Galileo E5b Rover Receiving E5a Corrections? No Problem!

Jean-Marie Sleewaegen, Wim De Wilde, *Septentrio*

BIOGRAPHIES

Jean-Marie Sleewaegen (M.Sc. and Ph.D in EE) is systems architect at Septentrio. He has been responsible for GNSS signal processing, system design and technology development since the company's inception in 1999.

Wim De Wilde (M.Sc. in EE) joined Septentrio in 2002. He works as a systems architect, with focus on RF and digital signal processing.

ABSTRACT

With the large selection of signals available from today's GNSS satellites, it becomes difficult to ensure that rovers get the corrections they need from the base station or the RTK network. For example, cases of Galileo E1&E5b rovers in an RTK network which is providing corrections for E1&E5a are not uncommon. In such situation, rovers used to have no other choice but to revert to a lower-accuracy single-frequency positioning mode.

The paper presents a patent-pending technique aimed at addressing the problem. It is shown that it is often possible to re-create the missing corrections at the rover side, enabling dual-frequency RTK with no significant loss of accuracy. The technique is demonstrated for Galileo E5a/b and BeiDou B1C/B1I corrections.

INTRODUCTION

High accuracy GNSS positioning relies on carrier phase measurements and on receiving corrections from an RTK or PPP network. With the help of the corrections from the network, a rover receiver can compensate for most of the errors affecting its own measurements, enabling centimeter or even millimeter positioning accuracy.

Traditionally, a rover is supposed to receive corrections corresponding to the carrier frequencies it is tracking. Back a few years ago, when the only two GNSS frequencies were L1 and L2, this was not much of a problem. The situation has dramatically changed in the recent years, with GNSS satellites transmitting signals on multiple frequency bands, as illustrated in Figure 1. The figure shows the frequency bands currently used by the four global GNSS systems. Only the bands for which signals are available as of September 2019 and for which a public ICD is available are shown.

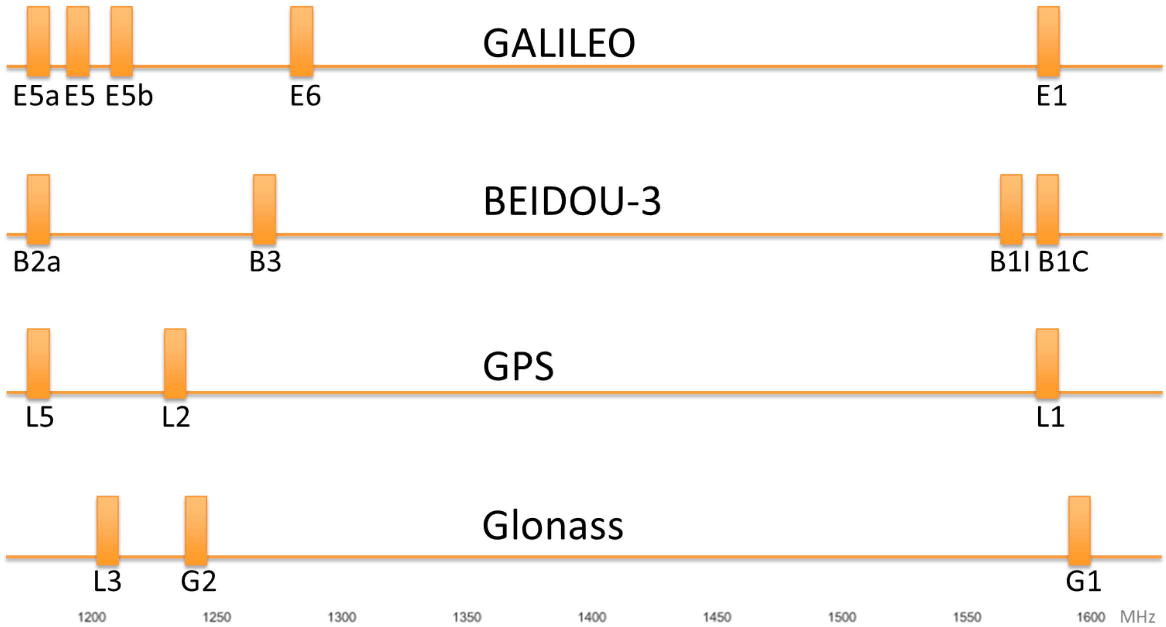

Figure 1. GNSS frequency bands as of September 2019.

