The joint ESA/NASA Galileo/GPS Receiver on-board the ISS – The GARISS Project

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BIOGRAPHIES

Werner Enderle is the Head of the Navigation Support Office at ESA's European Space Operations Center (ESOC) in Darmstadt, Germany. Previously, he worked at the European GNSS Authority (GSA) as the Head of System Evolutions for Galileo and EGNOS and he also worked for the European Commission in the Galileo Unit. For over 25 years, he has worked on activities related to the use of GPS/GNSS for space applications. He holds a master and doctoral degree in aerospace engineering from the Technical University of Berlin, Germany.

Erik Schönemann has joint the Navigation Support Office at ESA/ESOC in 2006 as a contractor and became permanent staff in 2015. He is involved in Galileo studies since the launch of the first Galileo validation satellite GIOVE-A and is the technical manager of the Galileo Reference Service Provider (GRSP). He is involved in the coordination of ESA's reference frame activities and contribution to International Services like ILRS, IGS and UTC. Erik Schönemann holds a master and a doctoral degree in Geodesy from the Technical University of Darmstadt, Germany.

Francesco Gini is a Navigation Engineer at the Navigation Support Office (OPS-GN) at the European Space Operations Center (ESOC) of ESA. He is responsible for the Space Service Volume (SSV) and Precise Orbit Determination (POD) related activities. He received his PhD in Astronautics and Satellite Sciences at the University of Padova, Italy in 2014 and since then he has been working in ESOC.

Michiel Otten is a Navigation Engineer at the Navigation Support Office (OPS-GN) at the European Space Operations Center (ESOC) of ESA. He is responsible for the LEO POD activities and the International Doris Service (IDS) Analysis Centre activities. He received his Master degree in Aerospace Engineering at the Delft University of Technology in 2001 and since then he has been working at ESOC.

Pietro Giordano holds a Master in Telecommunication Engineering from University of Padua (Italy) and a Second Level specializing Master in Navigation and Related Application from University of Torino (Italy). He worked in Thales Alenia Space (Italy) as GNSS receiver Engineer before joining ESA in 2009, where he worked first as GNSS receiver support to Galileo project and later as GNSS Security Engineer in the Galileo project. Currently he is in charge of multiple activities related with space GNSS receivers and R&D in space GNSS receiver technology such as Technical Officer for POD receiver in Sentinel, Proba3 missions, development of GNSS space borne receivers for real time on-board POD in CubeSats, development of LEO PNT payloads, support for definition of new AGGA chip and development of GNSS space borne receivers for lunar missions.

James J. Miller is Deputy Director of the Policy & Strategic Communications Division with the Space Communications and Navigation (SCaN) Program at NASA. He is responsible for advising Sr. NASA management on domestic U.S. and international PNT/GNSS policy and technology issues. Prior to his NASA assignment, Jim was the Deputy Director of the Office of Navigation and Spectrum Policy at the U.S. Department of Transportation. Prior to working for the Federal government, Jim was a Program Manager for United Airlines for nearly a decade. He served as an academic researcher at the Queensland University of Technology, Space Center for Satellite Navigation, in Brisbane, Australia, and is a commercial airplane pilot with degrees in Aviation Flight, Aviation Management, Master of Public Administration degree from Southern Illinois University and Master of International Policy and Practice (MIPP) from The George Washington University.

O. Scott Sands has been a Communications System Analyst at NASA, Glenn Research Center since 2000 where he develops space navigation, sensing and communications systems. Scott currently leads Position Navigation and Timing Policy related activities at GRC in support of the NASA's Space Communications and Navigation Office.

David Chelmins is a project management engineer at the NASA Glenn Research Center in Cleveland, Ohio. He manages space communication and navigation technology projects. Dave managed joint ESA/NASA development of Galileo and GPS software navigation receiver which was successfully demonstrated using NASA's SCAN testbed on the International Space Station in 2018.

Oscar Pozzobon Oscar is the founder and technical director of Qascom and is coordinating different activities in the domain of interference, signal authentication and advanced navigation with the European Space Agency (ESA), the European GNSS Agency (GSA), the European Commission (EC) and the National Aeronautics and Space Administration (NASA).
received a degree in information technology engineering from the University of Padova, Italy, and a master degree from the University of Queensland, Australia, in telecommunication engineering. He received his PhD in Aerospace, aeronautical and astronautical/space engineering from the University of Padova, Italy.

ABSTRACT

ESA and NASA conducted a joint Galileo/GPS space receiver experiment on-board the International Space Station (ISS). The objectives (Enderle 2017) of the joint project were to demonstrate the robustness of a combined Galileo/GPS waveform uploaded to NASA hardware already operating in the challenging space environment - the SCaN (Space Communications and Navigation) software defined radio (SDR) testbed (FPGA) - on-board the ISS. These activities data included the analysis of the Galileo/GPS signal and on-board Position/Velocity/Time (PVT) performance, processing of the Galileo/GPS raw data (code- and carrier phase) for Precise Orbit Determination (POD), and validate the added value of a space-borne dual GNSS receiver compared to a single-system GNSS receiver operating under the same conditions.

