Time and Frequency Transfer 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 Global Positioning System receivers together with their traditional GPS/GLONASS Common View receivers and Two Way Satellite Time and Frequency Transfer equipments. Time and frequency transfer using GPS code and carrier-phase, is an important research activity for many institutions involved in time applications. This was recognized when the International GNSS Service (IGS) and 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. 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. magicGNSS is a suite of GNSS SW products developed by GMV in Madrid, that 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. In the present work, time and frequency transfer capabilities of this tool are evaluated, with the aim of exploring a possible network solution for geodetic GNSS receivers located in National Timing Laboratories not necessarily taking part to the IGS and aiming at comparing their time scales at the maximum level of precision**.

I. Introduction

In time metrology, different techniques can be involved for the time 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 equipments. 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.

CCTF (Consultative Committee for Time and Frequency), at its 17th meeting in September 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)”.

One 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 [2],[3] have been performed in order to evaluate the time and frequency transfer capabilities of PPP, leading the BIPM to start with a pilot experiment which aim is to regularly compute some TAI links, that should provide a much improved statistical uncertainty, expecting that the pilot experiment will result in the future use of the PPP technique for TAI computation [4]. The PPP algorithm used for the BIPM pilot experiment has been developed by the Natural Resources Canada (NRCan) [5].

II. 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) 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.

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In the next Table I, characteristics of the two *magicGNSS* account types (free and *pro*) are reported:

TABLE I. CHARACTERISTICS OF MAGICGNSS ACCOUNTS

	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 2008/01/01
Navigation messages(2)	last 30 days	from 2008/01/01
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

With *magicGNSS* the user can analyze results in a convenient way, through comprehensive and colorful PDF reports, and organize the processing scenarios and history within his account in an easy way with a generous disk quota [6]. At present, *magicGNSS* supports GPS data. GLONASS processing is planned for autumn 2009.

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). In ODTS and PPP the stations must be static.

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 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.

NANUs are messages published by GPS operators to inform the users about events affecting satellite availability. *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.

In the next Table II, *magicGNSS* generated products are reported, whilst in following Figure 1, a screenshot of the main page of *magicGNSS* INRIM user account is shown.

TABLE II. MAGICGNSS PRODUCTS

Product	ODTS	PPP	Format	Accuracy (RMS)
Report	✓	✓	pdf	N/A
Satellite orbits	✓	✗	sp3	~2/6/4 cm(*)
Satellite clocks	✓	✗	clk	~0.15 ns
Station clocks	✓	✓	clk	~0.15 ns
Station tropo	✓	✓	txt	<1 cm (zenith)
Station coords	✓	✓	snx	<1 cm

(*) In the Radial/Along/Normal directions

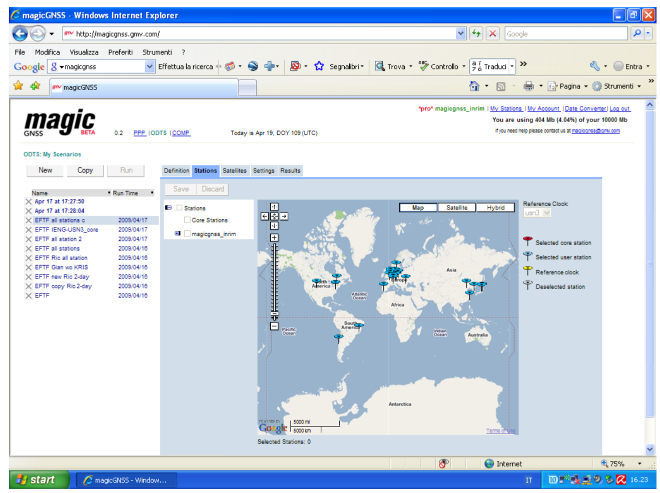

Figure 1. Screenshot of *magicGNSS* INRIM user account main page.

III. 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 core measurements are smoothed using the phase with a Hatch filter, thus reducing the code error from the meter lever 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, conversely to ODTS that, autonomously, provides all products.

