Assessment of Galileo Data with BayNavTech Performance Assessment Facility

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BIOGRAPHIES

Michael Kirchner is Engineer for Navigation Systems at EADS Astrium Satellites. He studied Geodesy at the Dresden Technical University, Germany and Chalmers Technical University, Gothenburg, Sweden. After graduation in 2002 he was responsible for a near real time tropospheric sounding project and quality assessment of GNSS data at the University FAF Munich. He joined EADS Astrium in 2005 and is mainly working in system performance and processing algorithms related activities for Galileo.

Johann Vilzmann graduated at the Technical University of Munich in Electrical Engineering. He joined EADS Military Aircraft (former Daimler-Benz Aerospace) in 1997. He was working in System Engineering and Software Engineering (including safety critical software) in the Eurofighter project. In 2004 he joined EADS Astrium and contributed to the Phase C0 of the Galileo Ground Mission Segment. Within the BayPAF project he is currently coordinating the technical activities.

ABSTRACT

This paper introduces the BayPAF - a performance assessment facility for operators and providers of GNSS related services and data - and its capabilities in test and early operation phases of the GIOVE satellites. The main mission of the BayPAF is to offer an independent assessment and verification environment for GNSS, serving the professional user community with specific products, providing significant characteristics regarding the GNSS performance and to support early phases of satellite operation. BayPAF is an integrated facility of independent components which are centrally controlled. The standard components include Data Simulation, Data Processing, Analysis, Signal-in-Space Accuracy computation and Local Augmentation and Integrity computation.

After a short introduction of the objectives and architecture of the facility together with a summary of the available components the emphasis in this paper is put on the module for GNSS data processing from the perspective of supporting test and early operation phases of navigation satellites. The BayPAF processing chain of ground tracking data of the GIOVE satellites to derive satellite orbit and clock estimations is presented and the quality of the results is evaluated. The processing is based on data collected by the ground tracking network of the GIOVE Mission, which has been developed by the European Space Agency. It is shown that even with a rather sparse ground tracking network the orbit determination can be done with an uncertainty meeting the target foreseen for the Galileo system, which highlights the stability of the estimation process.

INTRODUCTION

The central mission of the Performance Assessment Facility BayPAF being part of the BayNavTech Satellite Navigation Centre Munich is to support initial and early operation phases of satellites of a satellite navigation system as well as to assess and monitor the basic performance parameters of the entire system (i.e. including the ground segment) which are essential to aid guaranteeing the expected reliability of the system to the user. To fulfill this central mission a complete system evaluation process was implemented in the BayPAF. By this also many related topics can be served which define the complete set of BayPAF design targets: independent verification environment for GNSS processing algorithms, interactive development, analysis, training, and demonstration platform, support of services and applications and provision of major global GNSS products to the professional end user.

The major components and central facilities of the BayPAF have been finally developed and are currently under demonstration for different performance assessment purposes. While the purpose of regular constellation monitoring is demonstrated in [2] for the GPS case this paper presents the BayPAF support capabilities of early operation phases for the GIOVE satellites using the facility in a specific single satellite processing configuration.

BAYPAF OBJECTIVE

The BayNavTech Performance Assessment Facility has been developed with the main objective to be an independent assessment and verification environment for GNSS. Starting from ground tracking data of navigation systems the user of the BayPAF shall be able to determine significant figures allowing a post processed or near real time and in-depth analysis of the navigation system performance. Additionally, the BayPAF by its flexible, module based setup shall allow the accommodation of newly developed processing algorithms and hence the performance assessment of emerging navigation applications.

With these objectives in mind several relevant navigation system processes have been implemented in the BayPAF infrastructure. These processes are introduced in the following section.

With its main capabilities of flexible simulation and processing of navigation system ground tracking data several secondary objectives can be served:

- Hazard scenario analysis:
  It is of importance to assess and understand the propagation feared events or errors within the system. With BayPAF's capability to simulate abnormal or even critical tracking data and to inject them into the processing chain the resistance of the algorithms can be analyzed.

- Test platform:
  The module based and extendable architecture allows to independently run different modules. Newly developed processing algorithms (e.g. of emerging navigation applications) can be accommodated into new modules of BayPAF and can be tested.