Satellite System	Frequency Bands
Galileo	E1 (1575.42MHz), E6 (1278.75MHz), E5a (1176.45MHz), E5b (1207.14MHz), E5altboc (E5) (1191.795MHz) All the E5 signals are generated as a single wide-band modulation in the satellites.
BeiDou-3	B1C (1575.42MHz), B1I (1561.098MHz), B3 (1268.52MHz), B2a (1176.45MHz).
GPS	L1 (1575.42MHz), L2(1227.6MHz), L5 (1176.45MHz).
GLONASS	G1 (~1602MHz), G2 (~1246MHz), L3 (1202.025MHz).

For GPS and GLONASS, there is generally a consensus that base stations and rovers must at least support the two legacy frequencies (L1/G1 and L2/G2). However, such consensus does not exist for Galileo and BeiDou. For Galileo, base stations usually transmit corrections for E1 and one of the E5 frequencies (E5a, E5b or E5altboc). For BeiDou, it is common to get corrections for only one of the B1 frequencies (B1I or B1C).

In this new situation, it becomes difficult to ensure that the rover gets the corrections it needs, especially for Galileo and BeiDou. For example, cases of Galileo E1/E5b rovers in a network which is just transmitting E1/E5a or E1/E5altboc corrections are not uncommon. When this happens, the corrections for the non-matching signals are usually unusable, leading to degraded positioning accuracy.

The main reason why rovers need corrections for the carrier frequencies that they are tracking is the presence of satellite-dependent inter-frequency biases. A correction for one frequency cannot be used for another frequency because of the unknown, and sometimes time varying biases between the signals at different carrier frequencies.

The paper presents a patent-pending technique aimed at addressing the problem. We will show that, for some frequency bands, it is possible to operate an RTK rover receiving mismatching corrections without significant loss of positioning accuracy. The idea is to convert the corrections received from the base into the corrections needed by the rover. In the example of the E1/E5b rover receiving E1/E5a corrections, we will show that the rover can recreate the missing E5b corrections starting from the E1/E5a corrections from the base.

The next section explains how measurements or corrections can be converted between frequency bands. This generally requires compensating for satellite-dependent biases, rendering the conversion unpractical. However, it is shown that signals transmitted with strict phase relationship and in a consistent manner by all satellites, such as the signals being part of the Galileo AltBOC modulation (E5a, E5b and E5altboc) [1], do not suffer from this limitation. If measurements are available for any of those signals, it is possible to derive measurements for the other signals. Alternatively, if a correction is received from the network for one of those signals, it can be converted to a correction applicable to any other signal without the need for external satellite-specific information.

The accuracy of the conversion depends on the ionospheric delay at the base station. However, we will show that this dependence is weak and that the effect of the ionosphere can be accurately compensated for.

To demonstrate the positioning accuracy using this correction conversion principle, the paper concludes with the results of real-life static and dynamic RTK tests.

CONVERTING MEASUREMENTS BETWEEN FREQUENCIES

The pseudorange and carrier phase measurements at two carrier frequencies f_i and f_k for a given GNSS satellite can be expressed as follows:

$$
\begin{aligned}
P_i &= \rho + I_i + \delta P_i \\
P_k &= \rho + \frac{f_i^2}{f_k^2} I_i + \delta P_k \\
\varphi_i &= \frac{f_i}{c}\rho - \frac{f_i}{c} I_i + N_i + \delta\varphi_i \\
\varphi_k &= \frac{f_k}{c}\rho - \frac{f_k}{c}\frac{f_i^2}{f_k^2} I_i + N_k + \delta\varphi_k
\end{aligned}
\qquad (1)
$$

In these equations, P_i is the pseudorange at frequency *i* in meters, φ_i is the carrier phase at frequency *i* in units of carrier cycles, ρ is the satellite-to-receiver distance (and additional clock error terms that are not relevant in this context), N_i is the integer phase ambiguity, I_i is the delay in the ionosphere at frequency f_i, in meters, δP_i is the pseudorange bias, $\delta\varphi_i$ is the carrier phase bias, and c is the speed of light.

