Real time tropospheric delay measurements for time and frequency transfer using GNSS

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Abstract. Time and frequency transfer using GNSS is affected by disturbances in the link between satellite and receiver. This degrades the time solution of the receiver, implying in erroneous local clock evaluation and in some cases, wrong clock calibration. In modern receivers it is possible to measure the ionospheric delay using dual frequency observations, but the tropospheric delay in the way is still being modelled by receiver altitude and satellite elevation. In this text an evaluation of the effect of updating the default model with real-time tropospheric delay measurement using Temperature, Humidity and Atmospheric pressure data.

Introduction

Time transfer is fundamental to time and frequency metrology. Using global navigation satellite systems (GNSS), it is possible to provide UTC time dissemination services [1], positioning systems [2] and remote calibration [3]. Currently, time-dissemination services lead to a time transfer accuracy of the order of 1-2 ns, which can be improved by estimating uncertainty sources such as tropospheric delay [4] and signal transmission cables delay [5]. The troposphere disturbs the transmission of GNSS signals and is therefore a source of uncertainty for the realisation of the temporal transfer. Due to the temporal variability of the troposphere density, the signal propagation is modified, leading to a delay in the reception of the transmitted signal [6].

Concerning other earth's atmosphere layers such as the ionosphere, it is possible to rely on receiver's delay estimation using L1 and L2 frequencies code and phase observations [7] because its observations are made estimating the internal phase deviation of both carriers looking at its generation point, the satellite [8]. In line with the current demands for time and frequency metrology, the document referring to the strategic guidelines for Brazilian metrology from 2018 to 2022, highlights the development of the processes required to ensure the remote traceability of frequency standards and clocks using (GNSS) constellations [9]. In the scientific literature, there are some works describing methods such as: PPP (Precise Point Positioning), Optical Fiber Time Transfer and Two-Way Satellite Time and Frequency Transfer [10][11][12]. These are the most reliable ones, including the P3 frequency combination method, which is the one that is used in this text.

In this context, this paper presents first results for the estimation of the tropospheric delay associated with the UTC(LRTE) using real time environment data. The work is based on the comparison between the tropospheric delay estimated by the receiver and that estimated by the hopfield model. From this comparison, it is possible to verify that the Hopfield model for LRTE is a good choice for timescale troposphere correction at GNSS signals.

Methodology

For presented tests and evaluation, the UTC(LRTE) timescale structure was used. UTC(LRTE) is a traceable timescale that has time and frequency monitored and controlled 24/7, for its control an algorithm that processes GNSS data is running each 2 days and generating new frequency corrections for main timescale's synthesiser that is connected to the main timescale's cesium frequency standard.

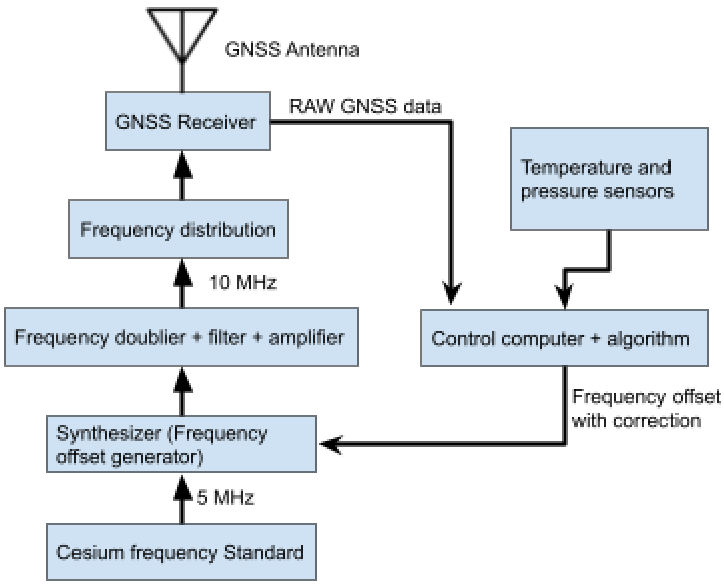

Fig. 1: UTC(LRTE) timescale simplified schematic.

So, the schematic above shows the timescale's basic structure. For this work wasn't implemented based on temperature and pressure data corrections. But as **Fig. 1** shows, temperature and pressure values were acquired at the same time of RAW GNSS data. The control computer runs an integrative algorithm that processes past two days phase data provided by P3 GNSS observations in nanoseconds. So, this is local frequency standard time compared to each satellite's frequency standard time. Using that it is possible to generate frequency deviation for the past two days and as result, a frequency correction for the synthesiser that is connected to the Cesium frequency standard.

For all data presented in this work, Hopfield's model uses real-time Temperature, Pressure and Altitude of our meteorological station. Temperature and Pressure was acquired using Bosch's BME 280 sensor. Altitude was used the precise BIPM's station position data calculations that are processed using UTC(LRTE) data contribution. Altitude can also be measured using a different path, for example using an altimeter, that will disconnect the altitude data of the tropospheric delay influence, providing an accurate comparison between the receiver's ZTD model and the Hopfield's ZTD real-time data.

