebold[1]
[1]German Aerospace Center (dlr), Neustrelitz, Germany

Introduction

Global Navigation Satellite Systems (GNSS) are increasingly used as the main source for Positioning, Navigation and Timing (PNT) information for maritime and inland water applications. With the rising availability of cheap jamming devices such as Personal Privacy Devices (PPD), there is a real threat to GNSS based navigation. Therefore, it becomes of upmost importance to estimate the accuracy of the satellite signals, even under disturbance.
The presented work examines the influence of jamming on the noise of the signals and if it can be modelled. Laboratory experiments showed that it is possible to accurately estimate the noise in jamming conditions which is even consistent with undisturbed measurements. Hence, the derived model describes the noise of GNSS signals in scenarios with and without jamming. It uses the elevation angles of the satellites and the Signal-to-Noise Ratio (SNR) of its signals to estimate the respective noise. The parameters of the model are calculated by fitting them to real measurement data of scenarios with different amount of jamming. The initial results show that this model estimates the noise of the signals better than classic weighting schemes using only the elevation angles or just the SNR.
This shows the potential of the model to be used in multi-sensor fusion scheme as a weighting scheme in an iterative least squares position solver or as a variance estimator in a Kalman filter setup in demanding environments.

Measurement Setup

Reliable navigation of maritime vessels is based on accurate positioning which is mainly obtained using GNSS. However, those signals can be easily disturbed using jamming or spoofing which was verified in several measurement campaigns. The question arises if it is still possible to estimate the accuracy of the signals in these difficult environments.

A measurement campaign using the civilian maritime jamming testbed in the Baltic Sea, established by the DLR in cooperation with the German Federal Network Agency, yielded the surprising result that the noise of the jammed signals was actually smaller than the undisturbed ones having the same SNR due to a higher elevation angle. This evoked the need for a more thorough investigation of the noise which cannot be estimated only by the SNR. Therefore, additional experiments in the laboratory were conducted to develop a refined model for the noise of GNSS signals under jamming conditions.
The experiment setup consisted of one antenna on the roof of the Institute of Communications and Navigation in Neustrelitz, Germany, connected to two receivers. For one of the receivers the incoming signal was disturbed using a standard jammer connected to several fixed as well as variable damping elements which allowed for adjusting the amount of disturbance.
Each of the four experiments lasted 48 hours with a data rate of 2 Hz. The jamming caused a decrease in the SNR of about 9 dB, 10 dB, 16 dB and 19 dB with respect to the undisturbed signals. This way even data for high elevation angles but low SNR could be obtained which hardly occurs in normal measurement environments.
The noise of the GPS signals is then determined using a linear combination of code and phase measurements in both L1 and L2 frequency. The carrier ambiguity is removed by applying a cycle slip detector. Afterwards, the variance of the linear combination is computed for different pairs of intervals of SNR and elevation angles.

Preliminary analysis of the results

The first analysis of the measurements of the GNSS signals indicates that the noise of the L1 code measurements increases with smaller elevation angle and smaller SNR in a monotonous manner. Furthermore the samples of the different scenarios are consistent with each other and show that the variance can be described in a continuous way. Therefore, it should be possible to estimate the noise with and without jamming in a single formula.
In the following, three models are compared whose parameters are determined using a weighted least squares ansatz with the goal of providing the best fit with regards to the samples. Two classic models – SNR based weighting described by an exponential term and elevation angle based weighting using a sine term were regarded. The third model combines both weighting schemes in an additive way as both inputs are assumed to be uncorrelated which is supported by the initial analysis of the measurements. Hence, the noises, i.e. the variances, can be added.
The evaluation of the computation yielded the result that the additive model has the best fit in both L_1- and L_2-norm. The classic weighting schemes using exclusively the elevation angles or the SNR have a worse fit than the model using both of them as input values, especially with respect to the quadratic error. Furthermore, the SNR based model is better in describing the noise of the GNSS signal than the classic elevation based model.