Clocks are calculated as snapshot values, i.e., as instantaneous values at the measurement time stamp. Clocks are estimated at the same rate as the internal measurements (typically every 5 minutes).

In ODTS, satellite and station clock offsets are estimated with respect to a reference clock, provided by one of the stations. In PPP the station clock is referred to the IGS Time scale (IGST), as derived from the satellite clocks on the IGS products.

The satellite and Earth dynamics are based on high-fidelity models that follow IERS recommendations. 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 1 or 2 hours), 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.

IV. Time an Frequency Transfer Evaluation Scenario

A preliminary evaluation of the time transfer capabilities of *magicGNSS* has been carried out selecting a network of 23 GNSS stations belonging to laboratories contributing to TAI and considered in BIPM TAI PPP experiment, as indicated in Table III.

RINEX files generated by considered receivers and uploaded into INRIM account, have been computed by means of *magicGNSS* ODTS algorithm, with respect to the clocks of PTB and USNO stations, chosen as reference.

Baselines formed by UTC(IT) time scale with respect to USNO and PTB ones, have been addressed and a comparison with the same estimates generated by *magicGNSS* PPP and NRCan PPP algorithms, together with TWSTFT outputs, has been performed in terms phase offsets and frequency stability.

Due to the ODTS (and other similar techniques) features, no more than 5 days batches can be processed.

For the present work, 2009 February 2nd (MJD 54864 , DOY 33) - 2009 February 6th (MJD 54868 , DOY 37) period has been considered and related analysis reported in the next session.

TABLE III. LABORATORIES CONSIDERED IN THE WORK

Lab.	***Country***	***Station***	***Receiver type***	***Reference***
ORB	Belgium	BRUS	Ashtech Z-XII3T	UTC(ORB)
TCC	Chile	CONT	Septentrio PolaRx2	Maser
INRiM	Italy	IENG	Ashtech Z-XII3T	UTC(IT)
NIM	China	IMPR	Septentrio PolaRx2TR	UTC(NIM)
KRISS	S. Korea	KRIS	Ashtech Z-XII3T	UTC(KRIS)
NIMB	Romania	MBRO	Septentrio PolaRx2	UTC(NIMB)
NICT	Japan	NICT	Septentrio PolaRx2TR	UTC(NICT)
NIST	U.S.A	NIST	Novatel OEM4 T-sync	UTC(NIST)
NMIJ	Japan	NM0C	Ashtech Z-XII3T	UTC(NMIJ)
NRC	Canada	NRC3	Ashtech Z-XII3T	Maser
NRL	U.S.A	NRL1	Ashtech Z-XII3T	UTC(NRL)
DLR	Germany	OBET	Septentrio PolaRx2	UTC(DLR)
OP	France	OPTM	Ashtech Z-XII3T	Maser
PTB	Germany	PTBB	Ashtech Z-XII3T	UTC(PTB)
ONRJ	Brazil	RJEP	Septentrio PolaRx2e	HP 5071A
ROA	Spain	ROAP	Septentrio PolaRx2	Maser
SP	Sweden	SP01	Javad	UTC(SP)
TP	Czech Rep.	TP04	Dicom GTR-50	UTC(TP)
TL	Taiwan	TWTF	Ashtech Z-XII3T	UTC(TL)
USNO	U.S.A	USN3	Ashtech Z-XII3T	UTC(USNO)
VSL	Holland	VSLD	Topcon Legacy-E	UTC(VSL)
METAS	Switzerland	WAB2	Ashtech Z-XII	Maser
IFAG	Germany	WTZA	Ashtech Z-XII3T	UTC(IFAG)

V. Results

In the next Figures UTC(IT)-UTC(USNO) and UTC(IT)-UTC(PTB) baseline estimates expressed in nanoseconds are reported, as generated by both *magicGNSS* ODTS and PPP algorithms, together with TWSTFT outputs. For purpose of plotting, mean value and linear drift have been removed. Evaluations about frequency stability have been performed in terms of Allan Deviation.