- Products for specific user needs:
  The processing chains provide a variety of different precuts which can be used to serve specific user needs in an efficient way. This could be near real time precise orbit predictions or real time augmentation.

BAYPAF ARCHITECTURE & CAPABILITIES

The functional architecture of the BayPAF as depicted in Figure 1 implements an order related concept. This is realized by independent software modules (yellow boxes) which are run consecutively. Depending on the objective

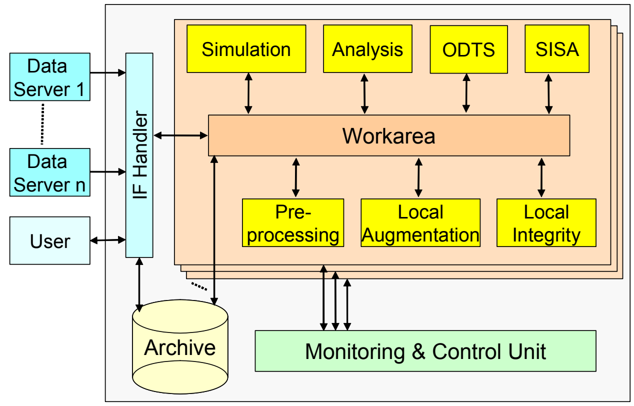

Figure 1: Simplified architecture of BayPAF platform.

of the assessment the modules are individually activated and configured. The complete configuration of the facility and the order is based on XML. Navigation system ground tracking data from external providers is regularly transferred into the BayPAF archive. A centralized monitoring and control unit is in charge of loading all necessary data into the shared work area, activating the individual modules, starting the process and notifying the user about status/progress and process termination.

The Performance Assessment Facility provides a number of standard modules as shown in Figure 1. With these modules a number of common standard tasks for GNSS system evaluation can be accomplished. These modules are:

- ODTS: GNSS Processing Products:
  It is the GNSS data processing core used to compute satellite orbit and clock corrections, atmospheric conditions, satellite signal biases, etc. It has full Galileo capability and allows a flexible configuration.

- DSDM: Data Simulation / Data Manipulation:
  It is used to generate artificial raw data and to manipulate existing data which can be introduced into the ODTS processing chains to verify the processing capabilities or study specific problems in detail. It is capable of simulating full Galileo and GPS constellation, atmosphere characteristics, local reception characteristics and a number of Galileo Feared Events.

- Analysis:
  It includes statistical functions to check the quality of processed data and generated products against internal or external references. It computes error contribution to User Equivalent Range Error (UERE) and Signal-in-Space Error (SISE)

