GNSS CLOCK PERFORMANCE ANALYSIS USING ONE-WAY CARRIER PHASE AND NETWORK METHODS

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Abstract

Analysis of GNSS clocks performance is traditionally carried out by network analysis techniques where orbits and all participant clocks are computed in a batch or Kalman Filter least-squares adjustment to a reference time scale and reference frame. Several companies, organizations, and IGS analysis centers produce postprocessing orbits and clock estimations mainly at 15 or 5 minutes respectively, from which it is possible to extract the onboard clock performance on the medium or long term. Final IGS solutions are used as reference for validation of any new algorithm.

Within the associated experimentation to the Galileo In Orbit Validation Element-A (Giove-A), GPS, and Giove-A satellite orbits and clocks are estimated by the Orbit Determination and Time Synchronization (ODTS) software from observations of a dual worldwide GPS/Galileo Network, being GIOVE-A results kindly augmented by Laser Ranging observations. Following the Galileo risk mitigation, the Giove-A satellite was launched on December 2005 carrying two RAFS clocks manufactured by Spectratime (formerly Temex Time).

While the medium- and long-term performance is of the highest importance for navigation and integrity at the corresponding user level, since the prediction errors are directly mapped into the User Equivalent Range Error (UERE), the short-term performance of the timing signal has to be low enough to allow the user receiver to integrate the received signals over long intervals.

The present paper analyzes ODTS estimations, IGS new 30-second clock solutions, and the new one-way carrier phase technique for the short term, in order to analyze the full clock performance from 1 second. Additionally, ground results for Giove-A rubidium clocks allow assessment of the difference between the physical and the signal (or "apparent") clocks. Detailed results will be presented for each GPS and Giove-A FM4 and FM5 clocks. In particular, special emphasis will be given to the clock estimations of the stations located at time laboratories, the analysis of the noise of the different methods, and limitations when characterizing the onboard clock performance.

INTRODUCTION

The restitution of GNSS clocks is carried out by network analysis techniques by the USNO, NRL, NGA, or IGS analysis centers. It is based on the processing of GPS observables gathered over a wide network of sensor stations and, therefore, requires complex processing of a large amount of data.

The timing information derived from network adjustment of orbits and clocks allows the characterization of all the clocks in the system (both the onboard and on ground) with respect to a given reference time scale. Results for GPS clocks are normally presented as the stability with respect to GPS time for 1 day **[1,2]**, since this is the nominal update rate of the navigation message, or from 5 minutes since this is the typical sample time for the clocks in the network adjustment algorithms. Best estimations are assumed to be obtained by the International GNSS Service (IGS).

This article analyzes the Giove-Mission Measurement System used in the Giove Experiment by comparing GPS results versus IGS solutions. In addition, it presents a different approach to characterize the onboard timing signal using One-Way Carrier Phase (OWCP) focusing on the short-term behavior from 1 second, validating the method versus the recently available IGS 30-second clock products for GPS satellites and with ground results for GIOVE-A clocks.

Initially, the concept of the Measurement System used to observe the GNSS clocks is introduced. Later, the results with the different techniques for GPS and GIOVE-A clocks are presented and, finally, a set of relevant conclusions is proposed.

MEASUREMENT SYSTEM

The Measurement System is composed of a network of sensor stations in charge of tracking the satellites' L-Band signals and dedicated software that processes the observations to obtain the orbit and clock solutions.

SENSOR STATION NETWORK

Any orbit and clock solution needs input observations gathered over a worldwide well-distributed network of sensor stations. Receiver code and carrier-phase measurements are the basic observations processed by the processing software. Observations have to be made available to the processing software with a latency that depends on the product objective: offline, rapid, ultra-rapid, or near real time. Consequently, typical latency has been daily files, later hourly files, and the actual trend is 15-min files or data streaming.

Several worldwide networks have been established by different governments, public organizations, and companies as the NGA National Geospatial-Intelligence Agency GPS Network used in GPS Operational Orbits, the NASA-JPL Global GPS Network (GGN), the German Federal Agency for Cartography and Geodesy (BKG) Network, the ESOC and ESA GPS/Galileo Networks, TIGA, or the commercial Omnistar Network. Additionally, several regional networks are available at different levels and with different objectives as the European EUREF, French, Swiss, and German geodetic and RTK networks. Finally, a selection of these and other additional stations are part of the IGS Network.

