

Near-real time synchronization through a network of GNSS receivers located in timing laboratories

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ABSTRACT

Today, an increasing number of users need high-quality GNSS products, such as precise satellite orbit and clock estimations and predictions, accurate receiver coordinates or tropospheric delays, for their applications (e.g., precise point positioning, GNSS augmentation services, weather services, etc). In recent years, many national timing laboratories have collocated geodetic GNSS receivers together with their traditional GPS/GLONASS AV/CV and TWSTFT equipments. Many of geodetic GNSS receivers hosted in national timing laboratories, operate continuously within the International GNSS Service (IGS), and their data are regularly processed by IGS Analysis Centers. Whereas participating stations must agree to adhere to certain strict

standards and conventions which ensure the quality of the IGS Network, a number of products and tools have been developed in order to allow time and frequency transfer without taking part to the IGS. Among these, magicGNSS, a web application (<http://magicgnss.gmv.com>) for high-precision GNSS data processing developed by GMV in Madrid, allows the users to perform a wide range of calculations and analyses related to GNSS, from the evaluation of performances at user level, to the computation of precise GNSS orbits and clocks, including the calculation of precise receiver coordinates. The algorithms that process station data to generate products in magicGNSS, are called ODTs, which stands for Orbit Determination & Time Synchronization, and PPP. ODTs is a network solution requiring a set of stations distributed worldwide.

PPP is a single-station solution (although several stations can be processed together for convenience). The advantages of a network solution compared to PPP are that the estimates of each station can benefit from the measures of all stations being in principle more robust and precise. Starting from promising results achieved in recent works, in this paper we want to investigate a possible network solution, similar to the IGS analysis center solutions, that can be easily managed by a network of timing centers to solve in a unique system all the clock differences (besides other quantities), to understand the feasibility and the advantages of this approach in time and frequency transfer. In particular, thanks to the automation of the ODTs process, the possibility to use magicGNSS as a tool for the near-real time synchronization of atomic clocks and time scales worldwide distributed with a latency of at least 30 minutes, is evaluated. Furthermore, the near-real time synchronization capabilities of the ODTs network solution are compared to PPP solutions provided by magicGNSS and other tools, as well as to IGS products and estimates generated by the traditional time and frequency transfer techniques.

INTRODUCTION

In time metrology, different techniques are used for time and frequency transfer, basically TWSTFT (Two Way Satellite Time and Frequency Transfer), GPS CV (Common View) and GPS AV (All in View) [1].

In recent years, many national timing laboratories have collocated geodetic GPS receivers together with their traditional GPS/GLONASS CV/AV receivers and TWSTFT equipment. Time and frequency transfer using GPS code and carrier-phase is an important research activity for many institutions involved in time applications, basically due to the fact that carrier phase measurements generated are two orders of magnitude more precise than the GPS code data. This was recognized when the

International GNSS Service (IGS) and the Bureau International des Poids et Mesures (BIPM) formed a joint pilot study to analyze the IGS Analysis Centers clock solutions and recommend new means of combining them. In addition, the CCTF (Consultative Committee for Time and Frequency), in 2006, passed a recommendation “Concerning the use of Global Navigation Satellite System (GNSS) carrier phase techniques for time and frequency transfer in International Atomic Time (TAI)”. Moreover, the BIPM in 2002 started a project named TAI P3 [2] to examine the use of code and phase measurements.

Many of geodetic GNSS receivers hosted in national timing laboratories, operate continuously within the International GNSS Service (IGS) and their data are regularly processed by IGS Analysis Centers. Participating stations must agree to adhere to certain strict standards and conventions that ensure the quality of the IGS Network. A number of products and tools have been developed in order to allow for highly precise time and frequency transfer without taking part in the IGS.

One standalone GPS carrier phase analysis technique is Precise Point Positioning (PPP), in which dual frequency code and phase measures are used to compare the reference clock of a single receiver to a reference time scale. Several works [3], [4], [5], [6] were carried out to evaluate the time and frequency transfer capabilities of PPP, leading the BIPM to start a pilot experiment which aims to evaluate the possibility of regularly computing some TAI links with the PPP algorithm to obtain an improved statistical uncertainty [7]. The PPP algorithm used for the BIPM pilot experiment has been developed by the Natural Resources Canada (NRCan) [8].