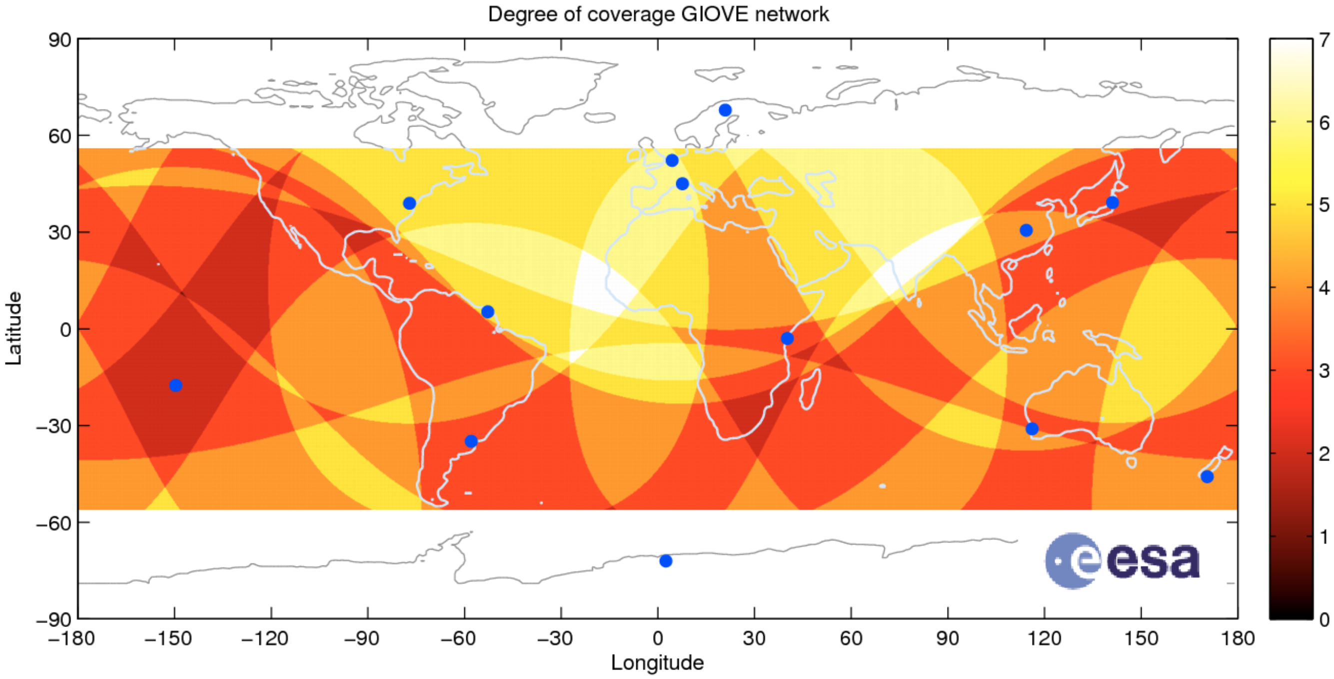

Figure 2: ESA GIOVE Mission ground tracking network and degree of coverage.

- LAIM: Local Augmentation and Integrity Module:
  It is the real time processing chain consisting of Pre-processing, Local Augmentation and Local Integrity Modules to generate augmentation data for professional users based on regional GNSS reference networks. The integrity part of the module is currently being developed.

- SISA: Signal in Space Accuracy:
  It computes the GPS and Galileo Signal in Space Accuracy (SISA) based on historic values of SISE.

For further details please refer to [1] and [2].

GIOVE MISSION EXPERIMENTATION

The Galileo System Test Bed V2 with its two test satellites GIOVE-A and GIOVE-B is an essential preparatory step for the Galileo In-Orbit Validation (IOV) phase. Related activities are concentrated in the frame of GIOVE Mission, an initiative of the European Space Agency covering spacecrafts, Ground Control Centers, GIOVE Processing Center and the ground tracking network of global coverage.

According to [3] the mission of the two satellites is not only to secure the frequencies allocated by the International Telecommunication Unit for the European radio navigation plans in time but also to test and verify most critical technologies. This includes the navigation signal generator as well as space atomic clocks. In particular the passive hydrogen maser on GIOVE-B is the first maser ever flown in space.

During the periods of GIOVE Mission (conducted by ESA) the satellites broadcast signals that are characteristic for the future Galileo system allowing to demonstrate their novel features. Beside a verification of their resistance against interference and multipath under real conditions also the development and test of user receivers is supported before the final Galileo satellites are available. An important field of study is to confirm that no inter-system interferences with GPS exist for the signals.

GIOVE-A built by SSTL was the first satellite launched on 28 December 2005 which was important for securing the frequency allocations. With this target being achieved the launch of GIOVE-B built by Astrium Germany was postponed to 26 April 2008 in order to allow for a modification of the signal generator to implement the final Galileo signals which have just recently been finally agreed.

An important part of the experimentation is the GIOVE mission segment containing the GIOVE Processing Center and the Galileo Experimental Sensor Stations for tracking the data. The network of ground monitoring stations contains 13 sites which show quite a homogeneous global distribution (see blue dots on Figure 2).