The ionospheric delay I_i is typically on the order of a few meters to a few tens of meters.

The pseudorange bias δP_i is the sum of a satellite-dependent and a receiver-dependent contribution. Both contributions are typically at the meter level. The satellite-dependent bias can usually be compensated for using information contained in the navigation message transmitted by the satellite. After compensation, the residual satellite bias is reduced to a few decimeters. The receiver bias is common to all satellites and cancels out in differential positioning.

The carrier phase bias $\delta\varphi_i$ is the sum of a satellite-dependent and a receiver-dependent contribution. Only the fractional part of $\delta\varphi_i$ is relevant as the integer part is absorbed into the integer ambiguity N_i. The receiver-dependent bias cancels out in the position computation and is therefore not relevant here, but the satellite-dependent phase bias is directly affecting the positioning algorithm if not compensated for.

By rearranging equations (1), one can express φ_k and P_k as follows:

$$\varphi_k = \varphi_i + \frac{f_k - f_i}{c} P_i - \frac{(f_k - f_i)^2}{c f_k} I_i + N_{ki} + \delta\varphi_{ki} - \frac{f_k - f_i}{c} \delta P_i \quad (2)$$

$$P_k = P_i + \left(\frac{f_i^2}{f_k^2} - 1\right) I_i + \delta P_{ki} \quad (3)$$

Where $N_{ki} = N_k - N_i$, $\delta\varphi_{ki} = \delta\varphi_k - \delta\varphi_i$ and $\delta P_{ki} = \delta P_k - \delta P_i$.

Equations (2) and (3) show how to derive the carrier phase and pseudorange at frequency f_k from the carrier phase and pseudorange at frequency f_i and the ionosphere delay at that frequency.

These equations can be used to convert corrections between frequencies. However, they are generally not very useful in practice because of the unknown satellite-dependent bias terms ($\delta\varphi_{ki}$, δP_i and δP_{ki}). We will show in the next section that these terms can sometimes be neglected. We'll first address the carrier phase conversion, and then the pseudorange conversion.

CARRIER PHASE CONVERSION

If we omit the bias and ambiguity terms in (2), the carrier phase conversion formula from a frequency f_i to f_k reduces to:

$$\widehat{\varphi_k} = \varphi_i + \frac{f_k - f_i}{c} P_i - \frac{(f_k - f_i)^2}{c f_k} I_i \quad (4)$$

where $\widehat{\varphi_k}$ is the derived carrier phase measurement.

The difference between the true carrier phase measurement at frequency f_k (given by equation (2)) and the carrier phase obtained from (4) is the sum of an ambiguity term and of a bias term:

$$\Delta\varphi_{k,i} = \varphi_k - \widehat{\varphi_k} = N_{ki} + B_{k,i}, \quad (5)$$

with

$$B_{k,i} = \delta\varphi_{ki} - \frac{f_k - f_i}{c} \delta P_i \quad (6)$$

The ambiguity term is irrelevant as carrier phase measurements are always defined with an unknown integer ambiguity, but the bias term $B_{k,i}$ is not. $B_{k,i}$ is a value from 0 to 1, as any integer part is absorbed into the integer ambiguity N_{ki}. $B_{k,i}$ is often satellite-dependent or even variable in time.

For example, Figure 2 shows the $B_{k,i}$ term corresponding to the case where GPS L5 carrier phases are derived from GPS L2 measurements ($B_{L5,L2}$) using equation (4). The $B_{L5,L2}$ values are shown for all the GPS satellites observed during one day from a mid-latitude location. Each trace corresponds to the pass of a satellite. It can be seen that $B_{L5,L2}$ is different for all satellites, and is not constant over the satellite passes. This fact is well known and has been documented for example in [2]. It makes it impractical for a rover to convert GPS L2 corrections to L5 corrections using (4).