Performance Analysis of FLL Schemes to Track Swept Jammers in an Adaptive Notch Filter

Ms Micaela Troglia Gamba[1], Ms Emanuela Falletti[1]
[1]*Istituto Superiore Mario Boella (ISMB), Turin, Italy*

In the field of Global Navigation Satellite System (GNSS), jamming signals are more than ever a real threat, demanding for an increasing need of countermeasures. Among several proposed detection and mitigation methods developed for specific types of interference, the Adaptive Notch Filter (ANF) is still an attractive solution to mitigate very narrowband interference signals, for its ease of implementation, low computational cost and reduced activation time. ANFs have been widely exploited in literature, with many

variations: albeit well known to be particularly effective for Continuous Wave (CW) interferes, an early proof of their suitability also against certain types of GNSS jammers has been shown.
In this paper, two recently proposed Frequency Lock Loop (FLL) models to implement the adaptive capability of the ANF are considered: the standard FLL and the FLL with exponential filtering. While both have already been analyzed in the presence of CW interfering signals, with constant carrier frequency, here an evaluation in case of fast sweeping central frequency is conducted, targeting the features of some of the most common jammers detected in the GPS L1/Galileo E1 band. A comparison in terms of tracking capability and noise performance is presented. While the standard FLL shows to be able to successfully track and mitigates jamming signals, the exponential filtering FLL proves it is not up to, suffering particularly from frequency discontinuities, which commonly characterize such kind of interferers.

A Dual Antenna GNSS Spoofing Detector Based on the Dispersion of Double Difference Measurements

Dr. Emanuela Falletti[Istituto Superiore Mario Boella (ISMB) & LINKS Foundation], Mr. Van Hien Nguyen[1]
[1]*Hanoi University Of Science And Technology, Hanoi, Viet Nam*

This paper presents the development of a dual antenna GNSS spoofing detection technique, based on the analysis of the dispersion of the double differences of carrier phase measurements, produced by two GNSS receivers. No synchronization of the receiver is needed for the algorithm to properly work. The algorithm is derived from the idea of the Sum of Squares detector, recently presented as a simple and efficient way to detect a common angle of arrival for all the GNSS signals arriving to a pair of antennas. The presence of such a common angle is recognized as an undiscussed indication of non authentic GNSS signals. Nonetheless, some limitations can be identified in the SoS algorithm, first of all the assumption that all the signals arrive from the same source; situations are possible in which the receiver tracks only a subset of counterfeit signals, out of the whole signal ensemble. The idea presented in this paper intends to overcome such limitations, properly modifying the SoS detection metric to identify subsets of counterfeit signals. The analysis is supported by several simulation tests, in both nominal and spoofed signal conditions, to prove the effectiveness of the proposed method.

IACT project: Impact Assessment of Cybersecurity Threats, from Theory to Realistic Flight Simulations

Dr. Luca Canzian[1], Dr Giovanni Gamba[1], Dr Oscar Pozzobon[1], Robert Geister[2], Jan-Philipp Buch[2], Emmanuel Isambert[3], Cyrille Rosay[3]
[1]*Qascom, Bassano Del Grappa, Italy,* [2]*DLR, Braunschweig , Germany,* [3]*EASA , Cologne, Germany*

Cybersecurity threats are of prime importance in the aviation context, given the increasing number of exploitable vulnerabilities and the improvement of attacker capabilities. There is lack of knowledge on the impact of security threats on Commercial Transport Aircraft (CAT) and Air Traffic Management (ATM) procedures. This information is of upmost importance for practical applicability of security certification.
This paper focuses on:

- Identify and prioritize threats to critical aircraft systems during different flight phases, with particular emphasis to GNSS spoofing;
- Perform flight simulation exercises with actual CAT pilots using the DLR AVES simulator, purposely enhanced to generate the above-mentioned threats;
- Analyze the results of the simulations and the feedback of the pilots, proposing possible mitigation strategies at the crew level.

More specifically, the paper describes different FMS and GNSS based threats having an impact on the aircraft navigation capabilities. Concerning the GNSS based threats, the activity focuses on spoofing events.

Indeed, for safety reasons, the aircraft navigation systems and procedures are already designed to cope with the absence of GNSS availability, which can be caused for instance by GNSS jamming, receiver malfunctions, or simply temporarily GNSS coverage issues. Instead, no security system or procedure has been specifically designed to cope with GNSS spoofing events. An assessment of the likelihood associated to GNSS spoofing threats is provided, considering both different spoofing signal dynamics (synchronous attack, asynchronous attack, or jam-then-spoof) and different attacker positions (insider spoofer or outsider spoofer).