The IGS represents the most extensive network with up to 345 active reference stations operational on November 2007 and additional ones being continuously proposed. It has been demonstrated to be one of the best networks, mainly due to the free data dissemination, dual GPS/GLONASS receiver availability, location at several time laboratories, reference frame sites, and clear maintenance or a long history which makes possible the reprocessing of large series of data dating from 1992.

NETWORK ADJUSTMENT SOLUTIONS

Analysis of GNSS clocks performance is traditionally carried out by network analysis techniques where orbits and all participant clocks are computed in a batch or Kalman Filter least-squares adjustment to a reference time scale and reference frame. Various methods for precise orbit determination (POD) are available mainly based on undifferenced and double-differenced GNSS code and phase measurements. Methods can be independently validated with Satellite Laser Ranging (SLR) if such data are available for the satellite during this period. It is also possible to combine SLR and L-Band measurements.

By forming double-differences of GNSS code and phase measurements, purely kinematic precise orbits can be computed. Ground and onboard clocks are eliminated assuming a good synchronization and neglecting different travelling times. Only kinematic coordinates and double-difference ambiguities are estimated in the least-squares adjustment. Once the reference orbit is estimated, ground and onboard clocks can be resolved in a second step by a dedicated algorithm such as Linked Common View Time Transfer (LCVTT) **[9]**.

Processing undifferenced measurements has the advantage of using all of the available data from the stations; also, the clocks and orbits calculated are consistent with each other, which can sometimes be a problem when using double-differenced observations. On the other hand, processing undifferenced measurements does have the additional complexity of estimating both the satellite and station clock biases, which can be rapidly changing time-varying parameters.

Numerous processing centers produce GNSS products using one of these approaches, plus a set of dedicated strategies and techniques in order to deal with different effects like ambiguity resolution, ionosphere, troposphere, relativity, phase center offsets, phase wind-up, tides, site displacements, ocean/atmosphere loading, etc. A dedicated group of centers combined their solutions in a weighting average to obtain the final IGS solutions.

Figure 1 presents the main clocks, reference points, and components of the Measurement System used in the GIOVE Experiment.

In the classical network adjustment used for orbit determination, orbits are estimated at the center of mass, while observations are referred to the transmitting antenna phase center; therefore, dedicated a-priori information for the Phase Center Offset (PCO) and Phase Center Variation (PCV) is required or needs to be computed. Coordinates are previously estimated in an International Terrestrial Reference Frame (ITRF) realization. The troposphere wet effect is estimated piece-wise and mapped to the slant direction using empirical mapping functions. Ionosphere first-order effects are eliminated by Linear Combinations (LC). Satellite Inter-Frequency Satellite Biases (IFB) are included in the clock bias for the LC used, while receivers' IFB and Inter-System Bias (ISB) are computed one per day (except for a reference station).

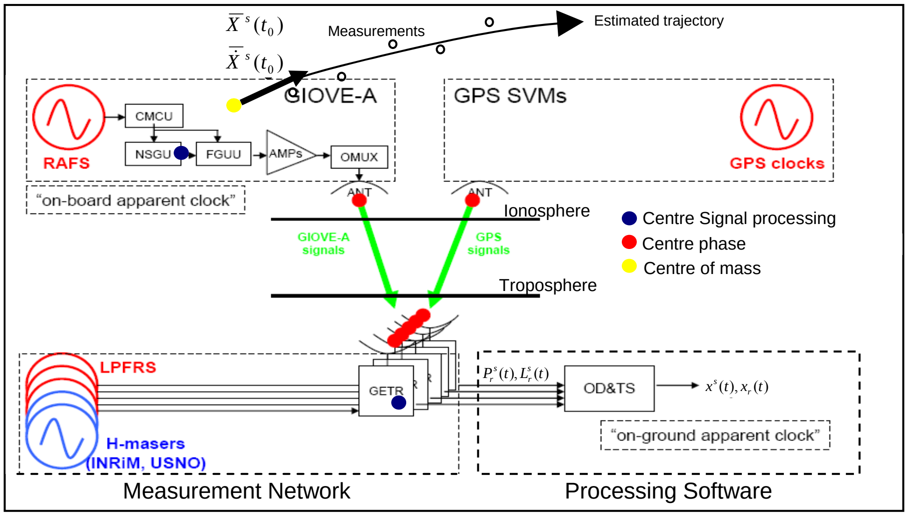

Figure 1. Measurement System.