MAGICGNSS

magicGNSS is a web application for high-precision GNSS data processing. It allows the calculation of GPS satellite orbits and clocks, and also of station/receiver coordinates, tropospheric delay and clocks. The user can upload his own station data (RINEX measurement files) and/or use data from a global network of pre-selected *core stations* from IGS.

magicGNSS is available at <http://magicgnss.gmv.com>. A free account can be requested online. A *pro* account can also be requested with advanced features for professional applications. In Table 1, the characteristics of the two *magicGNSS* account types (free and *pro*) are reported.

	free	*pro*
Available algorithms	PPP, ODTS, COMP	
Disk quota	1 Gb	10 Gb
Core station data	last 30 days	from 2008/01/01
IGS products ⁽¹⁾	last 30 days	from 2000/05/03
Navigation messages ⁽²⁾	last 30 days	from 2008/05/03
User station data in ODTS	no	yes
Max. no. of stations in ODTS	36	60
Max. no. of stations in PPP	10	60
Max. data span in PPP	1 day	5 days
Max. data span in ODTS	2 days	5 days
Ftp upload	no	yes
Deletion of user station data	after 30 days	never
Usage of public station data	PPP only	PPP and ODTS
Share your station data	no	yes
Technical support by email	limited	next-day basis

⁽¹⁾ Orbits and clocks needed for PPP and COMP

⁽²⁾ Needed for ODTS initialization

Table 1. Characteristics of *magicGNSS* accounts.

With *magicGNSS*, the user can analyze results in a convenient way through comprehensive PDF reports and organize the processing scenarios and history within his account in an easy way with a generous disk quota [9]. At present, *magicGNSS* supports GPS data, while GLONASS processing is planned for the end of 2009. One of the most interesting characteristics of *magicGNSS* is the easy way to use it. Inside the *magicGNSS* account, one has just to click on *New* to define a new scenario (network), then click on *Save*, and then click on *Run* to process the data and generate results.

The algorithms that process station data to generate solutions in *magicGNSS*, are called ODTS, which stands for *Orbit Determination & Time Synchronization*, and PPP. ODTS is a *network solution* requiring a set of stations distributed worldwide. PPP is a *single-station solution* (although several stations can be processed together for convenience). In ODTS and PPP, the stations must be static. The advantages of a network solution compared to PPP are that the estimates of each station can benefit from the measurements of all stations. This should be in principle more robust and precise. In addition, all clock differences are available in a single solution instead of asking a time consuming series of PPP single station solutions.

There are two types of station data within *magicGNSS*: *core station* data and *user station* data. For ODTS, the server maintains data from 36 IGS core stations distributed worldwide. Current *core station* data is available with a latency of typically one hour. The user (for **pro** account) can also upload his own station data (RINEX files) via the web or ftp. Batch upload and automation are possible using ftp. Normal or compressed data files can be uploaded, and if the RINEX file does not have P1, the C1 code will automatically be converted to P1 using the CC2NONCC tool from IGS. Station data uploaded and shared by other users can also be processed.

The GPS operators inform the users about events affecting satellite availability by publishing messages named NANUs. *magicGNSS* automatically downloads NANUs as they are issued and extracts the relevant information so that only healthy satellites will be considered in the data processing. An additional module, called COMP, allows comparing *magicGNSS* products with IGS and among themselves. Table 2 shows the products generated by *magicGNSS*.

Product	ODTS	PPP	Format	Accuracy (RMS)
Report	✓	✓	pdf	N/A
Satellite orbits	✓	✗	sp3	~2/6/4 cm ^(*)
Satellite clocks	✓	✗	clk	~0.10 ns
Station clocks	✓	✓	clk	~0.10 ns
Station tropo	✓	✓	txt	~5 mm (zenith)
Station coords	✓	✓	snx	<1 cm

(*) In the Radial/Along/Normal directions

Table 2. *magicGNSS* products.

DATA PROCESSING AND PRODUCTS

The basic ODTS and PPP input measurements are pseudorange (code) and phase L1-L2 dual-frequency iono-free combinations. On L1, the P1 code is used in order to be consistent with IGS. The raw input code and phase measurements are decimated and used internally by ODTS and PPP at a typical rate of 5 minutes (down to 30 sec can be used in PPP). The code measurements are smoothed using the phase with a Hatch filter, thus reducing the code error from the meter level to typically 25 cm.