Then the paper describes the architecture of the AVES simulator, the primary tool of the DLR Institute of Flight Systems for flight test preparation and research in flight-system, pilot training and simulation technologies. This simulator has been enhanced in order to emulate the GNSS spoofing threats. In particular, a GNSS threat simulator module has been developed and interfaced with the AVES simulator. This module receives in inputs the actual aircraft dynamic state (e.g., position, attitude, velocity), it generates GNSS position estimates including the application of error models and possibly of spoofing events, it generates inertial measurements including the application of error models, and finally it also emulates the fusion of GNSS and inertial measurements through a Kalman filter. The results are sent back to the AVES simulator and are used by the emulated aircraft navigation system for navigation purposes, for instance to show in a map the deviation between the estimated aircraft position and the flight plan.

Finally, the paper describes the seven simulation flights that were performed with eight CAT pilots and one ATCO, exploiting the AVES simulator and the GNSS threat simulator module. The pilots and the ATCO were invited to the trials under false pretenses, in order to obtain unbiased results. Cyberattacks on FMS and GNSS have been emulated at different flight phases. No involved pilot associated the experienced effects to cyberattacks. Indeed, at the end of the simulation trials, the pilots were very interested in the results and their awareness in cybersecurity was increased.

Most of the considered cyberattacks were not detected by the crew at the time of the attack. Mis-detected attacks always led to an increase workload of the crew and of the ATCO. Among the emulated attacks, the two attacks that were considered most critical are the “Hacked database” attack and the “GNSS spoofing attack”. The invaluable feedback from the CAT Pilots and the ATCO has been exploited to evaluate the criticalities of the considered cyberattacks and to propose mitigations procedures to be implemented in response to the attacks.

Even though much more simulation exercises should be performed to derive statistically significant results and different scenarios should be evaluated to assess the impact of different types of route and attack configurations, the limited number of tests performed within the activity already show the importance for the aircraft industry to investigate the impact of cyberattacks on different aircraft systems, in particular on GNSS receivers. Putting the pilots “in the loop”, analyzing their actions during simulated attacks and collecting their feedback afterwards, appears to be the correct path to pursue this investigation.

This paper is based on the outcomes of the IACT activity, an EASA activity whose consortium is made by the following partners: Qascom (the leading the project), DLR, ENAV, and CAT pilots.

Poster Session

Wintergarden North, December 7, 2018, 11:20 - 13:00

P1. TripleT: Transnational Time Transfer for GNSS Timing Infrastructure

Bernd Burger[1], Bastiaan Lagaune, Erick Dierikx[2], Yan Xie[2], Marijn van Veghel[2], Jos Weber[1], Pierre Waller[3]
[1]CGI, , , [2]VSL, , , [3]ESA, ,

Guaranteeing an accurate GNSS positioning is only possible due to precise timing. The European satellite positioning system Galileo ground infrastructure operates with two Precise Time Facility's (PTF) (Fucino, Italy and Oberpfaffenhofen, Germany) which serve primarily to generate, maintain and distribute Galileo System Time (GST). Each PTF's master clock is steered to each other as well to the UTC by comparing the PTF's to selected European National Metrological Institutes (NMI). These synchronisations guarantee an accurate and robust synchronization between the PTFs and the traceability to UTC. Currently, two methods are used which cover the required accuracy and availability: Two-Way Satellite Time and Frequency Transfer (TWSTFT) and GNSS Common-View (CV). Both satellite methods are ideal for long distance time transfers and achieve Time Transfer uncertainties of a few nanoseconds. Over recent years, significant progress has been achieved in optical fibre time and frequency transfer methods (OFTFT). These have major advantages over satellite-based transfer methods in terms of stability, authenticity and accuracy. Furthermore, the relatively weak radio signals broadcasted from the satellites in open air are vulnerable to interference threats like (unintentional or intentional) jamming and spoofing. During NAVITEC 2018, the intermediate results and progress of ESA's EGEP activity "Trans-national Time and frequency links over optical fibre for GNSS timing infrastructure" will be presented. The project is carried out by VSL, the national NMI of the Netherlands and CGI Nederland, an international IT services integrator. The objective of the project is to define, implement, deploy and validate a time and frequency transfer Test Bed over optical fibre crossing at least one national border over a total duration of at least six months of operation. Connecting two nodes on a trans-national level poses significantly more operational challenges compared to connecting two sites on a national scale only, such as dealing with multiple international fibre providers in order to have a single operational line with the same performance. Selected end-nodes are the radio navigation laboratory at ESA's ESTEC site in Noordwijk, the Netherlands and SMD, the national NMI of Belgium spanning 270 km over two different countries. Each end node contains an accurate timescale realization based on atomic clocks (providing a 1 PPS and 10 MHz reference signal).