Any biases or mismodeling of the involved deterministic effects by the ODTS software would be propagated together with other noise across the different estimations, with unclear effects. For example, no constants IFB or ISB at the reference station will affect the time scale and will propagate to all estimated clocks. No constant IFB on the satellite will be absorbed by the satellite clock offset. Additionally, transmitting antenna PCO, traditionally considered as a constant offset, propagates into troposphere, orbits, stations, and clock solutions. For GPS satellite antennas, dedicated PCO and PCV proposed by IGS are used **[1]**. As a consequence, the apparent clock behavior estimated as a phase offset will not coincide with the real physical clock behavior, since it may include stochastic and deterministic residual errors introduced by the IFB on the satellite and the Measurement System.

ONE-WAY CARRIER PHASE SOLUTION

The new One-Way Carrier Phase (OWCP) method has been proposed as a different approach to characterize the o board timing signal focusing on the short-term behavior in the [1, 300] second interval. The OWCP method uses the first derivative of the carrier phase to estimate in a simple and effective way the clock short-term stability from 1 second using a single sensor station equipped with a H-maser **[3]**. The OWCP method may be envisaged as an independent complementary mean to network adjustment methods that traditionally cover the [300, N] sec interval to observe the short-term behavior of the space clocks in the [1, 300] sec interval.

Unquestionably, network methods offer better estimates at medium and long term due to the extra accuracy gained by means of the physical models involved and the noise spreading over a large number of observations. However, estimations are normally constrained to 300-second sampling because of the long processing time due to the size of the normal matrix involved in the least-squares processing, implying ambiguity resolution, preprocessing, and a complex processing with a large number of physical models involved.

Similar conclusions may be drawn for the receiver clocks. Commercial clocks from receiver Sensor Stations can be characterized for their stochastic behavior, being the short-term behavior of this clock of high importance in the pseudorange and carrier-phase tracking. Additionally, the method allows for characterizing the carrier-phase noise intrinsic to each broadcasted navigation signal or its combinations.

RESULTS

DATA SET

In this paper, data from the ESA dual GPS/Galileo GIOVE Mission Network are processed. This network is composed of 13 identical antenna, dome, and receiver elements; measuring data at 1 Hz represents the minimum number of stations to observe the satellite from at least two stations; further information about the network can be obtained in **[4,5]**. Estimated GPS products are compared versus the official IGS products obtained with the IGS Network in order to validate the Measurement System.

The IGS average solution of undifferenced, double-differenced processing and different strategies are used to validate the results coming from the ODTS based in undifferenced measurements; further information about the ODTS configuration is covered in other publications **[6]**. A typical 5-day arc from 2007 doy 138-142 has been selected to analyze GPS results, while all nominal arcs for Giove-A clocks are presented.

The OWCP validation is carried out without any model correction in order to verify the limits of the method and with the highest possible masking angle. The Overlapping Allan deviation (ADEV) is preferred to the normal Allan deviation. For the sake of clarity in the plots, the ADEV is computed at all tau values. Data from the two GESSs (Galileo Experimental Sensor Stations) connected to an external active H-maser are used to characterize the onboard clocks, namely the GIEN station, located at INRiM, Turin, Italy, and the GUSN station, located at the United States Naval Observatory, Washington, D.C., USA. Since OWCP results are estimated by passes, the center day from the 5-day arc selected for GPS has been chosen to compare both methods, i.e. doy 140, 2007. For further verification of the method, the new IGS 30-second clocks products are used in order to compare against the OWCP for the GPS clocks in the 30- to 300-second interval.

GNSS CLOCKS FREQUENCY STABILITY

Figures 2, 3, and 4 present the Allan deviation obtained with both methods for GPS Block IIACs, Block IIA Rb, and Block IIR Rb respectively. The right side of the ADEV plots presents the clock stability obtained with the new IGS clock products in the [30, 10^5] sec interval with 30 sec tau and ODTS experimental clock products estimated for the [300, 10^5] sec interval with 300 sec tau. The left side presents the clock stability obtained by OWCP estimations for the [1, 300] sec interval with a 1 sec tau and GIEN as the reference station. Additionally, OWCP results have been cross-checked with GUSN as reference station, with excellent agreement. For visual reference, the green line corresponds to $5 \times 10^{-12} \tau^{-1/2} + 3 \times 10^{-14}$.