ODTS and PPP are based on a batch least-squares algorithm that minimizes measurement residuals solving for orbits, satellite and station clock offsets, phase ambiguities and station tropospheric zenith delays. In the case of PPP, satellite orbits and clocks are not solved for, but fixed to IGS products (*ultra-rapid*, *rapid* or *final*). For this reason PPP is not a total independent technique, unlike ODTS that, autonomously, provides all products.

Clocks are calculated as snapshot values, i.e., as instantaneous values at the measurement time epoch, without correlation to previous estimates. Clocks are estimated with a rate that typically is five minutes, conversely to the receivers measurements that are generated every second and, then, decimated to 30 seconds.

In ODTS, satellite and station clock offsets are estimated with respect to a reference clock provided by one of the stations and chosen by the user (taking into account that the overall clock stability could be affected by the stability of the chosen reference clock). In PPP, the station clock is referred to the IGS Time scale (IGST), as derived from the satellite clocks in the IGS products. From subsequent subtraction, the differences between station clocks can be inferred.

The satellite and Earth dynamics are based on high-fidelity models that follow IERS recommendations issued in 2003, trying to implement the partial updates that are published periodically, with some delay and only if they're relevant for *magicGNSS* application (it's not guaranteed that all updates have been considered). Modelled effects include a full Earth gravity model, Sun, Moon and planetary attractions, solid Earth tides, ocean loading, and solar radiation pressure (SRP), including eclipses.

Radiation force discontinuities during eclipse entry/exit are smoothed in order to improve orbit accuracy. The satellite attitude is modelled as a generic nadir-pointing yaw-steering law applicable to all GNSS satellites. In ODTS, the orbit fit is based on the estimation of the initial state vector (position and velocity) and 8 *empirical* SRP parameters. Earth Rotation Parameters (ERPs) are automatically downloaded from the IERS server, but they can also be estimated by ODTS itself. The tropospheric correction is based on the estimation of a zenith delay per station (a constant value every hour), using a mapping function to account for the satellite-station signal elevation. Small effects such as relativity and carrier-phase wind-up are also modelled.

For the core stations, a priori station coordinate values come from ITRF or IGS solutions, and they can be refined within the ODTS process. For user stations, the precise coordinates from PPP can be used as input values for ODTS. Satellite and station antenna offsets and phase centre variations are taken into account; the latest ANTEX file from IGS is always used.

TIME AND FREQUENCY TRANSFER EVALUATION SCENARIO

A preliminary evaluation of the time transfer capabilities of *magicGNSS* has been carried out selecting a network of 8 GNSS stations belonging to 6 laboratories contributing to TAI and considered in BIPM TAI PPP experiment, as indicated in Table 3.

Laboratory	TAI code	Country	Station name	Receiver type	Reference
INRIM	IE	Italy	ieng	Ashtech Z-XII3T	UTC(IT)
ORB	OR	Belgium	brus	Ashtech Z-XII3T	UTC(ORB)
PTB	PT	Germany	ptbb	Ashtech Z-XII3T	UTC(PTB)
ROA	RO	Spain	roap	Septentrio PolaRx-3TR	UTC(ROA)
SP	SP	Sweden	sp01	Javad JPS GGD	UTC(SP)
SP	SP	Sweden	sp02	Javad JPS GGD	UTC(SP)
SP	SP	Sweden	spt0	Javad JPS GGD	External H-Maser
USNO	US	United States	usn3	Ashtech Z-XII3T	UTC(USNO)

Table 3. Timing labs and GPS receivers involved in the experiment.

A total of 39 GPS stations are used in the ODTS algorithm, i.e. the 8 *user stations* and 31 *core stations* from IGS. The experiment duration was between 31 Oct 2009–19 Apr 2010 (DOY 304-106 ; MJD 55135 – 55302).

Hourly RINEX files generated by considered receivers and uploaded onto a dedicated *magicGNSS* account, have been processed by means of the ODTS algorithm, with respect to the IENG station clock, chosen as reference. Batches of 2-day duration have been processed in ODTS. This is a compromise between data processing computer speed and clock solution continuity.

The RINEX data is uploaded and processed in near-real time using the Scheduler in *magicGNSS*. The Scheduler runs every hour at 20 minutes after the hour. This delay is on purpose to account for the station data latency and upload time. The ODTS process takes around 5 minutes to complete, therefore synchronization results are typically ready 30 minutes after the hour, for the last hour and before. A live plots system has been set in order to monitor the clocks considered in this experiment at it's available at <http://magicgnss.gmv.com/efrf/>.