The OFTFT technique implemented between the two sites has been chosen to be White Rabbit (WR) Precise Time Protocol (PTP). Other candidate techniques considered were the ELSTAB and the SATRE technique. The most recent WR implementations show a performance similar to ELSTAB (Electronically Stabilised) [1, 2]and SATRE (Satellite Time and Ranging Equipment) [3, 4], but at significantly lower hardware costs. For the experiments in the project, a dedicated dark fibre was made available by a commercial fibre provider. This means that in this fibre there are no other signals than what is required for this project. Dark fibre is not strictly required for the WR technique, however, the implementation of the technique in a bi-directional mannerthrough a single fibre is uncommon in optical fibre data networks. Therefore, fibre providers are reluctant to lease just a few wavelength channels for the WR experiment while operating regular data traffic in other wavelengths channels on the same fibre. Within this fibre, two Dense Wavelength Division Multiplexing (DWDM) channels are used for the OFTFT and two Coarse Wavelength Division Multiplexing (CWDM) channels are used for equipment status monitoring. To automatically collect data and monitor the equipment in the test bed, including the amplifiers and end-node equipment, a dedicated dashboard has been created. This cloud-based dashboard produces daily status (graphical)reports and performance characteristics to evaluate the behaviour of the link in a near-real time manner.

The performance of the WR method is evaluated in terms of accuracy, stability and precision. The time transfer stability is expected to reach 100 ps at 1 s averaging time and less than 10 ps for averaging times (?) above 1000 s. The frequency stability, expressed in terms of Allan deviation is expected to be less than 10-11/?. To validate the long-term operation of the WR-link, the results are compared against the results of the

independent GPS-based timescale comparison. The analysis of the GPS data will be based on a daily common view comparison of CGGTTS (Common GNSS Generic Time Transfer Standard) data and on a monthly IPPP (Precise Point Positioning with integer ambiguity resolution) analysis from the Bureau International des Poids et Mesures (BIPM). In addition of monitoring the time transfer performance, the operational side will also be monitored. An important operational performance indicator is the mean time between failure (MTBF) of the optical fibre line and time transfer equipment.
The test bed operations are planned for November 2018 till April 2019 and the first results of the are expected by December 2018.
Acknowledgement: The work presented was performed under a programme of and funded by the European Space Agency, contract 4000120830/16/NL/AS.
Disclaimer: The work reported in this paper has been supported under a contract of the European Space Agency in the frame of the European GNSS Evolutions Programme. The views presented in the paper represent solely the opinion of the authors and should be considered as R&D results not necessarily impacting the present EGNOS and Galileo system design.

P2. GNSS Compare: A novel software framework for processing raw GNSS measurements on an Android smartphone

Mr. Mateusz Krainski[1], Eng. Sebastian Ciuban[1], Ms. Dominika Perz[1], Ms. Mareike Burba[1]
[1]*European Space Research and Technology Centre, Noordwijk, Netherlands*

GNSS Compare is an open source Android application, purpose of which is to ease the efforts of researchers that are interested in smartphone Global Navigation Satellite Systems (GNSS) raw observables processing. It is an easy to use and easy to extend Android-based framework for calculating the Position, Velocity, and Time (PVT) based on raw GNSS measurements.

With the release of Android API 24 in August 2016, Android application developers have gained access to the smartphone's raw measurements of GNSS signals. With that, every modern smartphone can be easily turned into a low-cost, mobile GNSS signal processing laboratory. Even further, in 2018 one of the major phone manufacturers has announced to start using dual-frequency GNSS receivers in their mass-market products. Other manufacturers and the Android system libraries are expected to follow this trend. It is also worth noting, that it is more and more common for Unmanned Aerial Vehicles (UAVs) and other robotic systems to be using Android as their Operating System (OS). GNSS Compare can be used as a development and test framework for GNSS related problems in those new emerging areas.