Figure 2 also shows the color coded Degree Of Coverage (DOC) of the tracking network. It represents the number

Table 1: Traceability between services and channels

Channel	Frequency	Service
L1A L1B L1C	1575.42 MHz	PRS OS/SoL Pilot
E5aI E5aQ	1176.45 MHz	OS Pilot
E5bI E5bQ	1207.14 MHz	SoL Pilot
E6A E6B E6C	1278.75 MHz	PRS CS Pilot
Combined tracking:		
E5a+bI E5a+bQ	1191.80 MHz	n/a Pilot

of ground stations the satellite is in view of when it is on a certain location over the Earth. A masking angle of 10° was applied for the determination of DOC. For the satellite clock offset estimation an observation of the satellite is necessary which ensures a continuous tracking by the network, i.e. DOC-1. For dynamic orbit estimation, i.e. by modeling and estimating the Keplerian elements there must be longer observation periods with a larger DOC. This, however, is the minimum requirement which does not provide any redundancy. DOC periods above this minimum add additional degrees of freedom to the processing making least squares solutions and outlier detection possible. While the network DOC is more than the minimum it is nevertheless still very limited. Especially for periods of station failure or data unavailability the DOC drops down and no reliable clock estimation might be possible.

DATA PROCESSING STRATEGY

The data assessment is divided into two parts. As no detailed information of the ground tracking network were available the first step covers the evaluation of ground tracking station characteristics based on GPS data. This includes precise coordinates, velocities, atmospheric conditions and signal biases. In a second step the GIOVE data are processed.

There are a number of channels and sub-channels defined to be broadcast by Galileo. Table 1 summarizes the traceability of the different sub-channels to the services (see [4]). According to [3] the two GIOVE satellites are able to broadcast all sub-channels on two out of three frequencies. Figure 3 therefore shows which channels are available over the analyzed period.

The regular processing for GIOVE data is based on L1C/E5bQ frequency combination as this is the one most continuously available and representative for SoL. For result evaluation certain periods are also processed with the L1C/E5abQ frequency combination. For GPS data the regular processing is based on dual frequency data of L1C and reconstructed L2P code.

For the processing undifferenced pseudo range and carrier phase observation data are used. The following procedure is applied for the GPS data:

- Data preparation
- Pseudo-range smoothing
- Receiver clock synchronization
- Iterative outlier screening (GPS part)
- Estimation of atmospheric conditions

In addition GIOVE data are processed in the following:

- Estimation of inter-frequency/inter-system biases
- estimation of a-priori orbit
- iterative outlier screening (Galileo part), orbit and clock estimation

Beside the assessment products itself it is of high interest to obtain an estimation of the quality of the results. Unfortunately, the variances of the least squares estimation process is typically much too optimistic to

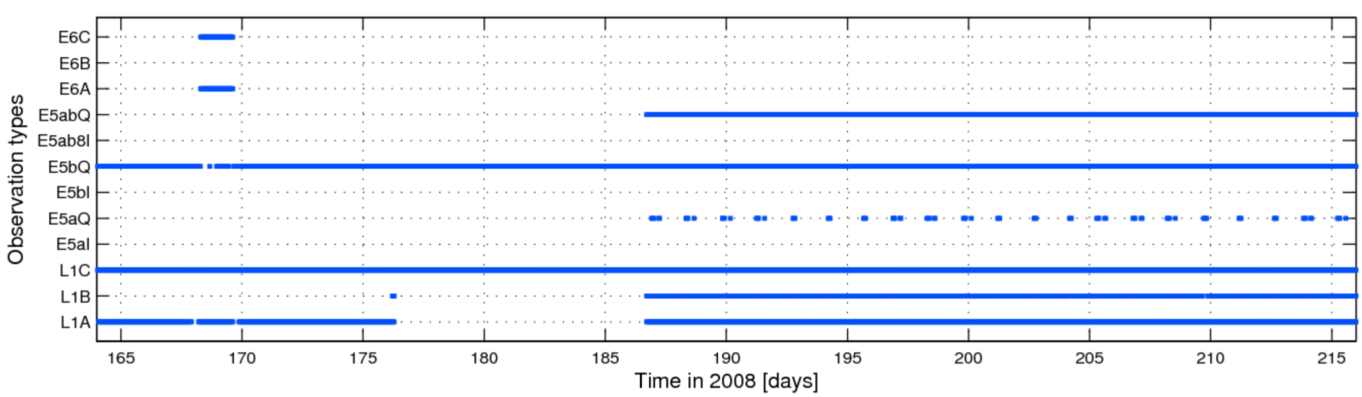

Figure 3: Availability of code channels over time. Note: Due to the limited resolution periods of channel switches slightly overlap and short interruptions are not visible. Particularly the days 168-170 contain several short periods of different broadcast channels but only two frequencies are broadcast at the same time.