This paper will provide a general overview of the Galileo/GPS experiment – called GARISS - on-board the ISS, describe design, test and validation and also the operations of the experiment. Further, the various analysis conducted in the context of this joint project and also the results obtained will be presented with a focus on the (Precise) Orbit Determination results.

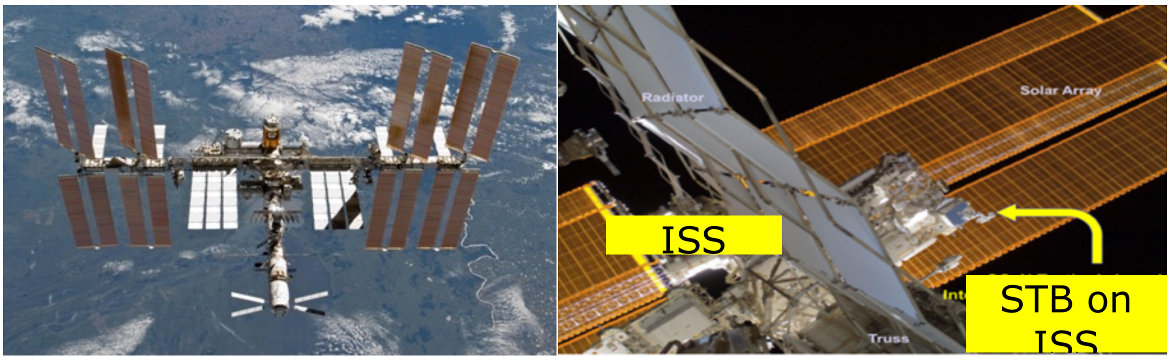


Figure 1: Galileo/GPS Receiver on-board the ISS

INTRODUCTION

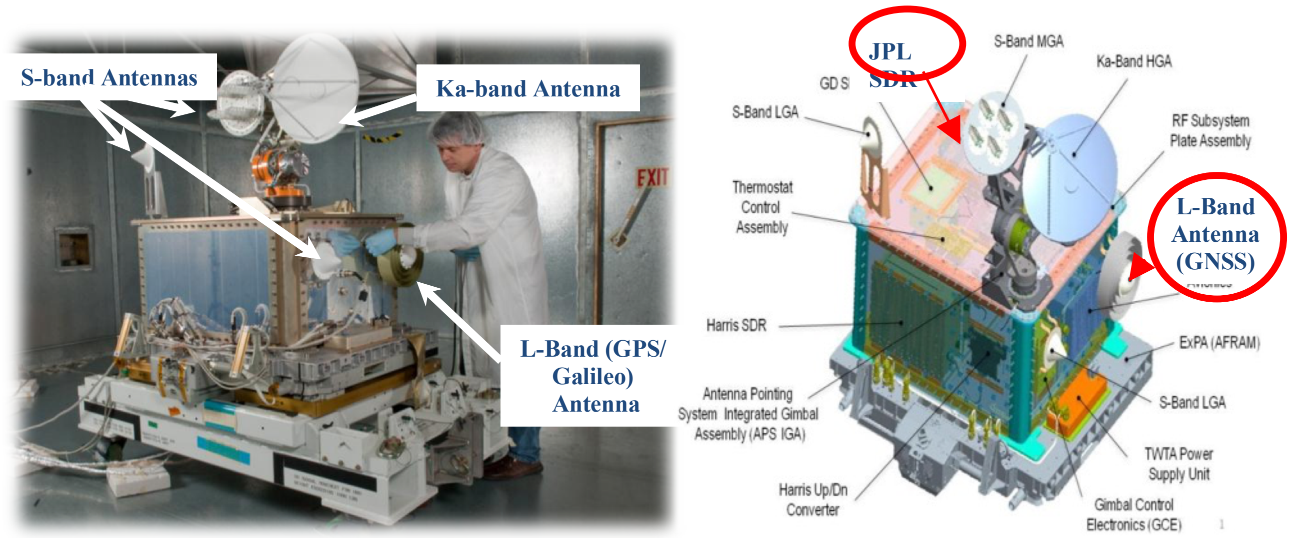
This ESA/NASA collaboration was initiated in 2014 and a Technical Understanding was signed in 2016. From ESA's site, ESOC's Navigation Support Office (NavSO) and ESTEC Experts for Radio Navigation Systems and Techniques (TEC-ESN) are involved in this project. The overall project management from ESA's side and also the POD aspects were under the responsibility of ESOC's NavSO, whereas ESTEC's Technical Directorate was in charge of the Galileo waveform development and implementation of the SW on the FPGA in cooperation with NASA. This activity was done with technical support under a specific contract from the European industry partner - Qascom. From NASA's side, the project was sponsored by the Space Communications and Navigation (SCaN) Program within the Human Exploration and Operations Mission Directorate (HEOMD) at NASA Headquarters in Washington D.C. Together with Qascom waveform integration and testing was performed at the NASA Glenn Research Center in Cleveland Ohio.