As it is well known in the GNSS scientific community, the GNSS raw observables (code-based pseudoranges, doppler measurements, carrier phase pseudoranges, etc.) have to be converted into pseudoranges. These pseudoranges are subject to multiple error sources (e.g., ionosphere, troposphere, relativistic effects, etc.) which have to be accounted for in the form of corrections. Finally, a PVT estimation algorithm is used to calculate receiver's position, velocity, and time. GNSS Compare defines easy to use programming interfaces for each of those steps. By the use of Object Oriented Programming (OOP) principles, such as polymorphism and inheritance, the detailed implementation of those steps can be changed, without the necessity to change the rest of the application's code. This allows the developer focus on his or her goals, instead of fixing unrelated system-level issues. GNSS Compare also implements an intuitive User Interface (UI), which allows the user to display the results of performed calculations in real time and change the chosen method for each of the aforementioned steps. One of the most valued features of the UI is a newly implemented ability to display internal state of the algorithms, in a form of plots or values (e.g., residual vectors from the Weighted Least Squares or innovation vectors from the Extended Kalman Filter), and change parameters by using sliders and switches, on application runtime.

The proposed application allows the user to display the results in real-time and compare multiple processing schemes. For example, the user can select that for scheme A they want to calculate the PVT based on GPS measurements, using their new algorithms, and for scheme B to use Galileo measurements and the same algorithm. Using GNSS Compare's User Interface, the user can quickly assess the quality of the calculated results. Using the data logging functions (estimated position, satellite signal strength, etc.), the user can log both processed results and raw measurements in the exactly same format as Google's GNSS Logger application for further post processing and detailed analysis. Therefore, with GNSS Compare the interested persons have full flexibility in terms of testing and analysis both in real-time and post-processing.

Since GNNS Compare is released as open source, it can be easily extended to include algorithms defined by its users. It must be added, that no knowledge about the Android system is required from the user to start working on the algorithms and define simple displays. Such knowledge is required only if the user wishes to make advanced changes to the UI. There is an online guide describing the details of implementation for GNSS experts, as well as the basics of OOP, the Android OS, and GNSS signal processing, for students interested in GNSS or software engineering.

The main purpose of this paper is to describe the software engineering principles implemented in the GNSS Compare framework. This description shall come in aid to the researchers or students interested in adaptation of GNSS Compare towards their needs (e.g., low-cost sensor fusion in Android smartphones, code framework porting on the microprocessor of an UAV, etc). Another paper proposed for the same conference is describing test results in the terms of PVT and raw GNSS measurement quality.

GNSS Compare has already received interest of multiple research institutions around Europe. Furthermore, it has been chosen as a winner of European Space Agency's internal challenge for smartphone application using the Galileo system. The competition was supported by the European Commission, European GNSS Agency (GSA), and Google.

Ongoing work focuses on extending the list of implemented algorithms, which are to serve as a starting point for everyone who would be willing to use GNSS Compare. Efforts also are to be taken to simplify the framework. Our goal is to provide this as a tool for any GNSS researcher to use, without the necessity to learn about the Android system or details of OOP. We are also increasing the robustness of the application, increasing code quality, and automated test coverage.

P3. Development of a GNSS Monitoring Network within the Mediterranean Area for Air Navigation Applications (BLUEGNSS Project)

Dr. Fabio Principe[1], Eng. Giuseppe Di Bitonto[1], Mr Andrea Tomei[1], Dr Vincenzo Pellegrini[1], Mr Giovanni Morelli[1]

[1]*IDS, Ingegneria Dei Sistemi S.p.A., Pisa, Italy*

1. Brief Introduction to BLUEGNSS Project

The declared intention of BLUEGNSS project is the promotion of European GNSS (E-GNSS) adoption for air navigation operations within the BLUE-MED FAB. Its consortium is made up of four partners, i.e. ENAV (the Italian ANSP and consortium leader), DCAC (Cyprus ANSP), HCAA (Greek ANSP), MATS (Maltese ANSP), and IDS (as industrial partner), and the entire activity has been funded by the European GNSS Agency, under Horizon-2020 research and innovation program: Grant Agreement nr. 687198.
Purpose of BLUEGNSS is therefore the development of specific E-GNSS aeronautical applications and services that are in accordance with ICAO recommendations [1]-[2]. A summary of the key tasks is reported below.

