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PROGRESS IN ACCURATE FREQUENCY TRANSFER BY GPS AND GEO CARRIER PHASE AT CNES

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Abstract - **This paper presents the recent improvements in accurate frequency transfer by GPS and GEO (SBAS) carrier phase at CNES. In a previous paper [4], we described the software used at CNES for GPS frequency transfer using carrier phase and we reviewed the performances obtained with two different clock resolution algorithms. In the best case, we obtained a stability of $\sigma_y(\tau) = 4.10^{-15}$ for $\tau = 10^4$ s between ALGO and NRC1, both stations being driven by a Hydrogen Maser.**
In this paper, we present the improvements performed on this software to process GEO measurements. The GEO satellites provide some advantages and drawbacks that are discussed. For the time being, in our configuration, the GEO carrier phase frequency transfer is limited by code noise and ionosphere correction.
***Keywords* - frequency transfer, GPS, GEO, carrier phase**

I. Introduction

For many years, the Global Positioning System (GPS) has been used to compare distant ground clocks. The classical technique is the common-view where the two receiver clocks are obtained by processing code measurements on one single GPS satellite (chosen using a predefined schedule). This processing is equivalent to use the single difference code measurement residual at each epoch.

Geodetic GPS receivers are now able to handle several channels (so that several satellites can be observed in the same time) and two frequencies (so that the ionospheric delay can be removed). So, using all the code measurements, an extension of the classical technique is possible in order to have more precise results. Moreover, they are able to record code and carrier phase observables. It is well known that the latter offers promising perspectives for accurate frequency transfer for integration times between several hours and several days [1,2,3].

In a previous paper [4], we described the software used at CNES Toulouse for frequency transfer using GPS carrier phase and we reviewed the performances obtained with two different GPS receivers and with two different clock resolution algorithms.

The software was initially developed by CNES Precise Orbit Determination Group, but it can also be used for ground and space clocks identification. The CNES Time/Frequency Department uses this software with GPS code and phase data coming from a GPS receiver connected to a Hydrogen Maser.

In this paper, we present the recent improvements in our software, especially to take into account GEO satellites. Three GPS/GEO receivers are currently used at CNES to collect RINEX files : a MiLLenium WAAS OEM-3 and an OEM-4 (NovAtel) and an Aquarius (Thales). Our software had also to be modified in order to take into account the Aquarius receiver which has a different working mode (emission synchronized measurements).

SBAS (Satellite Based Augmentation System) - referred to as GEO satellites in this paper - are very interesting thanks to their continuous observability, nevertheless they raise at least two problems that need to be looked into : orbit and ionosphere correction. The next section discusses the advantages/drawbacks of GEO satellites w.r.t. GPS for accurate frequency transfer. We present results on short baselines which enables us to compare the clock solution by GPS frequency transfer to local comparison, then we compare the noise transfer (in common clock configuration) using GPS only and using GEO only. Last, we perform a GEO frequency transfer between CNES and BIPM using parabolic antennas.

II. GPS vs. GEO FREQUENCY TRANSFER

In our work, we consider the Inmarsat AOR-E satellite (PRN 120) to perform frequency transfer on a short baseline (a few decimetres) and on a CNES/BIPM baseline (about 600 km). This satellite broadcasts code and phase pseudorange measurements on L1 only, navigation messages, …

The EGNOS network computes in real time a model for ionosphere correction, and this model is included in the message.

Other GEO satellites may be used, like WAAS (AOR-W, PRN 122) over North America, provided it is in common view of the 2 stations to compare.

As already mentioned the main advantage of GEO satellites is their continuous observability, which implies a simplification of the data processing.

The GEO broadcasting on a single frequency is obviously a problem because the usual way to cancel the ionosphere effects is to compute a combination of two frequencies (the iono delay is proportional to $1/f^2$). Two solutions can be envisaged to overcome this problem :

- use of broadcast information (EGNOS mapping)
- use of code/phase difference

The ionosphere distorts the code and the phase by the same value but in the opposite direction, so the ionospheric correction can be computed as half of the code/phase difference. But, in order to use this technique with a sufficient accuracy, we need to reduce the noise of the code that significantly affects the result. This can be done with directional parabolic antennas that provide a better signal to noise ratio.

III. THE SOFTWARE

The software part for frequency transfer uses two stations RINEX files for the measurements (one day measurements), the precise IGS ephemerides (sp3 format, available on the IGS web site [6]), and the EGNOS broadcast navigation files for the geostationary satellite ephemerides (estimated precision around ten meters).