Both ODTS and IGS Network solutions completely overlap in the [300, 10^5] sec interval with very good agreement, especially taking into account the different number of sensor stations used, over 300 by IGS and 13 by the ODTS. The behavior of the results around 10^5 sec is explained by the relatively low number of samples available to compute the statistic (5 days).

In the short term, OWCP and IGS solutions overlap on the [30, 300] sec interval with very good agreement that fully validates this new technique. As a general remark, OWCP solutions based on L1, L2 single frequencies and the ionofree linear combination match perfectly for integration times over 30 sec. Below 30 seconds, the ionofree noise is higher due to combination of both signals (L1 and L2), and L1 noise is around $\sim 1 \times 10^{-11} \tau^{-1}$ for all SVs. Most likely, the carrier-phase noise is masking the actual clock noise. L2 results are not conclusive under 5 seconds. The usage of the semi-codeless techniques to track

L2 could be the origin of the differences with respect to the L1 signal in this interval and the undetermined type of noise .

Regarding the results by clock technology:

Block IIA cesium-clock stability in Figure 2 seems to be driven from 1 sec by the carrier-phase White Phase Modulation (WPM) noise around ~$1.3 \times 10^{-12} \tau^{-1}$ for L1 and ~$1.8 \times 10^{-12} \tau^{-1}$ for the ionofree, then from 2/10 sec by an internal crystal oscillator until it reaches a clear White Frequency Modulation noise at ~$1.2 \times 10^{-11} \tau^{-1/2}$ around 30/100 sec that is driven by the Cs reference. Transition from WPM to WFM depends on the SV.

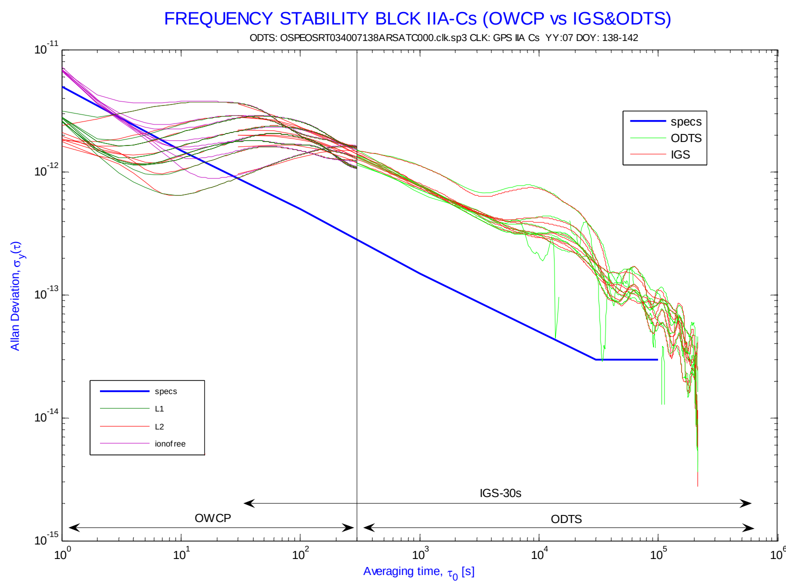

Figure 2. Block II-A Cs clocks, ADEV for 2007 doy 138-142.

Block II-A rubidium clocks in Figure 3 present a WFM noise slope characteristic of a Rb standard in the $5 \times 10^{-12} \tau^{-1/2}$ range. The carrier-phase WPM noise is observed only for the ionofree between 1-2 sec and around $1 \times 10^{-11} \tau^{-1}$. Most likely, the clock noise is over L1 and L2 carrier noise.

A small "bump" is observed in the ADEV around $2.1 \cdot 10^4$ sec, which corresponds to half the orbital period. As it will be shown later, similar bump is observed at $2.1 \cdot 10^5$ sec in Giove-A clocks, which corresponds as well to half the Giove-A orbital period. In the case of GIOVE-A, this has been explained by temperature effects. The bump in GPS clocks could be due to temperature effects or a residual component of the orbit in the processing. Further analysis with respect to the solar beta angle could clarify this point.