1) Design of RNP approaches with all 3 minima (LPV, LNAV/VNAV, LNAV) to be flown on pre-selected airports within States involved in the project.
2) The publication of previous procedures on national AIPs in order to permit their usage and to prove the consequent benefits in terms of accessibility, safety, operational and economic aspects.
3) Training of procedure designers for development and review of RNP approach procedures.
4) Disseminate an E-GNSS culture among BLUE-MED partners.
5) Design and implement a regional E-GNSS monitoring network provided with data recording capabilities in order to support the validation of RNP approaches and introduce Galileo as future Air Navigation enabler.
The 5th point is the main topic of the present abstract.

2. GNSS Monitoring Concept

ICAO SARPs [2] recommend that every State, approving GNSS-based flight procedure, should monitor and record relevant GNSS data in order to surveil the integrity of positioning signals and support any activity of accident/incident investigation. Furthermore, the use of long-term statistics based on the analysis of ad-hoc metrics (referred to as key performance indicators, KPIs) is essential to carry out periodic checks on GNSS performance within the service area of interest.
Therefore, the GNSS monitoring concept, as reported in ICAO GNSS Manual [3], covers the following use cases.
1) GNSS performance assessment: is a periodic off-line activity aiming at demonstrating the signal-in-space (SiS) conformance to ICAO Annex 10 relevant requirements, [2]-[3].
2) GNSS operational status monitoring: provides real-time information to technical staff and ATC services on the current operational status of GNSS services. RF interference (RFI) monitoring is typically part of this activity and aims at surveilling the GNSS spectrum and providing timely warnings in case of potentially critical RFIs.
3) GNSS data recording: is a legal recording service of GNSS data for post-incident/accident investigations.
The adoption of GNSS obliges ANSPs being aware of potential impacts that these new positioning systems may have on aeronautical services in terms of: positioning accuracy, service availability, integrity and continuity. Therefore, the GNSS monitoring network, developed in the framework of BLUEGNSS project, has been conceived to cope with the GNSS performance assessment activity, but also for interference analysis and data recording.

3. BLUEGNSS Monitoring Network: General Overview

The BLUEGNSS monitoring network has been designed to carry out the performance assessment of GPS, GPS/EGNOS and Galileo systems within the BLUE-MED area in compliance with the ICAO definition of the GNSS monitoring concept [3]. This network can be represented as a TCP/IP star network that connects all remote GNOME sentinels with a central monitoring facility (CMF). In this way all preprocessed data, provided by each sentinel, are sent to the CMF, which computes the required KPIs for:

• a global GNSS performance assessment within the BLUE-MED area;
• a local GNSS performance assessment of each monitoring site (that hosts a GNOME sentinel).

GNOME sentinels, [4], are very flexible GNSS monitoring stations that are addressed to assess the integrity of GNSS signals, monitor their performance and record measurements and data. Currently, the 4 GNOME sentinels belonging to the BLUEGNSS network are installed within the following airports.

• Kos airport, Greece;
• Luqa airport, Malta;
• Larnaka airport, Cyprus;
• Linate airport, Italy.

It is also worth noting that CMF is also fed by data coming from external, already existing GNSS networks. This architectural choice is motivated by the need to develop a flexible, scalable and easy configurable network that is able to integrate and process data coming from several monitoring stations even if they belong to independent networks. This approach allows increasing the number of monitoring points within the BLUE-MED FAB without the need of new additional infrastructures (so saving costs).

4.Achieved Targets

The following list contains a brief summary of the most important results achieved at the end of BLUEGNSS project.

- BLUEGNSS monitoring network is “up&running” H24.
- Reports are available (to registered users) on BLUE-MED website (http://www.bluemed.aero/).
- GNSS Italian reports were used as Performance Assessment Reference by Italian CAA (ENAC) to approve GPS-based procedures without any additional mitigation (ENAC letter of 16th March 2018, nr. ENAC-VDG-16/03/2018-0028476-P).
- Interference events detected by Kos and Larnaka GNOME sentinels were confirmed by Pilot reports on GPS loss in Nicosia FIR during some days of March and April 2018 (see the following links:

European Parliament:
http://www.europarl.europa.eu/sides/getDoc.do?type=WQ&reference=E-2018-001794&language=EN;

- European Commission answer:
http://www.europarl.europa.eu/sides/getAllAnswers.do?reference=E-2018-001794&language=EN;

- Cyprus information channel:
http://en.cyplive.com/ru/news/k-vostoku-ot-kipra-samolety-nachali-teryat-gps-signal.html.