Operations of this experiment have been started in the first half of 2018 and it is foreseen that they will be continued until 2 quarter of 2019. In the context of this joint experiment, the first ever successful position fix in space, based on a combined Galileo/GPS E5a, L5 signal could be reported.

Figure 2: GARISS Logo

DEVELOPMENT OF THE GARISS WAVEFORM FOR THE SCAN TEST BED

The SCaN Test Bed (STB) was installed on the Space Station in July of 2012 (Reinhart, 2014). As shown in Figure 3**Error! Reference source not found.** (a) and (b) the STB includes three separate spaceflight software defined radios from JPL, Harris and General Dynamics. Together the three radios provide the capacity to communicate in the L-band, S-Band and Ka-band and each radio supports the Space Telecommunications Radio System (STRS) standard so as to promote standardization of SDR operating environments and code reuse.



(a) (b)

Figure 3: SCaN testbed (a) during environmental testing (b) 3D model

The JPL radio is the only one on STB that provided L-band capability and was, therefore, the choice for the Galileo/GPS receiver. The set of software and firmware and support scripts for the receiver to function on the radio is, collectively, referred to as the Galileo/GPS Receiver on the Space Station or GARISS waveform. This waveform is being inserted into the STRS waveform repository and will be available to Government users with appropriate access.

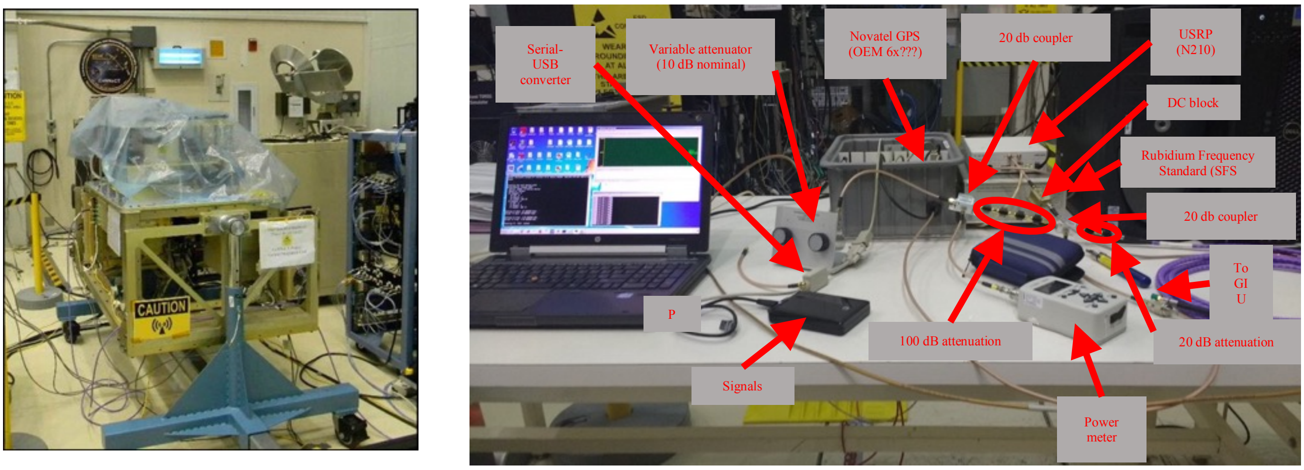
About five years after the STB was installed on Space Station, development of the GARISS waveform started. This ESA/NASA effort brought together products and efforts from several labs to produce the first-know on-orbit combined Galileo/GPS L5/E5a receiver using a build-test-analyze—and building again approach.

WAVEFORM DEVELOPMENT AND TESTING ON THE GROUND INTEGRATION UNIT

Contributions to the effort were made by NASA/JPL, the ESA contractor Qascom and NASA/Glenn Research Center (GRC). During the original STB mission project NASA/JPL provided and include the JPL SDR including the L-band module and bus logic as well as the STRS compliant Operating Environment. Through its contractor, Qascom, ESA adapted a software receiver to the SDR hardware and software architecture of the JPL radio by allocating the various functions of the receiver to the serial and FPGA processors. Qascom wrote the core software and firmware modules together with appropriate regression tests. ESA/Qascom defined testing for the ground integration unit and for the on-orbit testing and operations. The ESA team processed the primitive data logged during flight operations and produced a high accuracy orbit determination product.

NASA/GRC provided overall waveform integration and developed the control and data exchange mechanisms between the serial and FPGA processors as well as data logging and downlink. This took the form of a number of Interrupt Service Routines (ISR) for the serial processor. NASA/GRC conducted the bulk of the testing on the Ground Integration Unit and all of the flight testing including long-arc data collection for (Precise) Orbit Determination (OD).

Initial development of the GARISS waveform occurred on the STB Ground Integration Unit housed at NASA GRC (GIU see Figure 4 (a)). Test signals from a GNSS simulator were provided by ESA and Qascom at the Intermediate Frequency (IF) level and played-back through a GNU-radio based playback system (see Figure 4 (b)) to the STB GIU.