A comparison with the estimates generated by *magicGNSS*, PPP, and NRCAN PPP algorithms, together with IGS (*rapid* products), has been performed in terms of phase offsets and frequency stability.

RESULTS

In the next Fig., the USN3-IENG baseline estimates are reported as an example, as generated by both *magicGNSS* ODTS and PPP algorithms, together with IGS (*rapid* products) outputs.

For purpose of plotting, for each of the time series its own mean value and linear drift have been removed. Evaluations of the Allan Deviations are also reported.

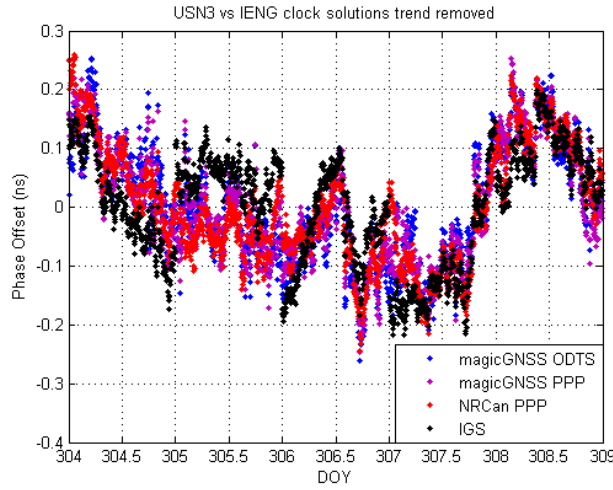


Fig. 1. USN3-IENG baseline clock estimates as obtained with *magicGNSS* ODTs and PPP algorithms, together with IGS (rapid products).

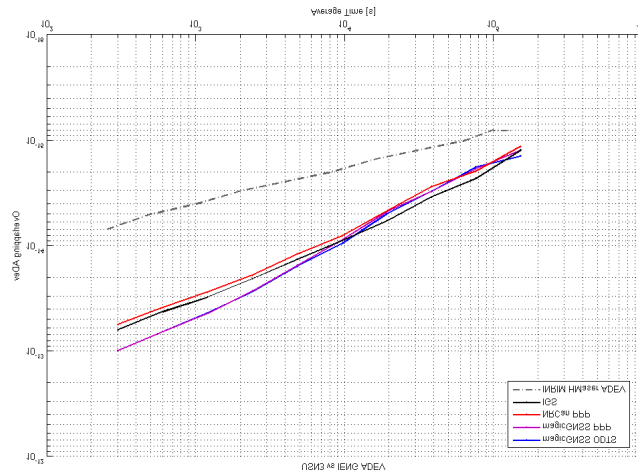


Fig. 2. USN3-IENG baseline clock estimates frequency stability, as obtained with *magicGNSS* ODTs and PPP algorithms, together with IGS (rapid products).

The two time scales comparison results and the frequency stability analysis show a good overall agreement among the estimates generated by the different synchronization techniques (two H-Masers in the case of INRIM and USNO). In particular, it seems that the ODTs technique, even in case of a limited network of 39 stations, offers clock comparisons with a precision that is comparable to the state of the art techniques, such as PPP or IGS products.

A higher short-term noise is observed in the ODTs and PPP solutions from *magicGNSS*. This is believed to be due to the *snapshot* clock estimation in *magicGNSS* (the clocks are estimated as independent values at each epoch, without any constraint with previous clock values), as opposed to sequential filter solutions (NRCAN PPP) or clock averages from different Analysis Centers (IGS), which tend to smooth the short-term clock estimation error.

For completeness, Fig. 3 shows the clock stability of all timing stations with respect to IENG, from ODTs results.

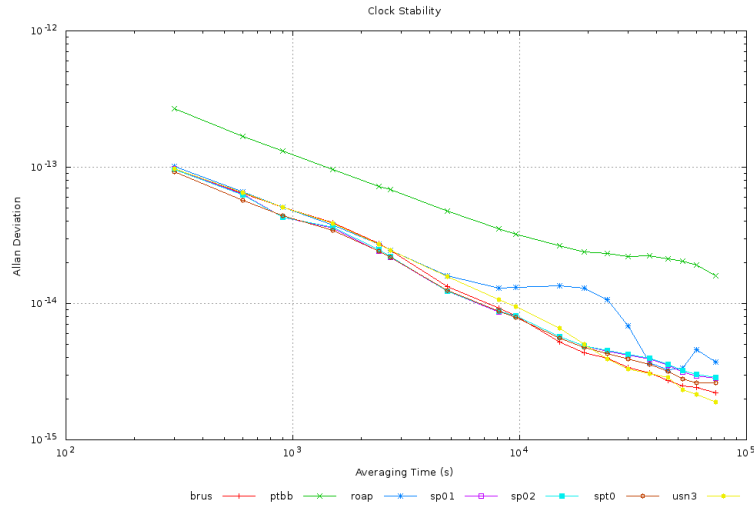


Fig. 3. Clock stability vs IENG from ODTs.