5. Acronyms

AIP, Aeronautical Information Publication
ATC, Air Traffic Control
ANSP, Air Navigation Service Provider
CAA, Civil Aviation Authority
E-GNSS, European GNSS
FAB, Functional Airspace Block
GNOME, GNSS Operative Monitoring Equipment
GNSS, Global Navigation Satellite System
ICAO, International Civil Aviation Organization
KPI, Key Performance Indicator
LNAV, Lateral Navigation
LPV, Lateral Precision with Vertical Guidance Approach
RFI, Radio-Frequency Interference
RNP, Required Navigation Performance
SARPs, Standards And Recommended Practices
VNAV, Vertical Navigation

6. References

[1] ICAO DOC 9613, Performance-based navigation (PBN) manual, 4th edition, 2013.
[2] ICAO, Annex 10 Vol.1 Amend. 89 (13 Nov. 2014), Aeronautical telecommunications – Radio navigation aids, 6th Ed., 2006.
[3] ICAO Doc 9849, Global Navigation Satellite System (GNSS) manual, 3rd Ed., 2017.
[4] V. Pellegrini et al., “The GNSS Operative Monitoring Equipment (GNOME): an SDR-Based Solution for Integrity Assurance,” in Proc. NAVITEC 2012, ESTEC Noordwijk (The Netherlands), December 5-7, 2012.

P4. Assessment on Use of GNSS for HEO Spacecraft

Dr. Mariano Wis[1], Mr. Pedro Freire Da Silva[2], Mr. Enrique Santiago[1], Mr. Ricardo Prata[2], Mr. Rui Nunes[2], Mr. Antonio Fernandez[1], Mr. Jose Antonio Garcia[3]

[1]Elecnor Deimos, Tres Cantos, Spain, [2]Deimos Engenharia, Lisbon, Portugal, [3]ESA/ESTEC, Noordwijk, Netherland

It is not new the technical compromise that represents the capability of proper process of GNSS signal in orbital conditions. This compromise is much more challenging beyond the GNSS orbit levels. The relative dynamics between the receiver and the SVs may reach accelerations up to 15 m/s2 in perigee, and the signal power can easily be below 15-20 dB-Hz and poor satellite geometries at apogee for a HEO orbit S/C. This issue has been analyzed in project HEOP for orbital missions aimed to HEO orbits. In this project (leaded by Elecnor Deimos, with the assistance of RUAG and the coordination of ESA-ESTEC) the problem issued above has been analyzed with two different approaches. The first part consisted in the development of a Space Service Simulation (SSV) tool [1] that has been used for the analysis of the problem from the system point of view. The system performance has been analyzed in a series of altitude levels beyond the geostationary orbit (GSO). The second part consisted on the development of a fully realistic receiver simulator (at bit true level) that in the frame of the project is known as Digital processing test bench (DSPTB). All the elements that compose the receiver (acquisition algorithms, tracking loops, measurements generators and navigation filters) have been implemented in order to evaluate the performance of observables and PVT solution at receiver level of this kind of orbital mission. For the development of the receiver, two models have been followed. A first model that assumes an AGGA4 chipset implements the receiver [2] and a second model that assumes an advanced DSP chipset is available and allows the implementation of a Double-Block Zero Padded Transition insensitive (DBZPTI) algorithm for the acquisition phase [3].

In [4] and [5], preliminary results of this project were already presented. Some results of the SSV analysis tool were detailed. These results showed the system performance for L1, E1, L5 and E5 bands using a 3D EIRP patterns for assessing the transmitted signal power. According to these results, it was claimed that a minimum of 6 satellites could be acquired at an orbital level of 71.000 km and 15 dB-Hz of signal power. Some preliminary results of acquisition with DBZPTI and its advantages over conventional acquisition algorithm under some conditions were also depicted.

A summary of the tools developed in the project and an overview of the final results obtained with them are depicted in this paper. These results focus on the simulations obtained following the PROBA-3 mission [6] as a model, assuming that the satellite was always following a pointing sun attitude law. These results are structured around the three altitude levels that were considered of interest in the project (perigee, GNSS altitude level and apogee). As a summary, it is shown for example that the differences between using 2D and 3D EIRP patterns are only significative at altitudes beyond 8000 km. Under those altitude levels, it is not worthwhile to use 3D pattern because the processing is also much slower. For the DSPTB, it is shown how the orbital filter estimated Doppler feedback is capable of helping keep the signal tracking. It is also shown that at GNSS altitude level, the PVT performance is below 3m both for L1 C/A and E1C signals. Results based on semi-analytical approach simulations replicating the DSPTB loop algorithms are also presented for the apogee phase given that tracking with DSPTB at this stage was not feasible. Despite of that, it is also shown that it is feasible precisions around 30m for L1 C/A signal and 6m for Galileo OS signal.