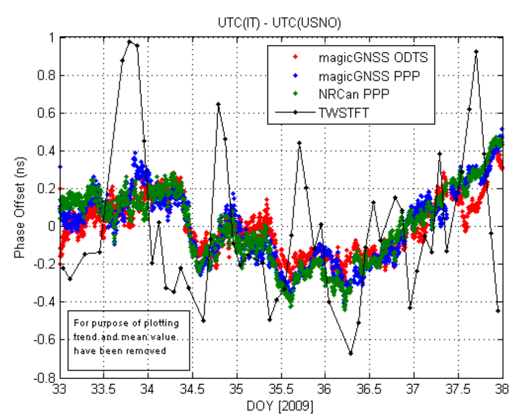

Figure 2. UTC(IT)-UTC(USNO) baseline clock estimates as obtained with *magicGNSS* ODTS and PPP algorithms, together with TWSTFT outputs.

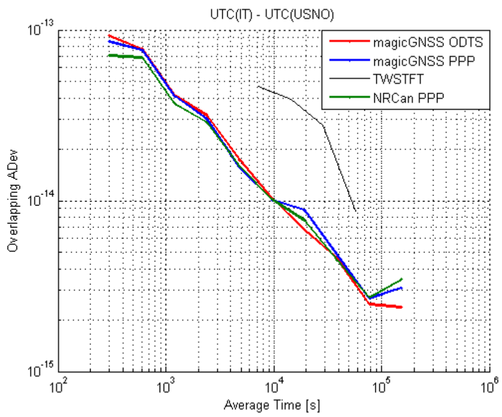

Figure 3. UTC(IT)-UTC(USNO) baseline clock estimates frequency stability, as obtained with *magicGNSS* ODTS and PPP algorithms, together with TWSTFT outputs.

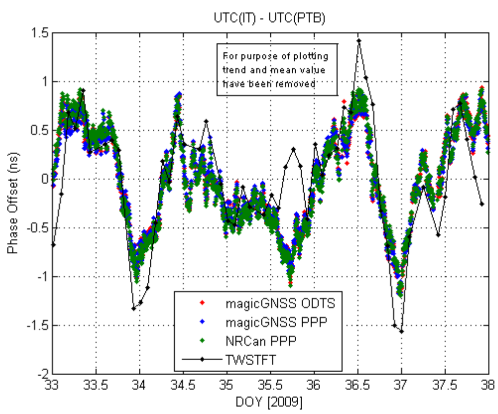

Figure 4. UTC(IT)-UTC(PTB) baseline clock estimates as obtained with *magicGNSS* ODTS and PPP algorithms, together with TWSTFT outputs.

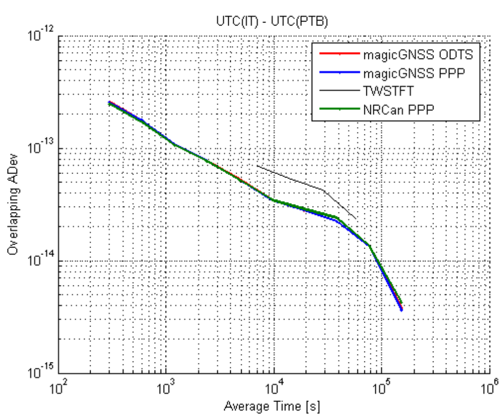

Figure 5. UTC(IT)-UTC(PTB) baseline clock estimates frequency stability, as obtained with *magicGNSS* ODTS and PPP algorithms, together with TWSTFT outputs.

The two time scales comparison data and the Frequency stability analysis show a good overall agreement among the estimates generated by the different synchronization techniques (Two H-Masers in case of INRIM/USNO, One H-Maser and one Cs standard in case of INRIM/PTB).