Let's start with the ZTD calculation using Hopfield's model:

First of all, the total local vapour pressure is calculated:

$$e = \left[1.007 + \left(3.46 \cdot 10^{-6} \cdot P\right)\right] \cdot 6.1121 \cdot \exp\left(\frac{17.502 \cdot T_0}{240.97 + T_0^2}\right)$$

Now, the dry and wet refractivity respectively:

$$N_{dry} = 77.631 \cdot \frac{P}{T_0}$$

$$N_{wet} = 77.631 \cdot 4180 \cdot \frac{e}{T_0^2}$$

And also, the dry refractivity index in function of altitude:

$$h_{dry} = 40136 + 148.72 \cdot (T_0 - 273.16)$$

Finally, is possible to find wet and dry components for ZTD computation:

Wet, in function of altitude:

$$d_{wet}^{z} = N_{wet} \cdot h \cdot 2 \cdot 10^{-7}$$

Dry:

$$d_{dry}^{z} = N_{dry} \cdot h_{dry} \cdot 2 \cdot 10^{-7}$$

And finally, to compose the total zenith tropospheric delay in metres:

$$ZTD = d_{dry}^{z} + d_{wet}^{z}$$

Where:

P is the local atmospheric pressure in hPa, T_0 is the local environment temperature, 77.631, 148.72, 4180 and 40136 are empirical constants from [13] used in Hopfield model. ZTD is the total zenith tropospheric delay. For the input data was used temperature and pressure from BME280 sensor, which, respectively has an uncertainty of +-0.1 ºC and +-1 hPa. Moreover, real-time altitude data. Which is processed using RT-PPP locally and has an uncertainty of +- 10 cm. The BME sensor data was acquired as a mean of 2 hours readings of 15 minutes interval point-to-point. The RT-PPP altitude was used also as a mean of 2 hours readings, but with a 30 seconds interval point-to-point. After computing the Tropospheric delay in metres, it is possible to easily convert it to nanoseconds delay using the speed of light in the vacuum to compare it with P3 observation data.

REFSYS is already corrected by MDTR, so, to evaluate it using MSTR it is mandatory to remove MDTR component from REFSYS doing a simple subtraction of it for each satellite and then apply MSTR correction to the uncorrected REFSYS. For CGGTTS data, 2 hours of point-to-point data. That consists of a dataset like this example. The common name for MDTR is Modelated Troposphere Delay. So, the authors decided to call the Real-time measurement of MSTR - Measured Troposphere Delay:

Satellite PRN	**Elevation (º)**	**REFSYS (ns)**	**MDTR (ns)**	**MSTR (ns) at antenna's zenith**	**MSTR for each satellite in function of elevation**
G06	43.5	3.1	10.7	7.063149233	10.23952692
G11	48.8	2.9	9.8		9.372309982
G12	33.7	7.2	13.2		12.6840764
G13	21.6	4.7	19.9		19.01947548
G15	24.4	6.6	17.6		16.9799702
G19	29.2	8.8	15		14.40795332
G24	62.2	5.2	8.3		7.978099499

PRN: Is the satellite identification. G for GPS constellation and respective satellite number.
Elevation: is the satellite elevation in the sky in respect to the ground.
REFSYS: Is the difference between local clock and satellite clock.
MDTR: Is the CGGTTS P3's default model for troposphere delay for each satellite.
MSTR: Is the model being analysed measuring live data of temperature, pressure and altitude.

To calculate the MSTR in function of elevation, this equation can be used:

$$MSTR_{\emptyset} = MSTR_z \cdot \frac{1}{sin\frac{\emptyset \cdot \pi}{180}} + \frac{0.00143}{tan\frac{\emptyset \cdot \pi}{180}} + 0.0455$$

Where:

$MSTR_{\emptyset}$ is the Measured Tropospheric Delay for the satellite with its respective elevation angle in the sky; $\emptyset$ is the elevation angle for a satellite and $MSTR_z$ is the Measured Tropospheric Delay for antenna's zenith.

Results

1. Evaluation between real-time acquired delay and real-time modelled delay

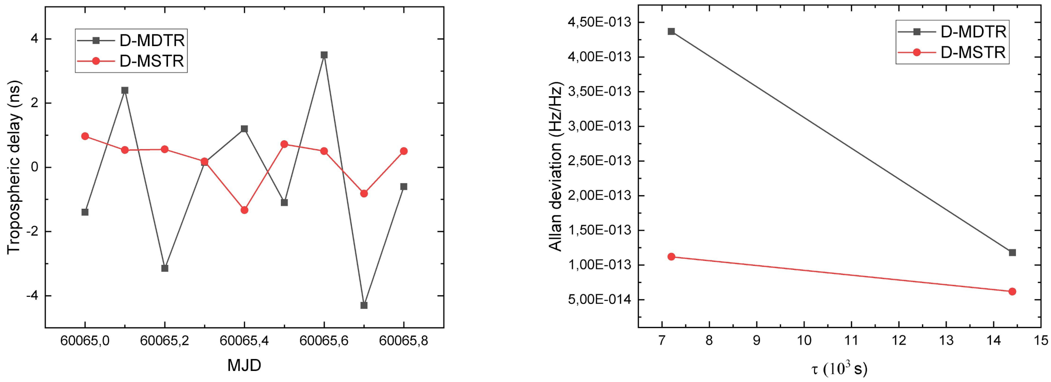

Fig. 2a and 2b - Variation of the tropospheric delay predictions and Allan deviation for each data (lower Allan deviation is better).