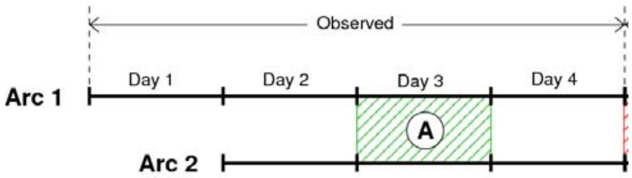

Figure 5: Orbit stability evaluation.

serve as reliable quality indicator. Therefore the results are rather checked for internal consistency and reproducibility. Due to the lack of independent sources no check with external results can be performed as it can be done for the GPS case (see [2]). Two strategies are thus applied:

- Stability evaluation based on different frequency pairs:
  The processing is performed twice selecting different frequencies or codes of the GIOVE data. The results are directly compared.
- Stability of orbit estimates based on long arc consistency.
  The orbit results for GIOVE are combined to obtain a long continuous arc over typically 4 days. The middle parts of two consecutive arcs shifted by a certain time span of typically 1 day are compared (see Figure 4). The differences are a strong indicator for the estimation stability. For prediction the last part is compared.

GIOVE RESULTS

The first part of the assessment focuses on the determination of network parameters. This is entirely based on GPS tracking data as for those precise reference values are available from the IGS [6]. Beside precise coordinates of ground tracking stations also station inter-frequency biases are estimated. A crucial point is the

Table 2: Correction of code ambiguities

Code	Pseudo Range [m]	Code Length [ms]	Code Amb.	Corrected Range [m]
L1A	398354845.957	10	130	8624650.557
L1B	-51333844.126	4	-50	8624647.474
L1C	-51333843.990	200	-1	8624647.610
E5aI	1147835716.118	20	190	8624375.718
E5aQ	1147835716.202	100	38	8624375.802
E5bQ	-51334116.584	100	-2	8624375.016
E5a+bQ	1147835715.204	100	38	8624374.804

antenna phase centre characteristic. As no specific information about the receiver antenna phase centers is available the hypothesis of zero variation was applied. This hypothesis was tested by means of least-squares residual evaluation. As no significant elevation dependency of the residuals could be identified the application of zero variations for the processing is reasonable. However, since the evaluation based on residual characteristic has a very limited sensitivity it is strongly suggested to make use of precise calibration values as soon as they are available.

Within the early operation and testing phases the satellites broadcast ranging signals according to the ICD (see [4]) which can be tracked by the receiver. Due to its experimentation character in most cases no valid navigation message is provided by the satellite. For the tracking the absolute reference is in this case missing to which the measurement can be referred. Due to this blind tracking pseudo range measurements are offset by several code cycles and an inconsistent set of measurements is provided. These code ambiguities are estimated and the measurements are corrected accordingly. Table 2 shows a snapshot for one observation epoch with the raw and corrected pseudo range measurements. It is important to derive a consistent set of code ambiguities while it is less important to derive the correct set. A consistent shift of