Finally, it is presented a follow-up activity based on this project AGGA4 EVKs and that demonstrates the practical feasibility of the techniques developed in the frame of HEOP. The final product of AGGA4 EVKS is an evaluation kit for the AGGA4 chipset that is distributed by Cobham-Gaisler.

References

[1] - F.H. Bauer, M.C. Moreau, M.E. Dahle-Melsaether, W.P. Petrofski, B.J. Stanton, et al., “The GPS Space Service Volume”, ION GNSS 2006, September 2006, Fort Worth, Texas, USA.

[2] - J. Roselló, P. Silvestrin, J. Heim, "AGGA-4: Core Device for GNSS Space Receivers of This Decade", NAVITEC 2010, December 2010, ESTEC, Noordwijk, The Netherlands
[3] - Myriam Foucras, Olivier Julien, Christophe Macabiau, Bertrand Ekambi, "A novel computationally efficient Galileo E1 OS acquisition method for GNSS software receiver"
[4] – Wis, M. Vecchione, G., Silva, J., Silva, P., Garcia-Molina, J.A., "Design and Analysis of High Sensitivity Algorithms for HEO orbit GNSS Receivers". Proceedings of ION GNSS 2017, September of 2017, Portland, OR
[5] – Wis, M., Fernandez, A., Silva, P., Garcia-Molina, J.A., " Design and Analysis of High Sensitivity GNSS processing Algorithms For Space Applications", Proceedings of 6th International Colloquium on Scientific and Fundamental Aspects of the Galileo Programme. October of 2017, Valencia, SP.
[6] - ESA's Proba-3 mission – Fact Sheet (accessed on 2015/08/13): http://esamultimedia.esa.int/docs/Proba/Proba-3_fact-sheet_final.pdf

P5. An Automated Floor Vehicle for Algorithm- and Sensor-Testing

Mr. Benjamin Tennstedt[1], Mr. Steffen Schön[1]
[1]*Institut für Erdmessung, Hanover, Germany*

To test new sensors and innovative filter algorithms and models for vehicle navigation it is quite common to use a multisensor platform, equipped with an array of GNSS antennas, one or more inertial measurement units, as well as other sensors like LiDaR or stereo cameras, on the roof of a car for instants, and undergo different test scenarios with it. Mostly this is very time-consuming and several scientists have to be involved in the process. To reduce the time and resources needed for the preparation of those real tests, and in the same time improve the repeatability of the test scenarios, a reliable system on a smaller scale is developed at the Institut für Erdmessung (IfE). In modern logistics such a system can be found in shape of small autonomous transport units. A sub-group of those vehicles, equipped with an optical line-following system and a propulsion unit able to turn around its height-axis, allows the use of motion models comparable to those of real cars with front wheel drives. The system makes it possible to define several reference trajectories and can be used as a carrier platform for a large number of sensor systems.

In this publication the current state of the development will be presented. This includes the modelling of a single vehicle, by using control input like linear and angular velocity of the propulsion unit via a user interface. Afterwards the model will be verified by using a tightly coupled filter solution with differential GNSS on the one hand, and on the other hand by automatic target tracking with a total station. Additionally, with the help of the sensors mentioned before, it will be stated how fast and precise the vehicle state reaches the control input values given by the user interface, and what class of repeatability of the trajectories given by the optical reference line on the ground can be achieved. At this rate, it can be evaluated beforehand which kind of test scenarios the system is suitable for.

First applications of the vehicle will be presented. It has already proven suitable as remote controlled mobile platform for the task of recording data of inertial sensors and GNSS-receivers. A few examples are the analyzation of the coverage of GNSS-signals by urban canyons, including the creation of elevation masks, examination of multipath-effects, or the effectiveness of filter algorithms when a sudden change in visibility of GNSS-satellites occurs (e.g. good visibility vs. no visibility when driving from an outdoor area into a building). Furthermore, with the help of mats with tape attached to it as a tracking line for the optical sensor, solid and reproducible reference trajectories can be created while still keeping a high level of flexibility.