To compare modelled and real-time data, a variation analysis was done. As is possible to see with **Fig. 2a and 2b** the measured real-time delay values (MSTR) presented a stabler behaviour. Meanwhile, the receiver's model (MDTR) presented a noisy behaviour. In an analysis of the real temperature and pressure values it isn't possible to see big differences in time, that means that the troposphere isn't noisy like MDTR shows, but it still has a continuous delay that affects the time and frequency comparsions.

2. Evaluating the real-time acquired delay in the receiver's clock solution

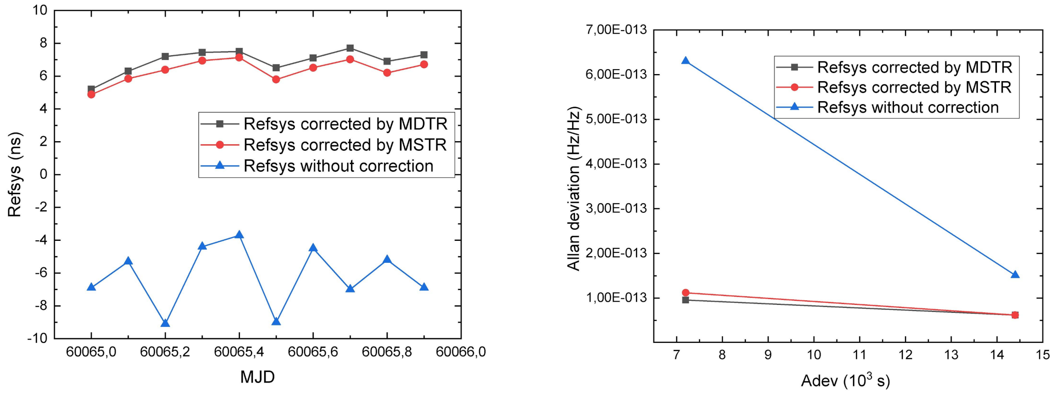

Fig. 3a and 3b - REFSYS variations using different troposphere delay corrections and Allan deviation for each data (lower Allan deviation is better).

Using no correction, it is possible to see the troposphere disturbances affecting the clock solution. Concerning the fact that Cesium frequency standards are stable frequency sources, it isn't necessary to apply frequency corrections for each hour, for example. It doesn't make sense if they're operating normally. It is hard to differentiate between MSTR and MDTR in the **Fig. 3a**, only a few nanoseconds offset are observable between two data points, and the variation seems to be the same for the eye. But if Allan's variance is applied in the both data, as was done in the **Fig. 3b**, it's possible to see a little difference between MSTR corrected REFSYS and MDTR corrected REFSYS. Both data are better than no correction data. For short term frequency stability analysis, MDTR seems to be better than MSTR, but the erroneous variation of MDTR should be taken into account, this may mask the real frequency source behaviour while evaluated using GNSS.

Conclusions

It is possible to use the MSTR data to increase the certainty of the time offset measured by REFSYS and also improve the evaluation short term stability of the local clock that is being analysed. With this it is possible to improve frequency corrections that will be applied to the local clock and also measure with more confidence the time offset between two clocks in different locations. Also, increase the certainty of frequency calibrations in different frequency sources using high rate phase data acquisition.

Concerning the fact of having good sensors for temperature and pressure, the MSTR can be an alternative to MDTR in P3 data and also, an alternative to modelled ZTD in PPP post processing, improving the accuracy of the final position solution. This can easily be a possibility of uncertainty removal for troposphere components applied to remote time and frequency calibrations. Of course, the MSTR should be measured in real time together with the clock measurements and PPP measurements.

Further Work

The measurements of Temperature and Pressure should be done side-by-side with the GNSS's receiver antenna. In this case, it was not possible to measure it side-by-side but the measurements were done close enough and in an open air area, so, here is presented the real behaviour of local climate changes to feed the Hopfield model. Also, the sensor used can be better and with bigger accuracy. Using these improved situations, the plan is to repeat the same conditions in other laboratories and then try to calibrate a frequency standard using P3 data and MSTR data.

This is the first work of a long term project with the goal of realising the estimation of the tropospheric delay using data science, such as neural networks and temporal series. Using this, it is possible to predict with better accuracy the real troposphere delay and noise, and also improve remote calibration methods that today are only available in the frequency domain, expanding it to time calibration domain.

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