(a) (b)

Figure 4: STB Ground Integration Unit (a) and GNU-radio based GNSS playback system (b)

Live-sky data was also provided to the GIU during testing from a rooftop mounted antenna. During waveform integration development and test on the GIU several iterations of the waveform architecture were required to achieve an appropriate allocation of receiver sub-functions to the serial processor and the FPGA processor. PVT was achieved in the GIU with both pre-recorded data and live-sky data and the 50m RMS 3D error requirement was met.

ON-ORBIT OPERATIONS

After development and testing on the GIU yielded a functional waveform the development effort moved to on-orbit operations and testing. The operational concept for on-orbit experimentation and operations is shown in Figure 5. During the on-orbit phase of project further waveform debugging, testing occurred. Additionally, primitive data was collected for the high accuracy OD effort occurred in the on-orbit phase.

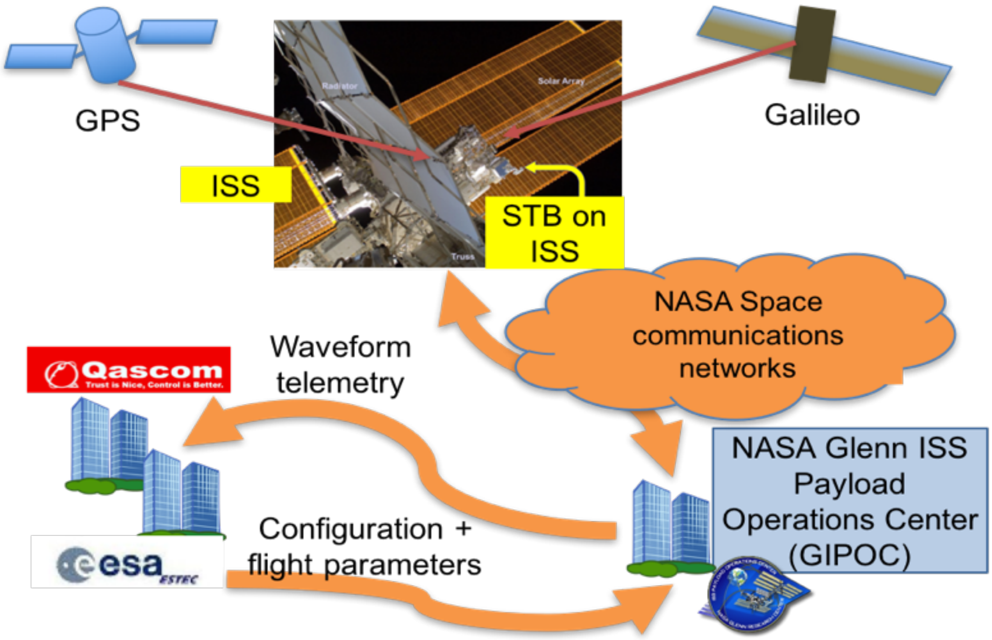


Figure 5: On-Orbit operations concept for GARISS

On-orbit operations is conducted through the Space Station Payload Operations Center at GRC and requires coordination with other waveform experimentation efforts that were part of the STB program. On-orbit testing and data collection efforts commence with the transfer of waveform configuration parameters, such as data on satellites that are anticipated to be in view and Galileo/GPS Time Offset. Such configuration parameters files enable warm start operations. Warm start data are obtained from ESA and Qascom at the GRC Payload Operation Center. Configuration data, with the waveform codes are then transferred to the STB through NASA space communications networks such as the Space Network (TDRSS).

Waveform log files containing debugging data and waveform primitive data such as code and carrier pseudo-range are then retrieved from the STB for debugging purposes or analyzed to assess waveform on-orbit PVT performance or to support OD and other experimentation.

Galileo/GPS Receiver Signal Performance

One way of assessing receiver performance is to examine C/N0 measurements for acquired signals. In Figure 6 on-orbit tracking and acquisition performance of GPS L5 and Galileo E5a signals is shown for a period of approximately 6 hours. The waveform/receiver performance is thought to be very adequate with curves demonstrating that signals are acquired as low as 35 or 40 dB-Hz and tracked down to 15 dB-Hz.