The measured data are pre-processed in order to detect all cycle slips, and construct the measurement passes where phase ambiguity remains constant. No integer fixing of the ambiguity is performed. The used measurements are directly the iono-free combination for both code and phase.

For GPS frequency transfer between two stations, the solution is performed on a daily basis, with adjusting of one set of station coordinates (three center of phase coordinates), tropospheric vertical delay for each station (two hours intervals linear evolution), floating ambiguities and clock difference at each epoch. All computations are performed in terrestrial frame.

It is also possible to perform such a solution on longer durations, but this has not been completely implemented yet in the least squares solution [4]. A Kalman filter was developed for such continuous resolutions on complete networks (stochastic modelisation of tropospheric delays, clock at each epoch, ambiguities and coordinates adjustment).

For the GEO, the residual of the single difference phase and code measurements is computed (coordinates and tropospheric delay are obtained by the corresponding GPS solution). Then various post processing can be performed (for example, combination of code and phase for ionospheric elimination, or application of the EGNOS broadcast iono corrections).

The clock time difference between the clock feeding the GPS/GEO receiver and ENT (EGNOS Network Time) or GPS Time is defined as the difference between the measured and the theoretical pseudorange. The former must of course be corrected of the atmospheric propagation errors.

We note P_{theo_a} the theoretical distance between a satellite and the antenna of station a and P_{meas_a} the corresponding measured pseudorange. These distances can be expressed in code (C) or carrier phase (L). So the clock time difference between station a (H_a) and satellite (H_{GPS}) is :

$$H_a - H_{GPS} = \mathrm{P}_{\mathrm{meas\_a}} - \left(\mathrm{P}_{\mathrm{theo\_a}} + \mathrm{tropo}_{\mathrm{a}} + \mathrm{iono}_{\mathrm{a}}\right) \qquad (1)$$

With bi-frequency GPS measurements, the ionospheric correction is removed by using the well-known iono-free combination. For GEO measurements, the iono correction can be computed with the broadcast information or with the code/phase difference. In the second case, the iono correction on station a is given by :

$$\text{IonoCorr by code/phase diff}_a = \frac{-\lambda_1 L_{1\_a} + C_{1\_a}}{2} \qquad (2)$$

The clock time difference between the two stations (referred to as clock solution in this paper) is merely the difference $H_{b/a} = H_b - H_a = (H_a - H_{GPS}) - (H_b - H_{GPS})$.

The clock solution using phase corrected by code/phase difference is (with an unknown constant bias due to phase ambiguity) :

$$H_{b/a} = \lambda_1 \Delta L_1 + \frac{-\lambda_1 \Delta L_1 + \Delta C_1}{2} - \Delta C_{theo} \qquad (3)$$

with $\Delta L_1 = L_{1\_b} - L_{1\_a}$ and $\Delta C_1 = C_{1\_b} - C_{1\_a}$.

Moreover, with GPS measurements, the clock solution is the mean of the residuals computed on each GPS satellite with the obtained global parameters of the problem (coordinates, ambiguities and tropo correction).

IV. EXPERIMENTS AND RESULTS

At CNES, several receivers were used : a NovAtel OEM-3, a NovAtel OEM-4 and a DSNP Aquarius. They can be connected to an omnidirectional antenna (NovAtel GPS-600) or to a 1.2 m parabolic antenna.

At BIPM, the data collected by two GPS-GEO receivers are available by ftp : a NovAtel OEM-3 that uses a 1.2 m dish antenna pointed on AOR-E and a NovAtel OEM-4 that uses a onmidirectional antenna (TSA-100). Both receivers are fed by the same Hydrogen Maser.

A. Validation on a short baseline

We carried out a frequency transfer using GPS only between two receivers fed by different clocks, and compared the result to an in-situ phase measurement between these 2 clocks :