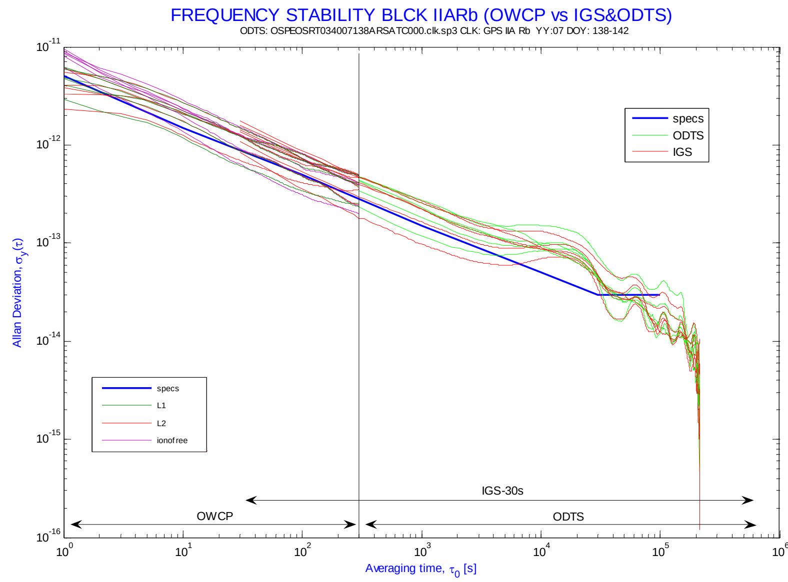

Figure 3. Block II-A Rb clocks, ADEV for 2007 doy 138-142.

Additionally, it is possible to observe some discrepancy between ODTS and IGS results. It can be seen that the WFM level is slightly higher for ODTS results for the best performing clocks. This point will be further analyzed with Giove-A clock estimations.

The Block II-R rubidium and time keeping system in Figure 4 present on the short term a WPM noise slope probably due to the PLL tracking noise, then a transition to a second White PM slope from around 100 seconds. The normal slope for a rubidium standard is White FM instead of PM, as specified in the stability specification for the PerkinElmer RAFS-IIR rubidium standard ($\sigma_y(\tau) \leq 3 \times 10^{-12}\,\tau^{-1/2} + 5 \times 10^{-14}$) **[1]**. Most likely, it is due to the Time Keeping System (TKS) onboard the Block II-R, where a 10.23 MHz digitally controlled VCXO is linked to the RAFS by a software-controlled loop to produce a navigation signal with the timing accuracy of RAFS **[7]**. Finally, from 2500 sec a third transition to WFM noise can be identified. This final period seems to reflect the onboard rubidium performance.

A similar bump to the Block II-A rubidium clocks is observed in the results, but mainly in the ODTS results. Most likely, in the overall II-R assessment it is due to a residual orbital effect in ODTS estimations and a possible second smaller temperature component.

As previously observed in Block II-A results, ODTS and IGS solutions diverge mainly for the best performing clocks. However, in this case the results are coincident for the initial WPN interval until around 2500 sec, after which a slight difference is observed, but only for the best performing clocks. This seems to indicate a WFM floor for ODTS results.

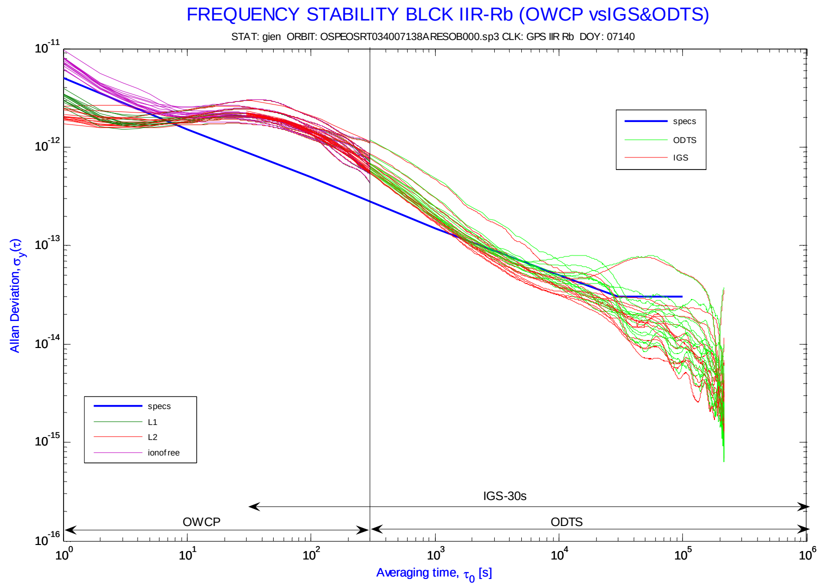

Figure 4. Block II-R (TKS), ADEV for 2007 doy 138-142.