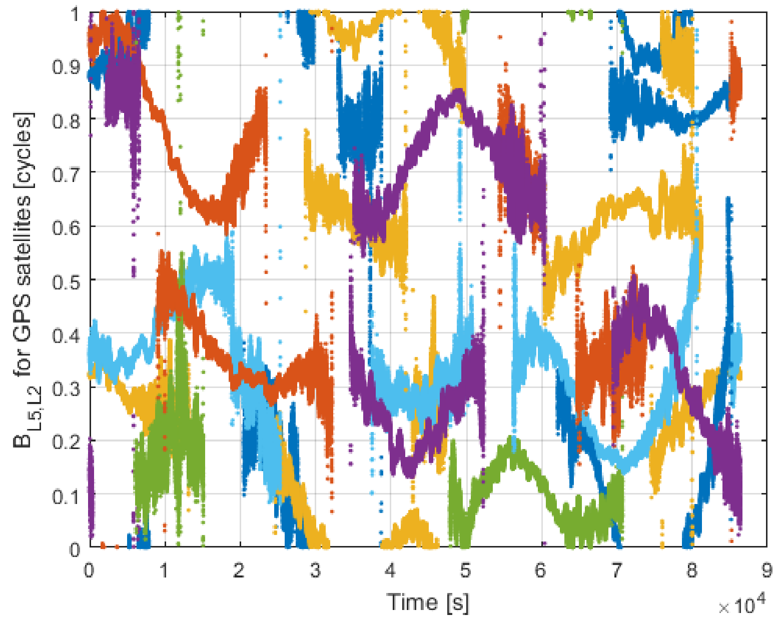

Figure 2. Bias between true GPS L5 carrier phases, and GPS L5 carrier phases derived from GPS L2, modulo 1 L5 cycle. The different colors correspond to different satellites.

However, the situation is very different when equation (4) is used to convert between frequencies within the Galileo E5 band. For example, Figure 3 shows the difference between the true E5b carrier phase and the carrier phase converted from E5a using (4), modulo 1 E5b cycle.

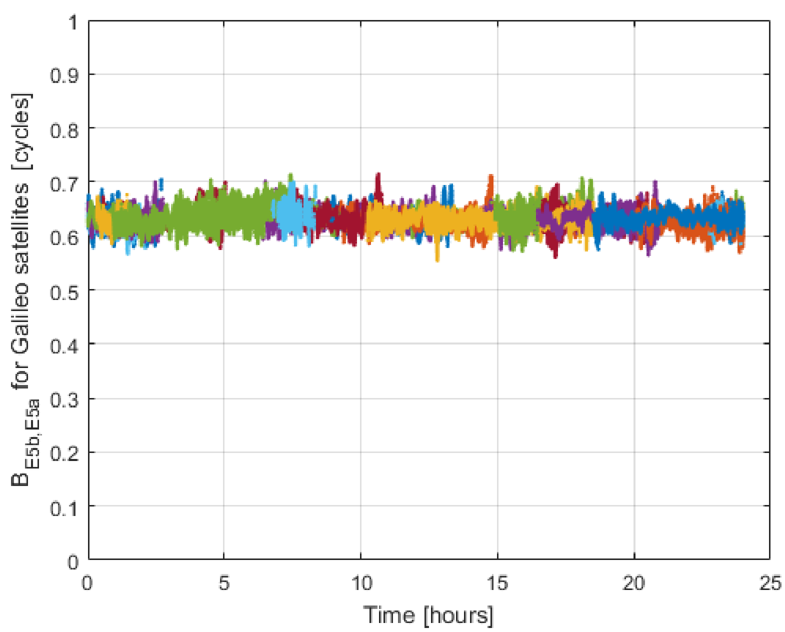

Figure 3. Bias between true Galileo E5b carrier phases, and E5b carrier phases derived from E5a, modulo 1 E5b cycle. The different colors correspond to different satellites.

Compared to Figure 2, Figure 3 shows that the predictability of the E5b carrier phase from E5a is much better than the predictability of GPS L5 from L2. As illustrated by Figure 3, the converted E5b carrier phase only differs from the true one by a constant offset, identical for all satellites (that global offset is receiver/antenna dependent; in the case of Figure 3, it is about 0.63 cycles). Such global offset is inherent to carrier phase measurements and is of no concern to the positioning algorithm.