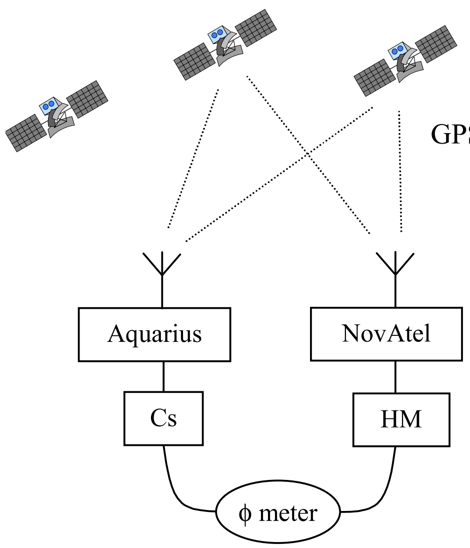

Fig.1 : Validation on short baseline

The figure below shows the clock solution by GPS frequency transfer (line) and by local phase comparison (dots) on one day. An arbitrary offset was added for clarity :

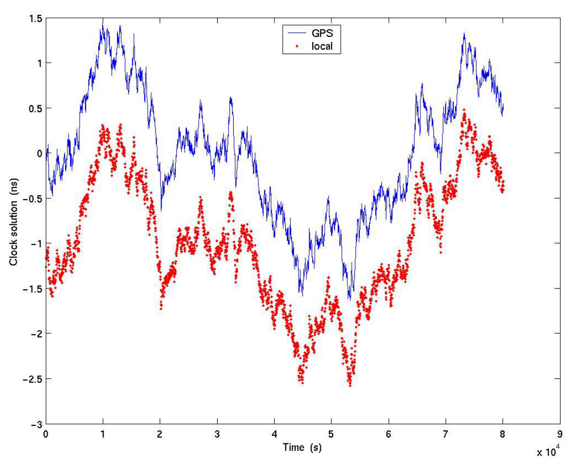

Fig. 2 : GPS frequency transfer vs. local comparison

The standard deviation of the difference is about 20 ps.

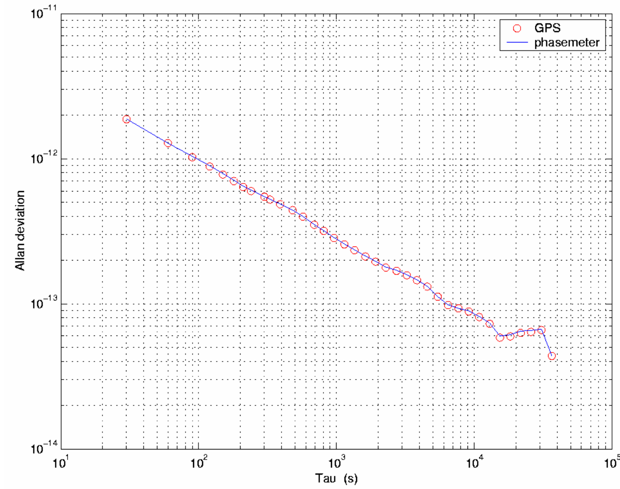

Fig. 3 : Allan deviation of clock solutions with GPS and with local comparison

We have a very go od agreement between the clock solution computed by GPS frequency transfer and by direct phase measurement. It proves that the clock solution provided by our software is valid on such a baseline.

B. Frequency transfer using GPS and GEO on a short baseline : comparison of the clock solutions

In order to overcome the problem of ionosphere correction, we decided to perform first GPS and GEO frequency transfers on a short baseline (about 50 cm). We used a common clock configuration to estimate the transfer noise.

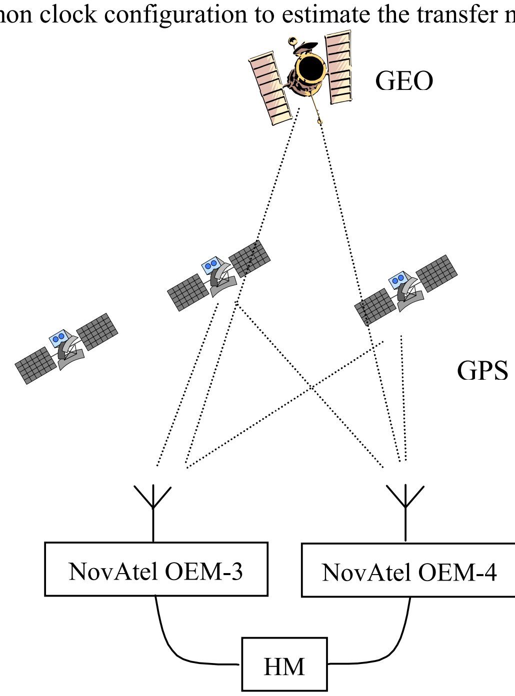

Fig. 4 : GPS and GEO frequency transfer (common clock configuration)

For the GEO frequency transfer, we didn't apply any ionospheric correction since the baseline is very short.