Another complementary assessment, can be obtained by comparing the clock difference between GPS *satellite* clocks as provided by *magicGNSS* ODTs and the same ones provided by the IGS (this kind of evaluation is provided automatically by *magicGNSS* ODTs), considered as reference. IGS solutions take advantage of the highest number of stations tracking GPS in the IGS network (>350), the different software and strategies used by different IGS Analysis Centers, a stable reference frame and most important clock solutions are computed against IGS time scale, avoiding any instability introduced by the reference station used by the ODTs. For the considered network, the total RMS difference is around 0.12 ns (see Fig. 4) and this quantity can be used as an indirect indicator of the precision of the station clocks estimates. Improvements can be achieved adding more station network and distributing the network in a more global way.

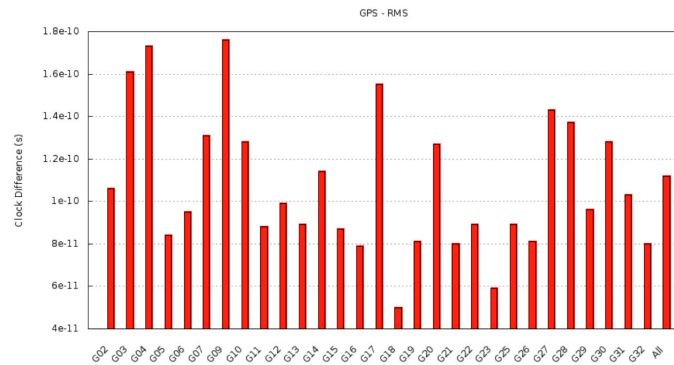


Fig. 4. ODTs vs IGS clock comparison for the GPS satellites.

An additional experiment has been carried out to assess the applicability of the ODTs technique to small station networks. In particular, what accuracy can we obtain if we process only the 8 timing stations in ODTs. The results show that even if globally the orbit determination and clock synchronization is greatly degraded, for short baselines satellite orbit and clock error largely cancel out, and for continental links the clock synchronization accuracy is nearly as good as when using a global network, but not so for inter-continental links.

This is shown in Fig. 5, to be compared with Fig. 3. Notice that except for the inter-continental USN3-IENG link (America-Europe, yellow line) the rest of the European baselines do not show much degradation with respect to the global ODTS network.

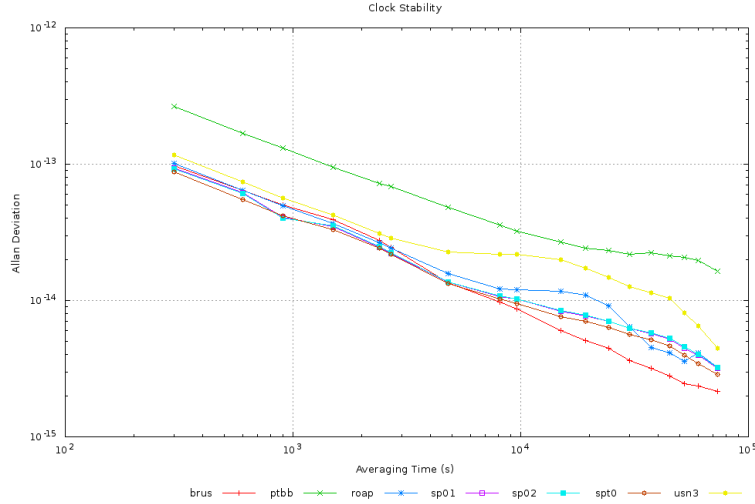


Fig. 5. Clock stability vs IENG from ODTS, using only 8 stations.