Next Figure 6 indicates the location of the laboratories considered in the experiment, whilst in the following Figure 7 the clock difference among GPS satellite clock estimates provided by *magicGNSS* ODTS and the same ones provided by IGS is reported (RMS difference of all satellites at each epoch). The total RMS difference is around 0.25ns. Satellite clock error (vs IGS) can be used as an indirect indicator of the precision of the station clocks estimates.

The best estimation precision that can be provided by ODTS using a dense global network is around 0.1 ns RMS (similar to IGS). With a sparse network like the analyzed one, a clock precision of around 0.25 ns is achieved. Improvements adding more station network are to be studied.

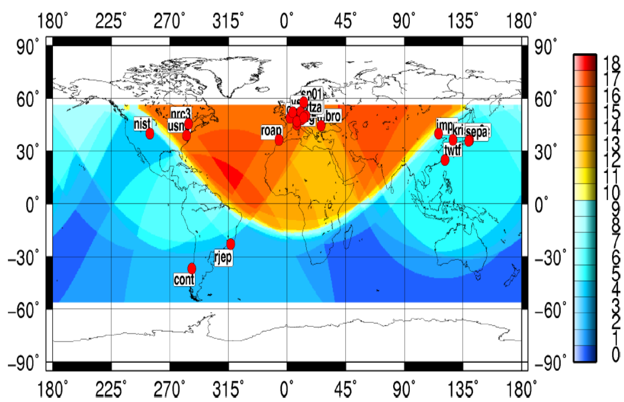

Figure 6. Location of the stations considered in the present work and belonging to laboratories contributing to TAI and considered in BIPM TAI PPP experiment.

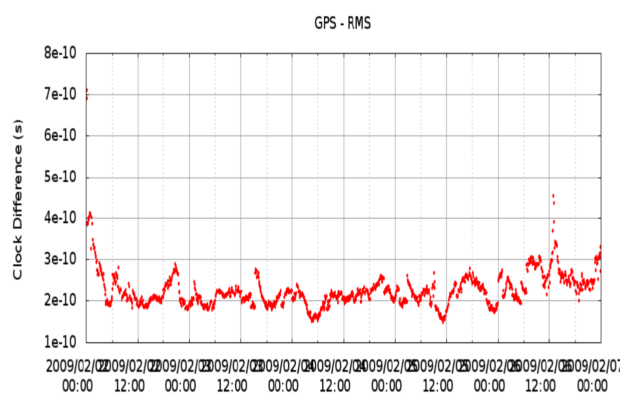

Figure 7. RMS difference between ODTS and IGS satellite clocks.

VI. A POSSIBLE APPLICATION: LINKS FOR THE INTERNATIONAL ATOMIC TIME COMPUTATION

The current configuration of the time links between laboratories and the techniques used for the computation of TAI , are depicted in the next Figure 8.

Figure 8. Current configuration of the time links between laboratories and the techniques used for the computation of TAI.

The time laboratories taking part to TAI form a sort of network, but their time scales are typically compared with single link techniques without taking complete advantage of the available redundancy and crosslink's. Recent works from BIPM [7] are exploring the advantages of treating a network of TWSTFT links.

A network solution based on worldwide geodetic GNSS receivers hosted in national timing laboratories not necessarily taking part to the IGS, could be considered as a viable solution for a precise time transfer network.

The use in TAI would also request accuracy of the time transfer and to this aim the calibration of the geodetic receiver is an important issue that has to be carefully addressed.

VII. CONCLUSION

Present work represent only a preliminary investigation about the time/frequency transfer capabilities of *magicGNSS* beta version suite. First results show promising performances. More investigations will be carried out in planned further works, taking into account for different periods, different types of network, looking also at the robustness and reliability of the algorithm.

VIII. AKNOWLEDGMENTS

Authors wish to thank all the people in timing laboratories involved in this experiment, colleagues at BIPM, namely Gerard Petit, for granting the use of their GPS and TWSTFT data and the Geodetic Survey Division, Natural Resources Canada (NRCan), for providing the NRCan PPP software.

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