The figure below presents the clock solution provided by GPS frequency transfer and by GEO frequency transfer on three days. An arbitrary offset was added for clarity.

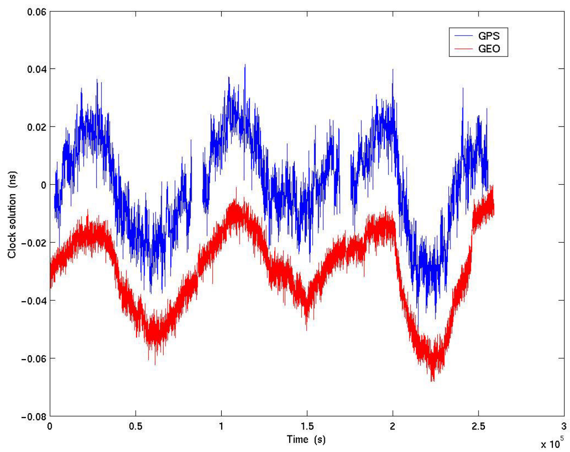

Fig. 5 : Short baseline transfer noise with GPS and GEO

The two clock solutions are very close. The sinusoidal perturbation at 24 h is not explained for the moment. It can be due for example to differential thermal effects in the experimental setup. The possible error in the geostationary ephemerides cannot explain the magnitude (~2 cm) for this short baseline. And the same 24 h perturbation is also observed in the GPS solution. In GPS solutions, important effects appear mainly at GPS orbital periods, and due to the length of the baseline, are totally negligible. The vertical tropospheric delay errors are also not sufficient to explain this result.

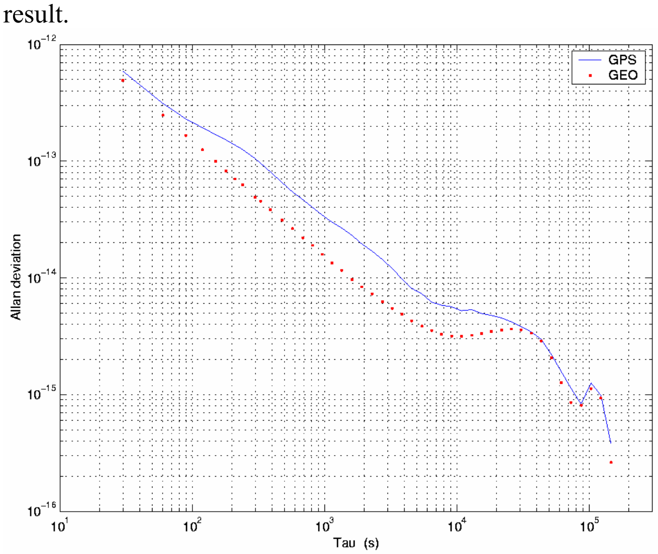

Fig. 6 : Allan deviation of the short baseline transfer noise with GPS and GEO

On the Allan variance, we can observe that the GPS solution is slightly noisier than the GEO solution below 100 s. Due to the use of iono free combination for GPS, the elementary measurement noise is about three times higher than the GEO noise. Because there are several GPS satellites in common view, this factor has to be divided by the square root of the number of satellites leading to a factor close to one.

Around 100 s, there is an increase of the Allan variance for the GPS solution. This may be due to errors in the ambiguity resolution, but this has to be investigated further, as one would expect such a behaviour to appear at higher integration times.

On such a baseline where no ionospheric correction is needed and where orbit errors have almost no impact, the GEO frequency transfer seems more interesting in terms of transfer noise than the GPS frequency transfer. Nevertheless, it is necessary to resume the comparison on longer baselines.

C. Frequency transfer using the GEO on a long baseline using parabolic antenna

We used a BIPM/CNES baseline (about 600 km) with parabolic antenna, both being pointed to INMARSAT AOR-E (EGNOS) :

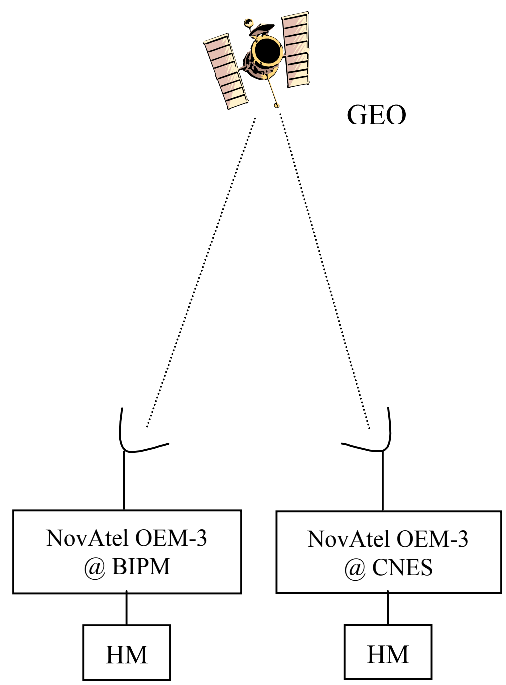

Fig. 7 : BIPM/CNES GEO frequency transfer

First, we can compare the ionospheric correction computed on one station from code-carrier difference to the one broadcast by EGNOS :

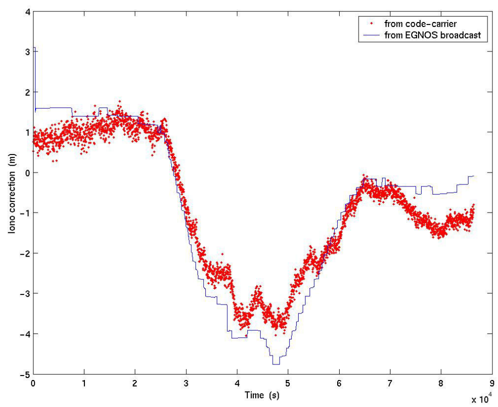

Fig. 8 : Ionospheric correction by code/phase difference and with broadcast information

The iono correction computed from code-carrier difference is obviously noisier but is continuous, unlike the EGNOS broadcast that presents numerous steps.

We can also compare the stability of the clock solution with iono correction (the two methods) and without :

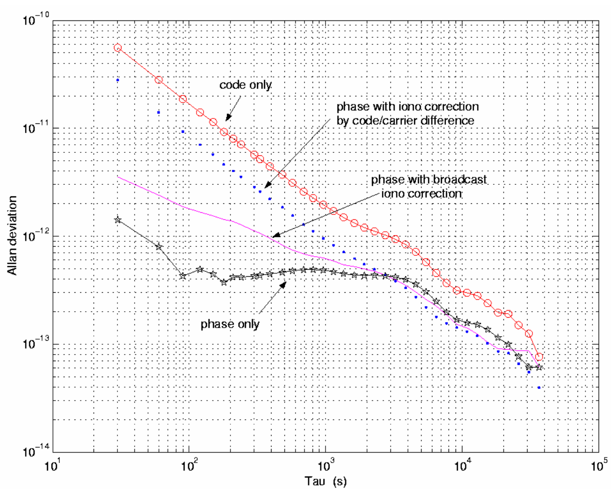

Fig. 9 : Allan deviation of the different clock solutions

The clock solution using uncorrected phase is obviously the best in the short-term, but the lack of iono correction affects the mid-term stability. The clock solution using phase with iono correction by code/carrier difference is very noisy in the short-term due to the noise of the code. After an integration time of about one hour, the uncorrected phase and the phase with both corrections are very close.

To improve such a result, it is necessary to reduce the noise of the code and this could be done with larger antennas. In our case, the diameter of the antenna is 1.2 m, it yields a standard deviation of the code noise of about 40 cm. This code noise is proportional to the inverse of the diameter of the parabolic antenna, in first approximation. Another solution can be envisaged : the code could be smoothed by the carrier phase, but it implies to find a good trade-off for the smoothing.

Besides we can remark that the result is not as good as what we could expect in comparison to GPS [4]. A possible explanation is GEO code/phase inconsistencies in the receiver and/or at the emission.

V. CONCLUSION

We carried out a comparison of frequency transfers by GPS and GEO carrier phase. The main advantage for using GEO is that it can greatly simplify the data processing thanks to the continuous observability. Unfortunately, it broadcasts on a single frequency, so that the ionospheric correction is more difficult. Two solutions can be envisaged : the use of broadcast iono correction or the use of code/phase difference. The latter offers interesting perspectives provided the noise of the code is reduced with large parabolic antennas and/or code/phase smoothing.
In the next years, it is foreseen that GEO bi-frequency navigation payloads will be available, so that the ionospheric correction will not be a problem any more.

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