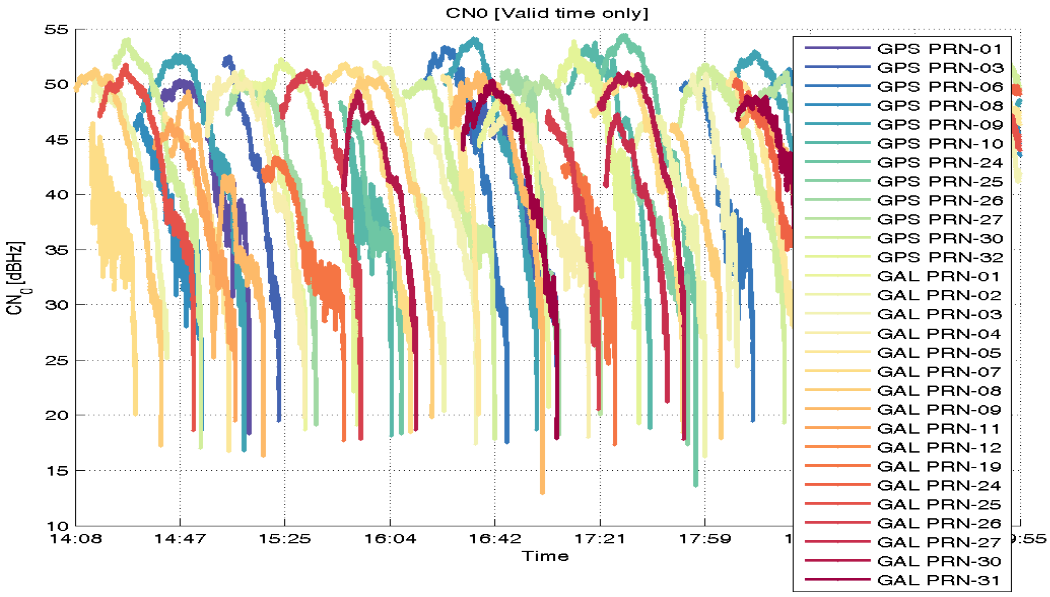


Figure 6: Carrier to Noise Power Spectral Density (C/N0) for 12 GPS and 17 Galileo Space Vehicles (SV)

(PRECISE) ORBIT DETERMINATION OF ISS – PROCESSING OF GALILEO/GPS RAW DATA

Precise Orbit Determination (POD) for a satellite/spacecraft in the Low Earth Orbit (LEO) is a complex task, which requires detailed information about physical properties of the satellite/spacecraft as input for the modelling and also a large number of high quality Galileo/GPS measurements. In the case of the International Space Station (ISS) this task can be considered as very challenging because of the pure dimension, mass, mass distribution, Center of mass and related history and also the complex geometry of the ISS.

The POD concept applied by ESOC in the context of this project was a Dynamic POD. This means that based on the modelling of the forces acting on the ISS and the numerical integration of the derived equation of motions it is possible to calculate a nominal orbit for the ISS. The nominal orbit will then be processed together with the Galileo/GPS raw observations in a Least Square method (LSQ) in order to estimate the orbit for the ISS in an optimal way, based on the combination of the dynamic model of the ISS and the Galileo/GPS raw observations (code- and carrier phase measurements) measured by the Galileo/GPS receiver on board the ISS over a certain period of time. The entire dynamic POD computation was done on the ground in a post processing mode, using a batch of Galileo/GPS observations.

The described POD concept can provide cm level accuracy of the spacecraft position, if detailed information about the spacecraft is available and the Galileo/GPS measurements covering a sufficient period of time (about 3 days) with good quality. However, in case of the ISS, it was clear that due to the complexity of the ISS, the modelling of the forces is a challenge and would need very detailed information, which was not always available with the requested level of detail and therefore assumptions and simplifications have been made, which had an impact on the achievable level of accuracy for the POD.

Visibility Analysis – Added Value of Interoperability for Galileo and GPS

The visibility of Galileo and GPS satellites for the space user, in this case the ISS, is of fundamental importance and also one of the most critical performance parameter, because only if the space user is tracking a sufficient number (standalone min. 4, interoperable min.5) GNSS satellites, a real-time, on-board PVT solution can be generated. However, as already outlined in the abstract chapter of this paper, one of the objectives of this project was to validate the added value of an interoperable Galileo/GPS receiver compared to a standalone Galileo or GPS receiver. In general, it can be concluded for this experiment that the interoperable Galileo/GPS receiver was always outperforming the standalone Galileo and GPS obtained results in terms of visible number of GNSS satellites. This fact is also reflected in a characteristic way in Figure 7 below. Figure 7 shows clearly that the interoperable Galileo/GPS receiver could provide most of the times a sufficient number of Galileo/GPS satellites in order to calculate an on-board PVT solution in real-time, whereas the standalone Galileo and GPS scenarios could either not at all provide an on-board PVT solution in real-time or the number of times where a standalone PVT real-time solution on-board could be generated was significantly reduced compared to the interoperable Galileo/GPS receiver scenario.