In order to assess the presence of the so called “batch boundary discontinuities” in *magicGNSS* outputs (both ODTS and PPP algorithms), for the USN3-IENG baseline, 3 consecutive 5 day batches processing has been performed and compared with the same estimates got by using PPP algorithm developed by NRCan and IGS estimates which are estimated on daily batches. Results are reported in Fig. 6 and Fig. 7

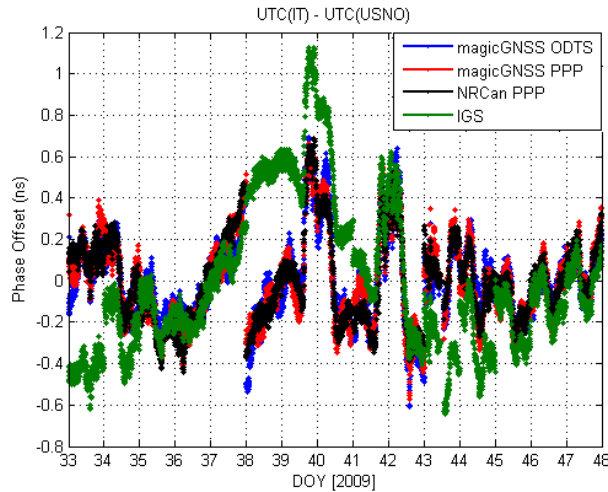


Fig. 6. USN3-IENG baseline clock estimates as obtained with *magicGNSS* ODTS and PPP algorithms, together with NRCan PPP and IGS (rapid products) outputs.

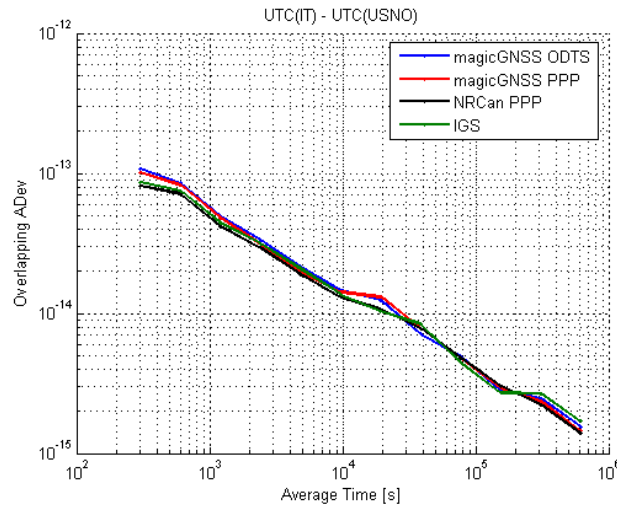


Fig. 7. USN3-IENG baseline clock estimates frequency stability, as obtained with *magicGNSS* ODTs and PPP algorithms, together with NRCan PPP and IGS (rapid products) outputs.

The accuracy of GPS-based time and frequency transfer using combined analysis of code and carrier phase measurements greatly depends on the noise of the GPS signals. In particular, the pseudorange noise is responsible for batch-boundary discontinuities that can reach, for some stations, more than 1 ns in the time transfer results obtained from geodetic analysis. These discontinuities are caused by the fact that the data are analyzed in batches and within each batch the station clock offset and carrier-phase ambiguities are estimated by the observed pseudoranges.

The pseudorange noise is sometimes and for some stations not white noise, for example, because of near-field multipath effects or variation of instrumental delays. The averaging of this colored pseudorange noise induces clock datum changes between (daily) batches at the level of a few hundred ps to a few ns [10]. IGS uses daily batches, therefore the boundary jumps are visible from day to day. PPP is based on the IGS estimates and therefore may inherit this effect. *magicGNSS* at the moment is used on batches of 5 days and therefore the boundary jumps are mostly visible on that boundaries. The effect of batch boundary jumps can be reduced through averaging over multi-day intervals of different duration [4] or mixing GPS geodetic results with other independent techniques such as the TWSTFT.

CONCLUSIONS

The presented work represents a preliminary investigation about the time/frequency transfer capabilities of the *magicGNSS* web application, in near-real time with a typical latency of 30 minutes in the results. First outcome show promising performances.

The results presented in this paper can be browsed in near-real time on the following *live* web page: <http://magicgnss.gmv.com/eftf>.

More investigations are in progress taking into account different periods and different types of networks, looking also at the robustness and reliability of the algorithm. Also, since that through PPP/ODTS techniques the clocks are “seen” at the receiver phase center antenna (measures are not “calibrated”), in future works “calibration” issues will be specifically addressed.

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