Figure 5 presents Giove-A clocks results, together with clock solutions of stations equipped with H-masers. On the [300, 10^5] sec interval, ODTS and IGS results are presented for all the nominal ODTS processed arcs in 2007 at the moment of this publication. It can be observed how the ODTS solutions for GUSN are almost one order of magnitude higher than expected compared to IGS solutions of USN3 and IENG. Additionally, this solution is almost coincident with the WF noise observed for GIOVE FM4 and FM5 clocks.

On the [1, 300] sec interval, OWCP results obtained for FM5 with all available signals, using the GIEN station for one typical day at the maximum elevation, show very good agreement with ground results and a clear difference with respect to ODTS solutions for FM5.

Two timing laboratories INRIM (former IEN) and USNO host in common clock IGS (IENG, USN3) and GIOVE-M stations (GIEN, GUSN). Driven by a well monitored H-maser, the results for these stations obtained with IGS and the ODTS may be used as a quality control and as identification of the system noise floor. As the typical behavior of the H-maser is below the value observed by the network solution, this can be considered as the noise floor of the Measurement System. Additionally, ground measurements from the qualification of the RAFS in thermal vacuum are available as a reference data set to compare to the onboard results.

As a consequence, the main conclusions are twofold. First, it seems as if the noise floor of the Measurement System composed of the GIOVE-M Network and the ODTS software processing is limiting the estimations; the apparent clock can be observed using ODTS estimations only if this limit is surpassed. Second, the OWCP method allows confirmation that on the short term, FM5 White FM noise is similar to the ground results. On the longer term, it is limited by the expected temperature effect clearly observed at half of the orbital period.

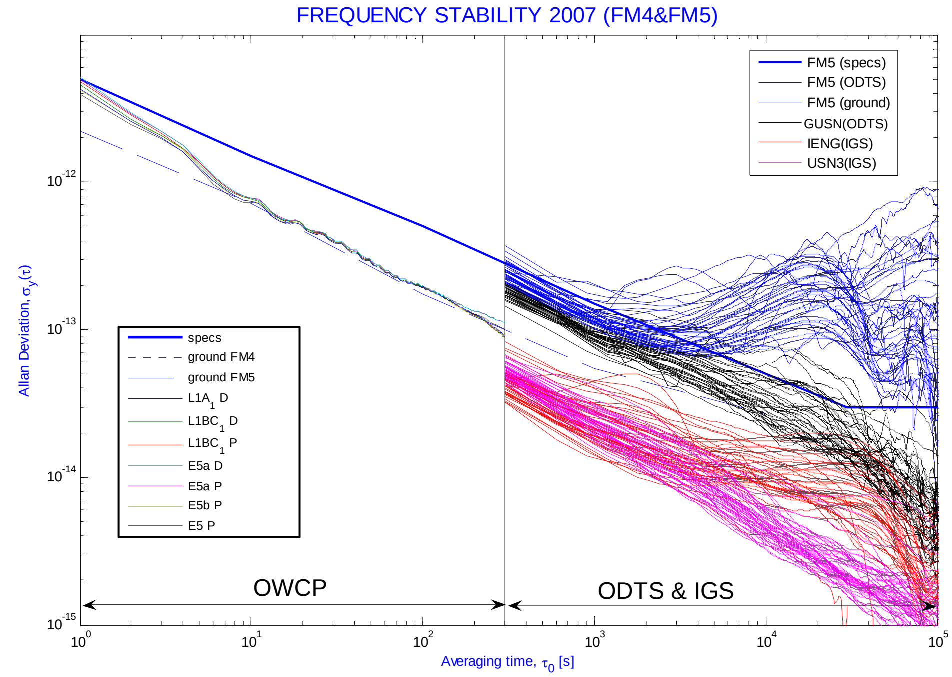

Figure 5. Giove-A ODTS clock results on the right side (2007) and OWCP single frequency results on the left side (doy 140).

Basic observation after the preprocessing in network adjustments is the ionofree linear combinations. The clock information as obtained and disseminated to the user refers to this combination. In order to better compare OWCP and ODTS results, all possible ionofree combinations with GIOVE signals have been computed. Additionally, some GIOVE signals are transmitted in the Pilot and Data component. The Pilot minus Data combination eliminates all common errors, allowing for a pure characterization of the carrier-phase error, as a consequence of which this combination has been computed whenever possible for single-frequency and ionofree combinations.