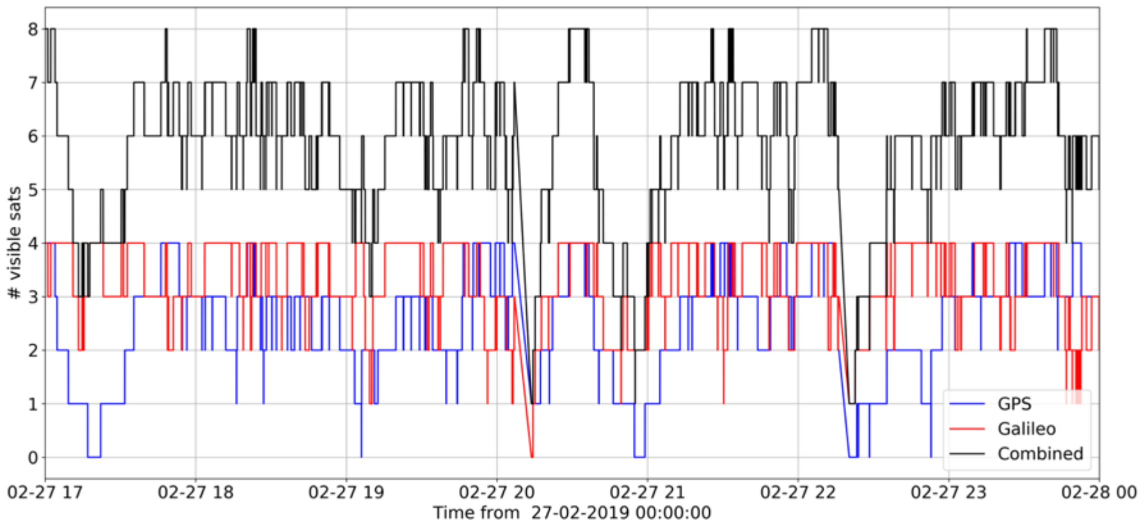


Figure 7: Visibility of Galileo and GPS satellites for Receiver on-board the ISS

Observations and Processing Concept for (Precise) Orbit Determination (OD)

The GNSS observations playing a key role in the Precise Orbit Determination for space users. Normally, for applying the POD concept, raw measurements (code and carrier phase) from a minimum of two frequencies (in order to eliminate ionospheric effects) will be used in the processing. One of the drivers in the POD process for the achievable accuracy is the quality of the carrier phase measurements and the capability to resolve the associated cycle ambiguities. By using carrier phase measurements, it is possible to obtain a measurement quality which is between one and two orders of magnitude better than that of code phase measurements.

This means that the code phase measurements playing in general only a lower level role in POD. However, in the context of the GARISS project, the interoperable Galileo/GPS receiver had some technical problems related to the E1/L1 frequency and therefore only the E5a/L5 frequency could be used. This means, that instead of a dual frequency (E1/L1, E5a/L5) Galileo/GPS receiver only a single frequency (E5a/L5) Galileo/GPS receiver and associated raw measurements (code and carrier phase) could be used for Precise Orbit Determination. Hence, it was only possible to perform an Orbit Determination (OD) instead of a POD, with the consequence to obtain reduced accuracy for the ISS orbit solution.

Based on the fact that only measurements (code and carrier phase) from a single frequency (E5a/L5) were available for the GARISS project, a linear combination between code and carrier phase measurements called GRAPHIC from a single frequency were used in the OD process (Yunck, 1993). The advantage of GRAPHIC is that the observation is free from the ionospheric effect. However, the accuracy of the GRAPHIC observation is driven by the quality of the code phase measurement (~ ½ code phase) also the cycle ambiguity from the carrier phase measurement is still existing and needs to be resolved.