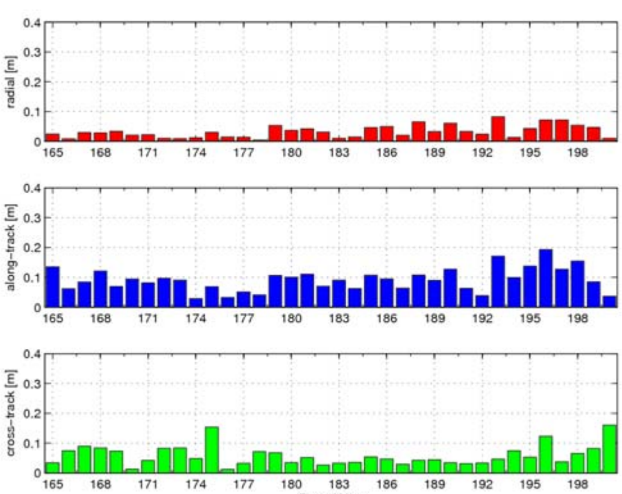

Figure 4: Orbit consistency GIOVE-A

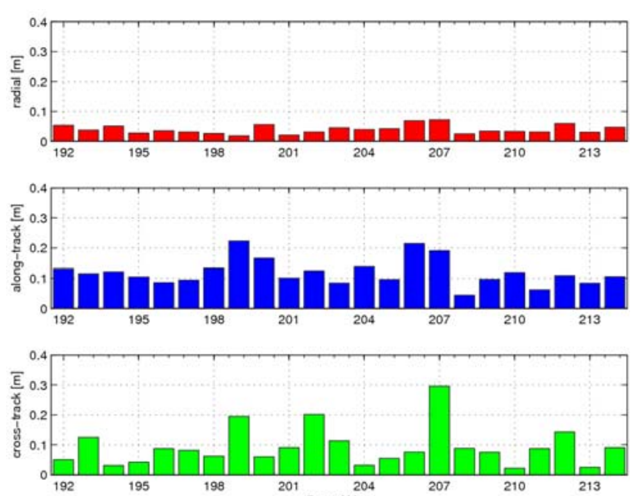

Figure 6: Orbit consistency GIOVE-B

the ambiguities adds a constant clock offset but does not degrade the result itself. The consistent set of measurements is fed into the orbit determination and time synchronization process.

With the strategy described above orbit and clock difference estimations are performed for GIOVE-A and GIOVE-B satellites for the available data. Due to lack of initial orbit data it was necessary to split the orbit determination process into a coarse and precise part which is run iteratively. The orbit estimate of the iterations converges and after typically 5 iterations no significant improvement is achieved any more. For consecutive days the estimated orbit is predicted and used as a priori information for the next processing.

The final orbit result is combined into a long orbit arc. Consecutive overlapping arcs are evaluated for the stochastic differences (cf. Figure 4) with a common shift subtracted. Figure 4 and Figure 6 show the RMS of the differences in radial, along-track and across-track component for orbit estimations of GIOVE-A and GIOVE-B respectively. It is obvious that the estimation of radial component is usually best while the estimation of along-track component is weakest. This is a very typical sensitivity behavior which can also be observed for well conditioned problems such as GPS orbit determination based on data of a dense IGS ground network. There is no major difference for the orbit determination for GIOVE-A and GIOVE-B. It should again be noted that these are test satellites and an important goal of the GIOVE mission experimentation is to evaluative the performance under certain conditions and with different configurations. This also includes changes in the payload configuration on the satellites which might certainly affect the navigation signals. As configuration changes are not known in detail those periods are assessed with the same procedure. This might lead to slight inconsistencies or degradations of the derived results.

An important result is the overall orbit determination consistency which can be estimated to be ~20cm. Keeping in mind the rather sparse tracking network this is a very reasonable level of consistency. According to [7] the contribution of combined orbit determination and time synchronization error to the user range error budget (UERE) is specified to be 67cm. With the obtained orbit estimations is can be concluded that it seems to be well possible to reach this target. It can even be expected that the final results are significantly below this specified value.

Beside a precise orbit estimation clock synchronization accuracy and prediction is one of the major drivers for navigation performance. As navigation information is not provided by the satellites on a continuous basis there is no uninterrupted access to the Galileo system time scale. For this reason the synchronization is referred to the final re-adjusted IGS time scale aligned but not identical to GPS system time (cf. [5]).

The upper part of Figure 7 shows the absolute clock offset with respect to IGS time scale. The high absolute level of the difference is due to the uncorrected inter-system time bias. The large drift is due to typical strong drifts of the rubidium clocks in early phases of operation. The lower part of Figure 7 shows the de-trended data which allows a close look into the fine variations over one day. The level of ~4ns is a typical level of variation for space clocks.