In OWCP results, Figure 6 additionally to Figure 5 shows the noise as observed with all possible ionofree combinations (dashed lines) and the Pilot minus Data combinations. Ionofree signals are characterized by an initial higher noise intrinsic to the combination, which follows a WPM until converges with the WFM of the rubidium clock. Pilot-Data combinations are characterized by pure WPM around $5 \times 10^{-12} \tau^{-1}$ for the single frequencies and $\sim 1.5 \times 10^{-11} \cdot \tau^{-1}$ for the ionofree. The Pilot-Data combinations identify the WPM of the carrier as the noise observed in the single and ionofree frequencies until it converges with the clock WFM noise.

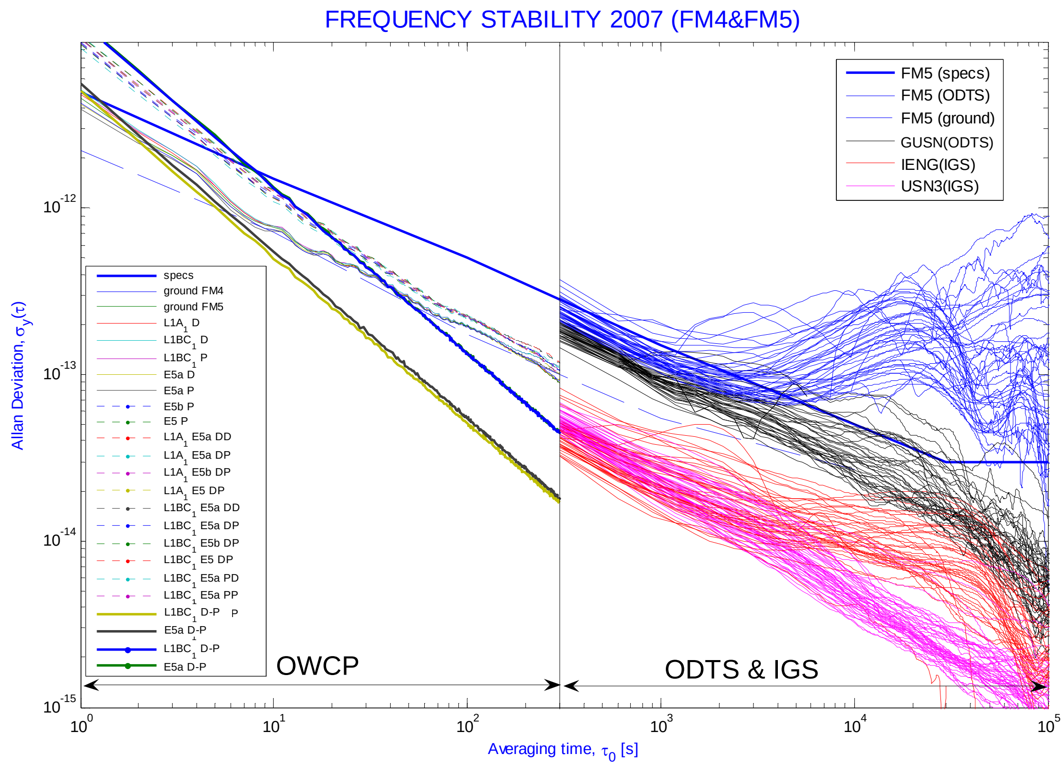

Figure 6. Giove-A ODTS clock results on the right side (2007) and OWCP results on the left side for single freq, ionofree LCs and Pilot-Data (doy 140).

CONCLUSIONS

GPS and GIOVE clocks have been characterized using the GIOVE-Mission Measurement System by network adjustments and the proposed OWCP technique.

OWCP appears to be a simple and interesting technique for the detailed short-term characterization of GNSS clocks. It has been validated against the recently available IGS 30-second clock products and ground results for Giove-A clocks with excellent results. Short-term behavior for GPS and Giove-A clocks has been characterized and the different noise sources on the short term identified.

In addition, the OWCP technique has been used as an alternative and independent method to characterize the noise floor limitations in the actual Giove-M Measurement System, actually over the Giove-A clocks performance. Both OWCP and network techniques have been demonstrated as complementary techniques to fully characterize the clock behavior from 1 second.

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