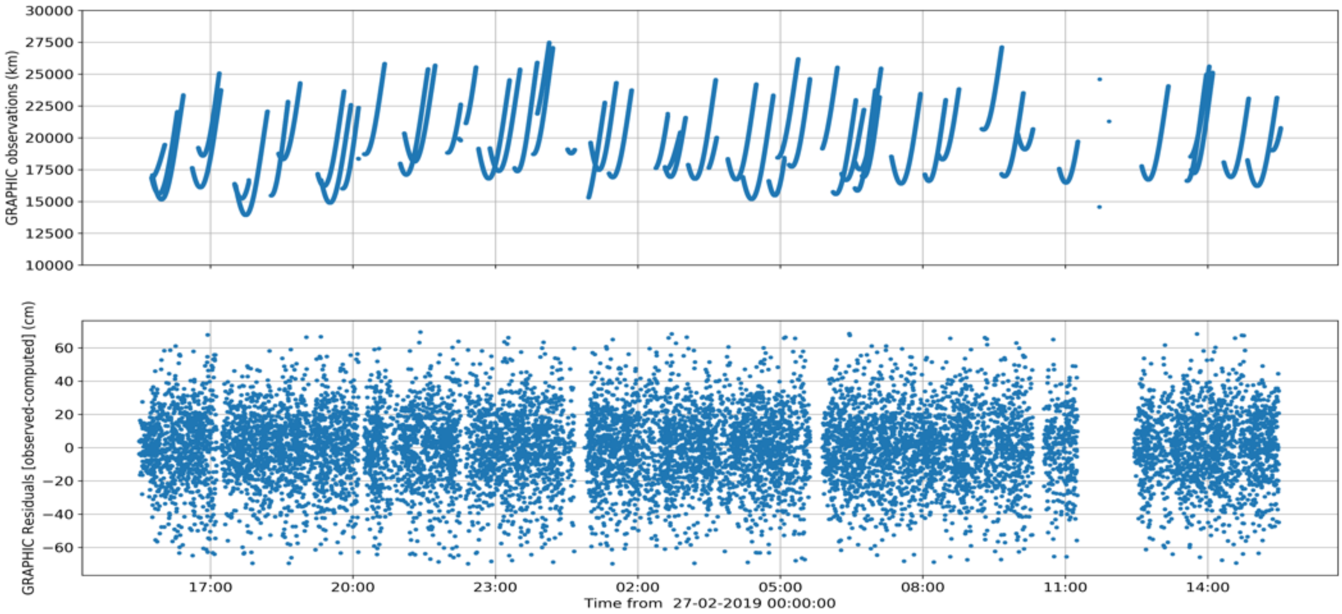


Figure 8: GRAPHIC observations (top) and GRAPHIC Residuals

The plot on top of Figure 8 shows the GRAPHIC observations generated from the linear combinations of code and carrier phase measurements at each epoch. The quality of the GRAPHIC observations obtained in the context of the GARISS project is outlined in Figure 8 (plot on bottom). Of particular interest are the residuals for the GRAPHIC observations, because they are providing a very good indication about the quality of the dynamic modelling for the ISS. Please take note that the data gaps in the GRAPHIC observations resulting from a mandatory manual restart of the Galileo/GPS receiver about every four hours.

The GRAPHIC residuals are generated by building the difference between the observed measurements and the computed measurements (reconstructed, based on the dynamic modelling). As can be seen in Figure 8 (bottom) the GRAPHIC residuals showing a RMS of about 20 cm, which is considered as very good having in mind the complexity of the ISS and the related dynamic modelling of it. With this level of accuracy for the GRAPHIC residuals, it is expected to obtain a position accuracy for the ISS < 1 m (1 Sigma, 3D).

Comparison between (Precise) Orbit Determination and the Reference Position Solution from SCaN

In order to compare PVT solutions or POD solutions generated by GARISS to the Space Station on-board position solutions, the moment between the on-board GPS receiver antenna for the Space Station reference position must be accounted for, using a calculation that includes the reference Space Station attitude. As illustrated in Figure 9 the distance (~18m) between the Space Station GPS reference antenna and the antenna on the STB, which is used for GARISS, is non-trivial to obtain. Accurate attitude for the Space Station has also not been available and the two factors together are considered a significant source of uncertainty for comparing GARISS position results and Space Station PVT solutions, obtained from the ISS reference GPS receiver in a consistent way.

In Figure 10, results are shown from the comparison between and ESOC’s position solution (outcome of OD processing) and the on-board real-time position solutions received from the PVT reference solution for SCaN. The comparison provides a 3D RMS value of about 15 m for the difference of both solutions. However, this result is considered not consistent with the very good residuals of the GRAPHIC observations and therefore further activities are needed in order to solve this issue.

Taking into account the situation, as described in the paragraphs above, it can be stated that a real comparison between the on-board real-time PVT reference solution for SCaN and ESOC’s OD solution could not be conducted. Hence, the evaluation of the OD accuracy, based on GARISS raw measurements is still pending and additional activities have been initiated in order to obtain further information, which hopefully will allow to solve this issue and allow a real evaluation of ESOC's OD solution accuracy.

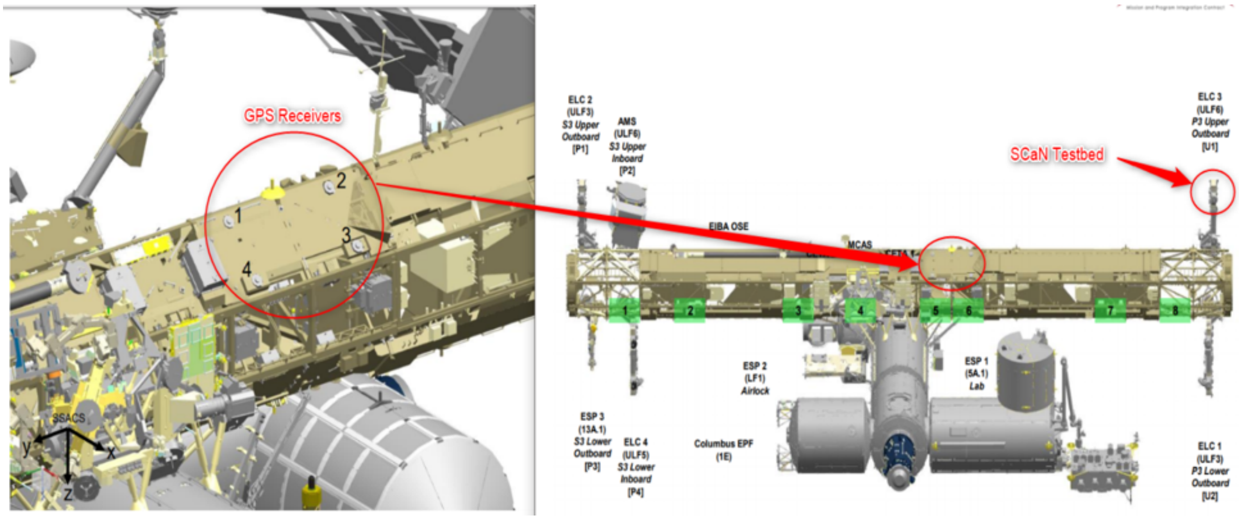


Figure 9: International Space Station Configuration during the experimentation period

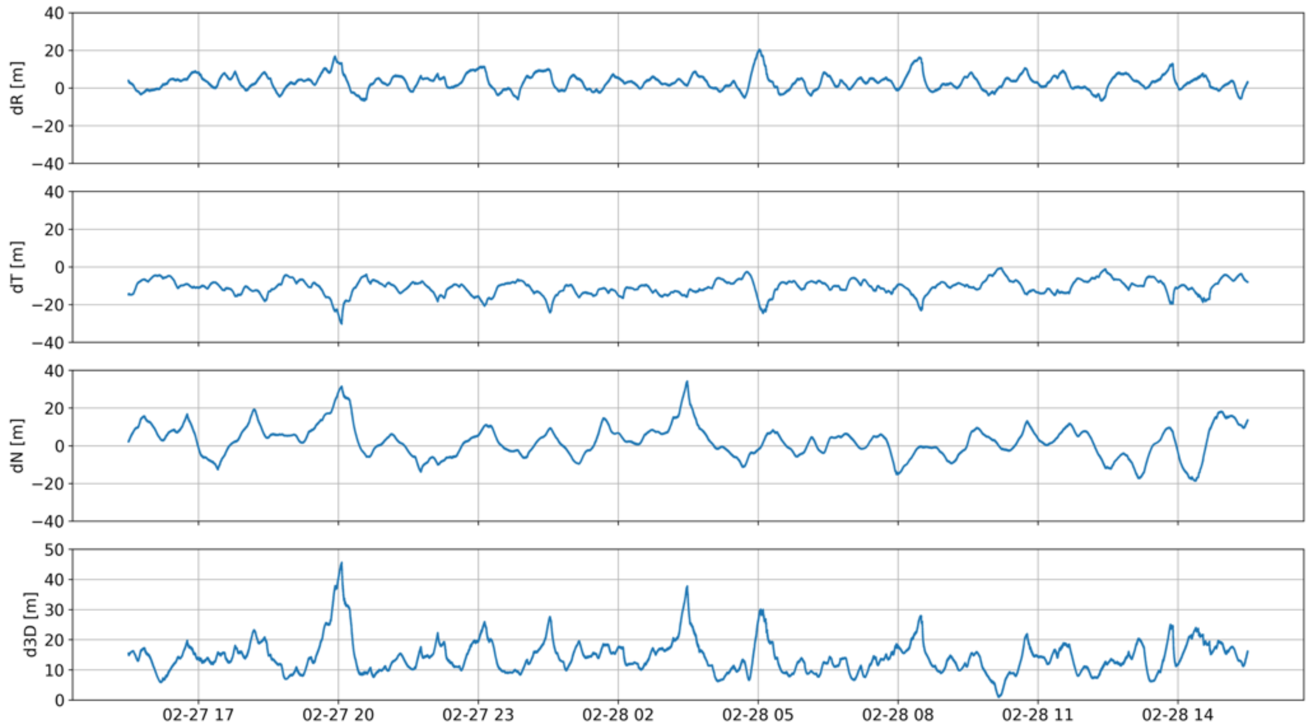


Figure 10: Comparison between the on-board real time PVT reference solution from NASA's SCaN Testbed with ESOC's post processing Orbit Determination solution

CONCLUSIONS

The conclusions of the joint ESA/NASA project named GARISS can be summarized in the following way:

- The combined Galileo/GPS waveform was jointly developed, tested, uploaded to NASA’s SCaN testbed on-board the International Space Station and also successfully operated over a period of more than one year.
- According to the author's knowledge, this was the first time that a PVT solution was generated in space, based on Galileo/GPS E5a/L5 signals only.
- The signal and PVT performance of the interoperable Galileo/GPS receiver was analyzed and improved during the experimental phase on a continuous basis.
- The added value of an interoperable Galileo/GPS receiver compared to a standalone Galileo- or GPS receiver for space users could clearly be demonstrated. Of particular importance is the capability to generate on-board real-time PVT solutions over nearly the entire experimentation phases, based on the significantly improved Galileo/GPS satellite visibility in comparison to the standalone Galileo- or GPS scenarios.
- The GARIS observations (E5a/L5) demonstrated to be of good quality with respect to consistency of code and carrier phase measurements.
- Due to some technical issues, unfortunately only Orbit Determination (OD) based on GRAPHIC observations but no Precise Orbit Determination (POD) based on dual frequency observations could be performed and therefore the accuracy of the OD solution was limited.
- ESOC’s Orbit Determination solution compared to the ISS on-board PVT reference solution for SCaN shows a 3D RMS of around 15 m, which is more than three times better than the requirement for position accuracy.
- The results of the orbit comparisons between ESOC’s Orbit Determination solution and ISS on-board PVT reference solution for SCaN does not match with the very good residuals for the GRAPHIC observations (RMS ~20 cm). For this reason, additional activities are needed in order to solve this issue.
- The cooperation between the ESA teams, the NASA teams and the Qascom team was simply considered as excellent and therefore the entire GARISS project could be conducted and completed in a very productive and successful manner.

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