While the characteristic in the time domain is important to assess which method for clock prediction should be applied the evaluation in frequency domain is more important to assess the stability of the oscillator over certain time periods. Figure 8 shows the sample Allan deviation of these data over sampling times from 30s up to 30 000s. Beside the GIOVE-A RAFS oscillator also the requirements for IOV are shown for RAFS (magenta) and

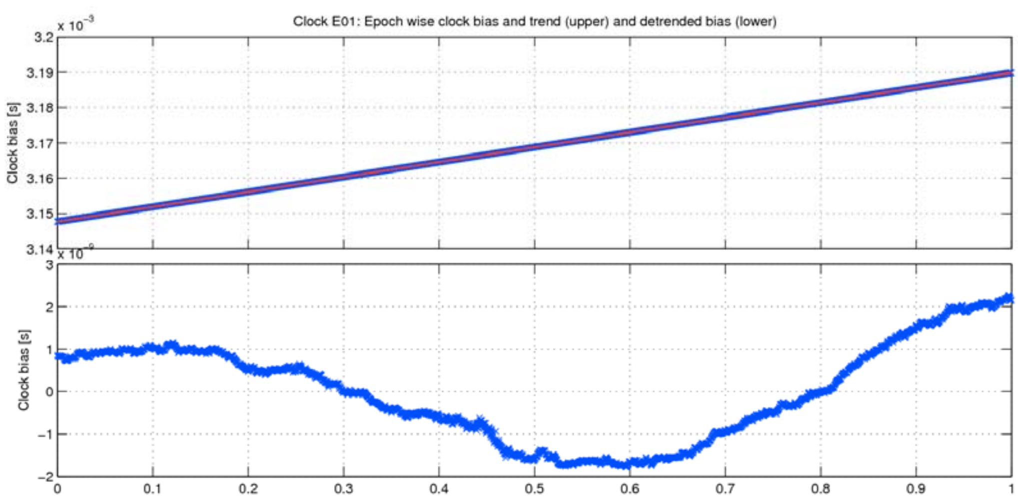

Figure 7: GIOVE-A clock difference.

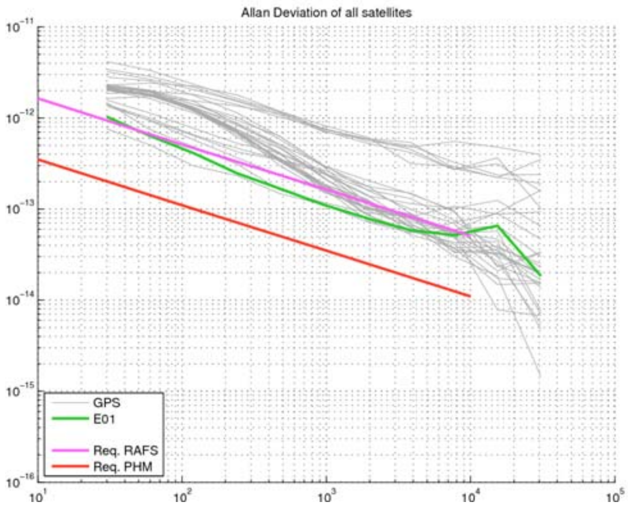

Figure 8: Allan deviation GIOVE-A clock.

PHM (red). For the evaluated period the RAFS on GIOVE-A meets the performance required for IOV. This is very important as no major design adaptations are foreseen for the RAFS to be flown on IOV satellites. The various grey lines show the stability of GPS clocks and give an impression about the typical stability which is achieved for space clocks today.

CONCLUSION

A longer sample period of GIOVE ground tracking data was analyzed. To do so a dedicated processing chain capable of single satellite processing was implemented in BayPAF. The results obtained for the two GIOVE satellites show that even with the quite sparse ground tracking network reliable and stable products can be generated by BayPAF. The clock assessment clearly shows that the stability of the rubidium atomic frequency standard meets the IOV target value for the analyzed time span. The estimation of the orbit of the satellites is stable down to a level of 20cm. Comparing this figure with the target ODTS error of 67cm foreseen in the UERE budget one can already conclude that the orbit determination and time synchronization targets can be met and the processes might even show significantly better performance compared to the specification.

With the GIOVE tracking data assessment the capabilities of BayPAF to support early satellite operation phases and especially IOV and deployment phase for Galileo was demonstrated. The capability of the monitoring of the final constellation is demonstrated in [2] for the GPS case.

ACKNOWLEDGEMENTS

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Note: