Fast PPP Convergence Using Multi-Constellation and Triple-Frequency Ambiguity Resolution

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BIOGRAPHY

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ABSTRACT

PPP is a relatively new but powerful technique for GNSS positioning. The main difference between PPP and standard positioning is the use of the carrier-phase measurements, whose noise is two orders of magnitude lower than the code measurements. It is now widely accepted that PPP techniques can achieve centimeter accuracy globally in real-time, in particular when they are combined with phase integer ambiguity resolution. However, one important drawback of the PPP is the convergence time. Dual-frequency PPP convergence is long, typically half an hour, which makes it impracticable for many applications.

However, with the development of the modernized GPS, Galileo and the Beidou constellations, a third frequency is now available on a growing number of satellites. For example, for a user located in the Asia-Pacific region, there are always more than 15 triple-frequency satellites in view nowadays. This number is expected to increase in the next few years thanks to the deployment of the Galileo constellation.

In this paper, we will explore the different measurement combination possibilities offered by the new triple-frequency signal capabilities, namely with the availability of "widelanes only" intermediate combination. This is the ionosphere-free combination that is composed of only phase widelanes. The extra-widelane ambiguity can be solved easily thanks to the Melbourne-Wubbena combination. Once the extra-widelane ambiguity is determined, the remaining ambiguity can be easily solved thanks to a loose knowledge of geometry, because the associated wavelength is relatively high (2.40 m for GPS). Once all the widelane ambiguities are solved, this combination is equivalent to a non-ambiguous ionosphere-free measurement. By performing a noise analysis based on actual measurements, we show that the different characteristics of this combination are compatible with a very fast ambiguity resolution, on all the constellations.

We then offer a real life experiment of the concept using the tools provided by the IGS Real Time service. In this context, satellite phase biases are computed for the three frequencies thanks to the MGEX network of stations. We characterize these biases in terms of noise and time stability, and show that they can be encapsulated in the uncombined SSR representation offered by the RTCM for phase biases messages. All these computations are carried out in real time conditions.

A similar implementation is proposed at user level. We show how the uncombined formulation for phase biases can help partial ambiguity fixing. The improvement of the convergence time compared to the dual-frequency case is demonstrated. In particular, we show that quasi-instantaneous convergence below the 20 cm level is achievable.

This concept is implemented in the CNES PPP-Wizard demonstrator. SSR representation adopted by the IGS real time service is compatible with partial ambiguity fixing. The CNES user open-source PPP implementation presented at the ION GNSS 2015 meeting is upgraded to take into account the new biases. Some actual real-time results, in particular in the Asia-Pacific region, are provided.

1. INTRODUCTION

It is well known that one major drawback of the PPP in dual frequency is the convergence time. This is due to several factors, such as the use of the noisy code measurement to solve the widelane ambiguity, and the relatively small value of the remaining ambiguity wavelength (around 10.7 cm). In triple frequency, new combinations of observables are possible, in particular combinations that involve only phase measurements and with a large ambiguity wavelength. The number of triple-frequency GNSS satellites is increasing rapidly, particularly in the Asia-Pacific region. Figure 1 shows the number of triple-frequency satellites in sight for a given location, as of September 2015 (GPS, Galileo and Beidou combined).

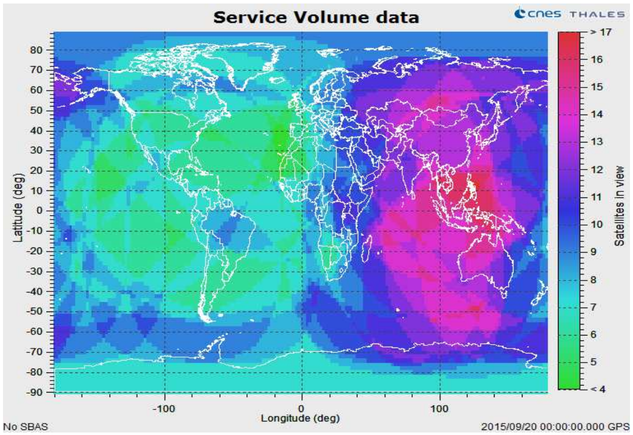

Figure 1: Number of triple frequency satellites in view

With more than 15 satellites in view, it is already possible to explore the possibilities of precise point positioning in the triple frequency context, in particular in terms of convergence time.

2. DUAL-FREQUENCY AMBIGUITY RESOLUTION

Dual frequency ambiguity resolution is a well-known technique to carry out accurate positioning. In general, the resolution is conducted in two steps [3]:

- The widelane ambiguity, which is solved by means of the Melbourne-Wübbena combination
- The remaining ambiguity (N1), which is solved thanks to the ionosphere free phase combination

The ambiguity resolution process itself can be performed either in double-differences, simple differences or zero-differences.

This technique leads to centimeter accuracy PPP-AR. In addition to the standard orbit and clock information used for PPP, the rover needs two additional biases (widelane and N1 or their equivalent) to carry out ambiguity resolution. Figure 2 shows a general overview of dual-frequency PPP-AR. The network side aims at computing the standard orbits and clocks in real-time, as well as additional biases for ambiguity resolution. All these quantities are sent to the rover in order to compute its accurate positioning.

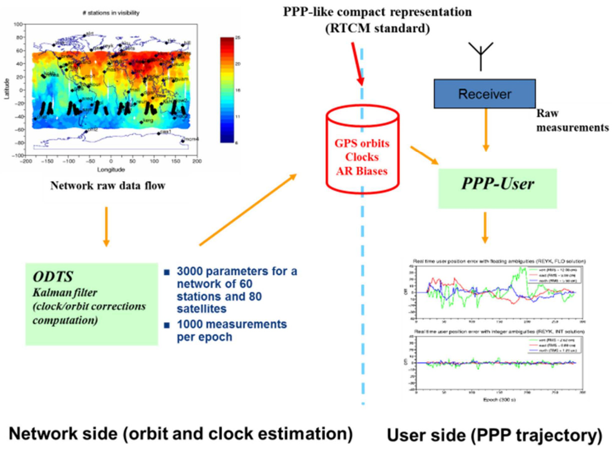

Figure 2: Typical PPP-AR architecture

One drawback of dual-frequency PPP is its convergence time. Figure 3 shows this time, as obtained by the PPP-Wizard demonstrator [10], for the two constellations GPS and Glonass. It requires approximately 10 minutes to reach the 10 cm level, and 30 minutes to reach the 5 cm level. Here, the impact of ambiguity resolution on convergence time is marginal. Additional external atmospheric information can speed up the process.

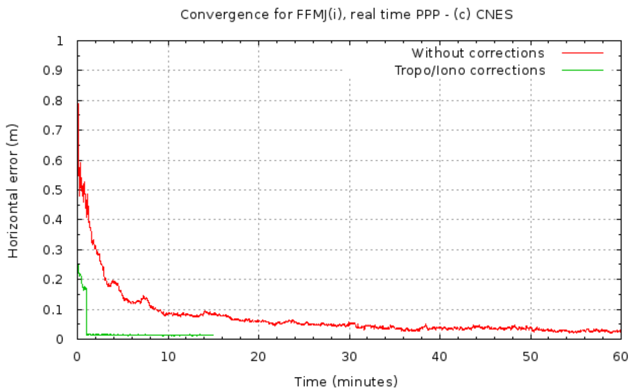

Figure 3: Typical dual-frequency PPP convergence

3. TRIPLE-FREQUENCY WAVELENGTHS AND NOISE ANALYSIS OF NOTEWORTHY COMBINATIONS

The new modernized GPS, Beidou and Galileo constellations now transmit their signal on three distinct frequencies. We can note here these 3 frequencies (A, B, C) according to table 1.

Table 1. Frequency plan

Frequency	GPS	Galileo	Beidou
A	L1	E1	B1
B	L2	E5a	B3
C	L5	E5b	B2

We will now focus on widelane combinations only.

Table 2 depicts the wavelengths associated with the relevant widelane combinations. The first three lines of the table correspond to the three possible widelane combinations. The fourth line represents the ionosphere-free widelanes phase combination. The fifth line corresponds to the geometry-free widelane phase combination. For the last two lines, we can assume that the extra-widelane ambiguity has already been solved.

Table 2. Widelane combinations

Combination	GPS Wavelength (m)	Galileo Wavelength (m)	Beidou Wavelength (m)	Approx. Noise (cycle)
Extra-widelane (B, C)	5.86	9.76	4.88	0.02
Widelane (A,B)	0.86	0.75	1.02	0.1
Widelane (A,C)	0.75	0.71	0.85	0.1
Widelane only phase geo	3.40	3.21	4.52	10 cm 0.03
Widelane only phase iono	1.98	1.84	2.84	10 cm 0.05

Figures 4 and 5 show the noise for three combinations of interest (GPS and Beidou respectively), on a typical pass. Expressed in cycles, we see that the additional combinations to the dual-frequency case, i.e. the extra-widelane and the widelane-only, have a very low noise. The widelane-only combination is not geometry-free; thus, its ambiguity must be solved simultaneously with the position of the rover [6].

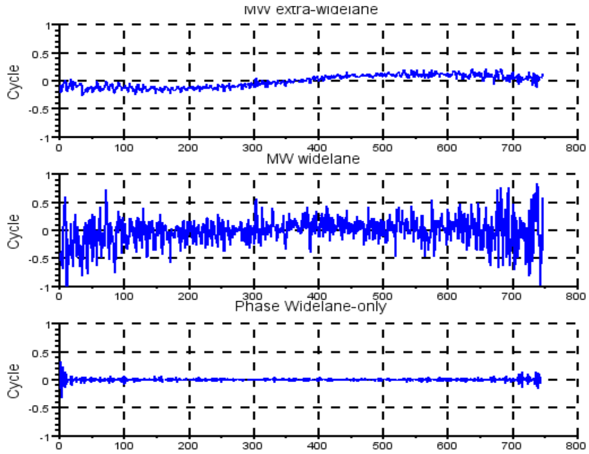

Figure 4: GPS noise combination

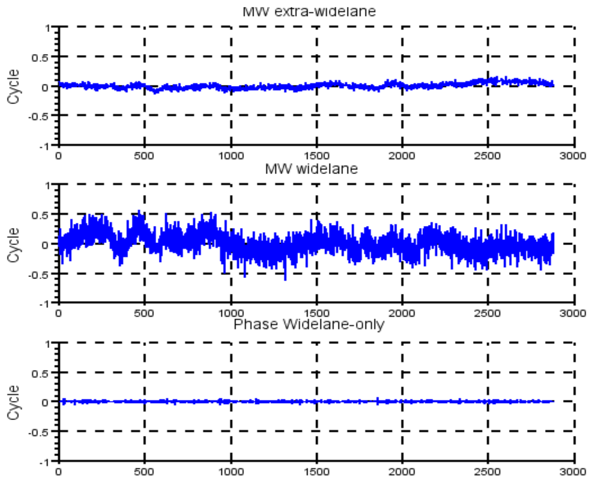

Figure 5: Beidou noise combination

The widelane only combination is of particular interest. Indeed, if all the widelane ambiguities are known, this combination is equivalent to an ionosphere-free range measurement with a noise of approximately 10 cm.
In addition, its dual equivalent in the ionosphere domain can be advantageously used for gap-bridging, even for large gaps, with the additional advantage that it has no dependency on wind-up effect. Therefore, there is no need to monitor a possible rotation of the receiver during the gap.

4. BEIDOU CODE BIAS

As shown by Wanninger [9], Beidou code measurements show an elevation-dependent code variation, with an amplitude of 1 meter. The nature of this bias is not fully understood yet but the effect can be mitigated by using predefined corrections. Such correction tables are given for IGSO and MEO satellites.
Figures 6 and 7 show the effect of the variation on a MW-widelane (simple-differences) before and after applying the

correction. We show here that the corrections preserve the integer nature of the phase ambiguity, which allows the use of the Beidou constellation for our triple-frequency study.

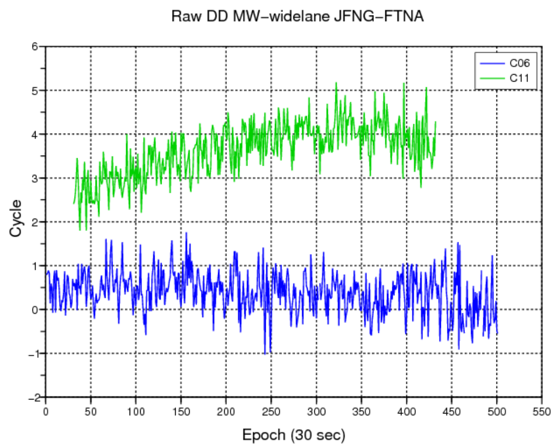

Figure 6: Raw Beidou MW-DD

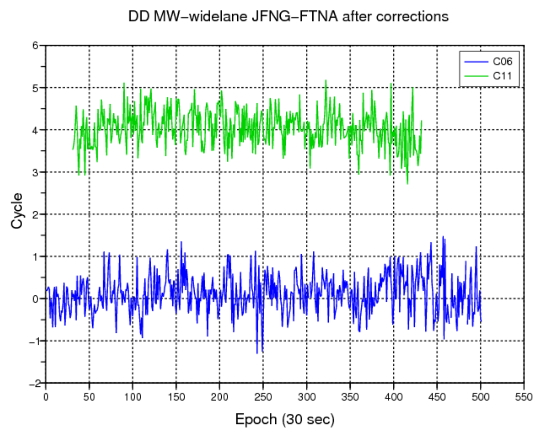

Figure 7: Bias-corrected Beidou MW-DD

5. TRIPLE FREQUENCY AMBIGUITY RESOLUTION FOR PPP

Using the same method as in the dual-frequency case, we can now imagine the triple-frequency ambiguity resolution in two steps:

- The extra widelane ambiguity resolution, which is solved thanks to the Melbourne-Wübbena combination.
- The remaining widelane ambiguity, which can be solved either by the Melbourne-Wübbena combination or the widelane-only combination. The latter option is chosen because of its lower noise.

In our PPP additional bias scheme, this leads to the estimation of two additional quantities:

- The MW extra-widelane bias, whose estimation is straightforward.
- The widelane-only bias.

6. ESTIMATION OF THE WIDELANE-ONLY BIAS IN THE NETWORK

For GPS, a set of 47 compatible and well-distributed stations are chosen from the MGEX network [8] (figure 8):

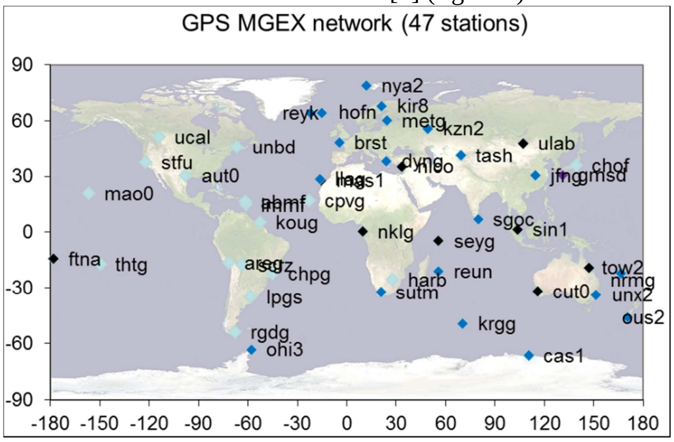

Figure 8: GPS MGEX network

Then, the biases are computed by means of a Kalman Filter using the same procedure as phase biases for N1 [4]. Figure 9 represents the evolution of these biases during one day. Individual satellite biases are shifted for clarity purposes. With 47 stations and 8 satellites, the biases can be estimated continuously. The relatively high noise of the solution is consistent with the noise amplification factor of the combination.

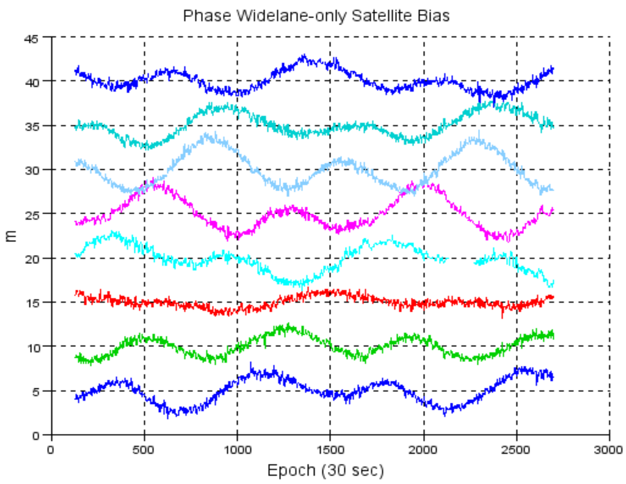

Figure 9: Widelane-only GPS biases

Figure 10 shows the network used for Beidou.

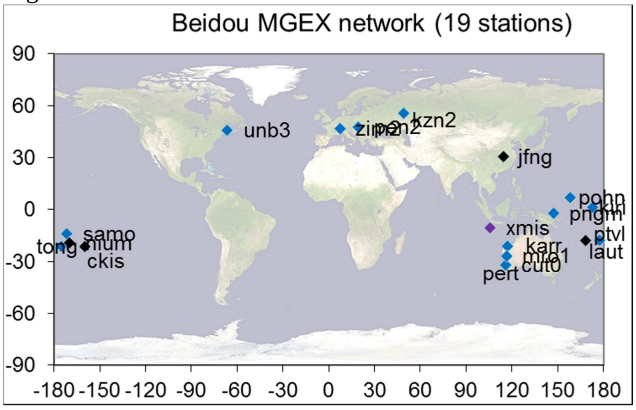

Figure 10: Beidou MGEX network

Despite the limited number of available stations, estimation of the biases is still possible, as shown in Figure 11. A continuous bias estimation is possible with 19 stations only on GEO and IGSO satellites. There is a discontinuity of the 3 MEO satellite biases outside the Asia region because of the low density of the network.

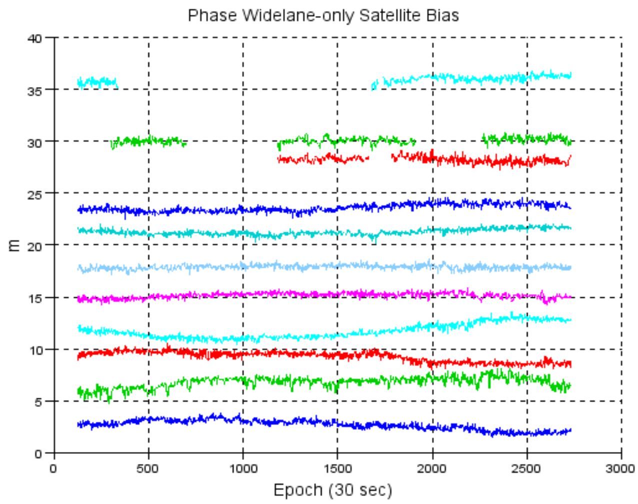

Figure 11: Widelane-only Beidou biases

7. USER RESIDUAL ANALYSIS

In order to demonstrate the full potential of the phase-only biases, a residual analysis has been conducted at station level. Figure 12 shows the residuals of the GPS and Beidou widelane-only measurements, assuming that all widelane ambiguities are solved, and atmospheric parameters are known.

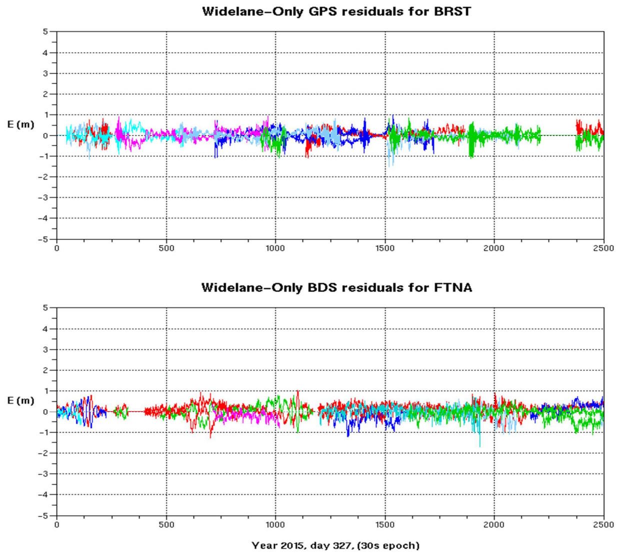

Figure 12: Widelane-only user residuals

The residual noise is consistent with the noise of the corresponding bias (10-20 cm) and can lead to a robust and fast decimeter PPP accuracy.

8. RTCM-SSR REPRESENTATION

The useful quantities for ambiguity resolution in dual and triple frequency contexts presented above are heterogeneous (MW biases, phase biases on various combinations). The RTCM now provides a unified framework for code and phase biases, which can be also be used for ambiguity resolution [7]:

- Code and phase biases are defined as quantities to be added to the raw measurements.
- There is one code and phase bias per observable.
- The ambiguity nature of phase measurements is preserved and the integer ambiguities can be estimated at the user level, regardless of the combination chosen by the rover.

The PPP-Wizard demonstrator adopts the RTCM concept for phase biases and broadcasts these biases on a routine basis on the CLK93 stream of the RTS project [7]. The phase biases are compatible with widelane and N1 ambiguity resolution on GPS, and widelane ambiguity resolution on Beidou and Galileo.

The following tables summarize the different products available and their estimated quality:

Table 3. CNES real-time RTCM messages

Constellation	Nature	Type	Occurrence (sec)	Streams
GPS	orbits/clocks	1060	5	CLK91, CLK93
GPS	code biases	1059	5	CLK91, CLK93
GPS	phase biases	1265	5	CLK93
Glonass	orbits/clocks	1066	5	CLK91, CLK93
Glonass	code biases	1065	5	CLK91, CLK93
Galileo	orbits/clocks	1243	5	CLK93
Galileo	code biases	1242	5	CLK93
Galileo	phase biases	1267	5	CLK93 (tentative)
Beidou	orbits/clocks	1261	5	CLK93
Beidou	code biases	1260	5	CLK93
Beidou	phase biases	1270	5	CLK93
	Ionosphere VTEC	1264	60	CLK91, CLK93

Table 4. CNES products characteristics

Constellation	Orbit source	Median orbit error (cm)	UERE (cm)	Ambiguity resolution
GPS	IGN (internal) IGS, ESOC	3	1	Yes
Glonass	IGN (internal) IGS, ESOC	5	2	No
Galileo	TUM/DLR GFZ	15	5	Yes (widelanes only)
Beidou (MEO, IGSO)	GFZ	15	5	Yes (widelanes only)
Beidou (GEO)	GFZ	800	A.D.	No

9. USER-SIDE PPP

The user PPP freeware provided along with the PPP-Wizard demonstrator [10] has been upgraded to process the triple-frequency biases and deal with partial ambiguity fixing such as the widelane only. This new version (1.3) is available for educational purposes.

The following result (Figure 13) shows the median horizontal convergence figures for a user station (FTNA), in the dual-frequency case (red curve), the triple-frequency case (green curve), and the triple frequency case with tropospheric knowledge (blue curve), over approximately 50 runs.

For this test, 10 triple-frequency satellites were in view for the GPS and Beidou constellations. By using the triple-frequency biases, 20 cm accuracy is reached in 2 minutes, compared to 5 minutes with the use of the dual-frequency biases. Instantaneous convergence can be achieved assuming that the troposphere delay is known.

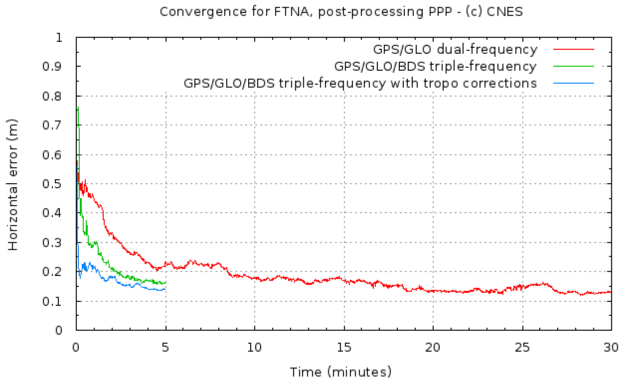

Figure 13: Convergence figures in various configurations

Finally, it is shown on Figure 14 that the knowledge of the troposphere alone does not help the convergence in dual-frequency. This demonstrates that instantaneous convergence at 20 cm can only be achieved with the combination of the triple-frequency biases and the knowledge of the troposphere.

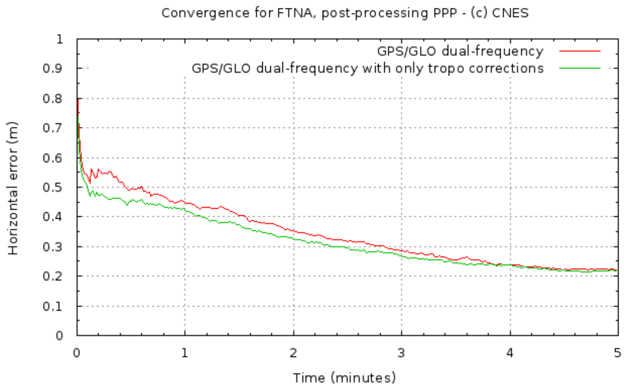

Figure 14: Comparison with and without troposphere knowledge in dual frequency

10. TROPOSPHERE ESTIMATION

A detailed analysis of the real-time troposphere source needs to be conducted. The required accuracy for the troposphere considering an average mapping factor of 2, is estimated to be half the accuracy of the desired one for PPP, that is to say a 10 cm slant or 5 cm ZTD.

Private communications [1] show that having a real-time estimate of the ZTD with such accuracy should not be a problem either by using a local PTH sensor, or a local meteorological service combined with an appropriate model. For example, the Galileo Tropospheric Correction model has an overall RMS value of the ZTD of 4.6 cm, in blind mode (Figure 15) [2].

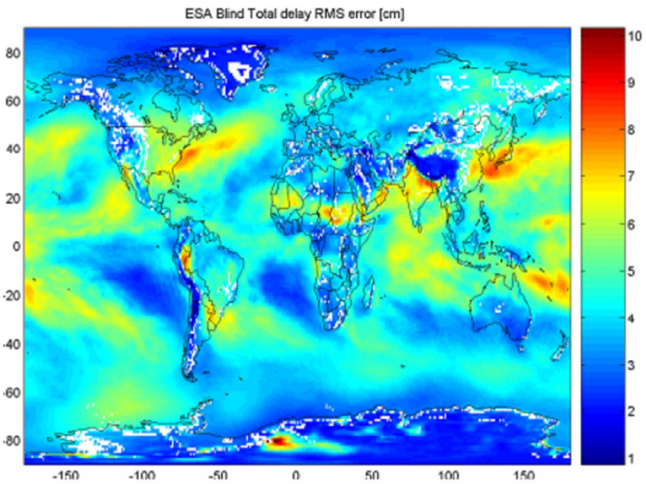

Figure 15: Galileo tropospheric correction model (courtesy of Navipedia)

CONCLUSION

In this paper we have demonstrated that fast (and even instantaneous) convergence at an intermediate level of accuracy is already possible over Asia thanks to the use of the third frequency available on the new GPS satellites and on the Beidou constellation.

This new technique is now implemented in the PPP-Wizard demonstrator, the user software is updated and now available, and its performance is routinely monitored.

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