It can be verified that the same holds when converting between any two frequencies within the E5 band (E5a/E5b/E5altboc). This means that, at least for the Galileo E5 band, it is not necessary for a base station to transmit corrections for all individual frequencies. The rover can recreate the missing correction using equation (4).

This remarkable property stems from the fact that Galileo satellites generate the E5a/E5b/E5altboc signals as a single wide-band modulation with well-defined phase offsets and delays between the different components [1].

Interestingly, conversion of carrier phases from BeiDou B1I into B1C and vice versa also seems to be possible without satellite-dependent biases. This is illustrated in Figure 4, showing the difference between the true B1C carrier phase, and the B1C carrier phase converted from B1I using equation (4). To the author's knowledge, these signals are not part of a single wide-band modulation, but they still seem to be transmitted with the same phase offset by all the current BeiDou-3 satellites.

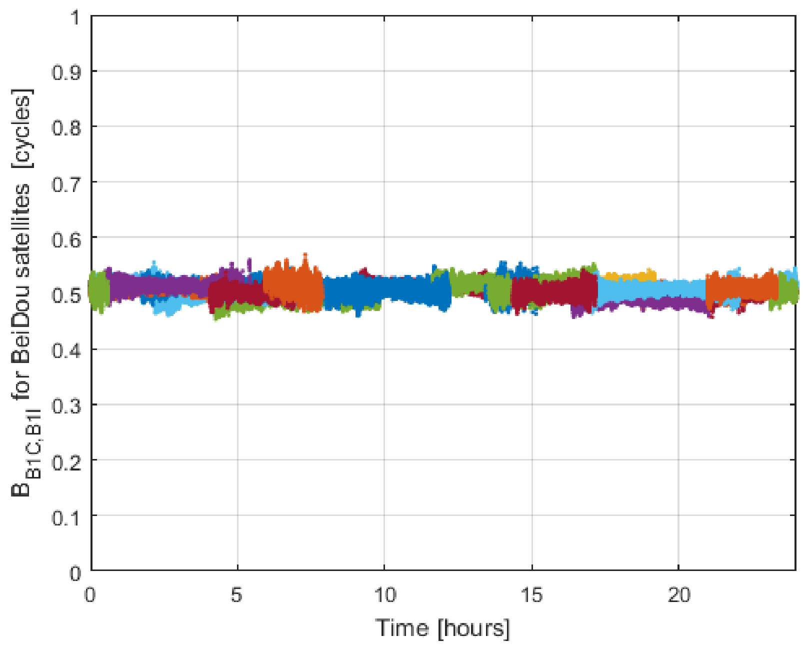

Figure 4. Bias between true BeiDou B1C carrier phases, and BeiDou B1C carrier phases derived from B1I, modulo 1 B1C cycle. The different colors correspond to different satellites.

SENSITIVITY TO PSEUDORANGE NOISE AND IONOSPHERE DELAY

The table below illustrates the numerical values of the coefficients in equation (4) for selected frequency conversions.

Table 1. Examples of carrier phase conversion formula

To recreate carrier phase for ...	from ...	use ...
BeiDou B1C	BeiDou B1I	$\widehat{\varphi_{B1C}} = \varphi_{B1I} + 0.0478P_{B1I} - 0.00043I_{B1I}$
Galileo E5b	Galileo E5altboc	$\widehat{\varphi_{E5b}} = \varphi_{E5} - 0.0512P_{E5} - 0.00066I_{E5}$

Galileo E5b	Galileo E5a	$\widehat{\varphi_{E5b}} = \varphi_{E5a} + 0.1024P_{E5a} - 0.00260I_{E5a}$
GPS L5	GPS L2	$\widehat{\varphi_{L5}} = \varphi_{L2} - 0.1706P_2 - 0.0074I_{L2}$

In all the formulas, the coefficient of the pseudorange term is small. For example, when converting E5a to E5b, a pseudorange error of 0.2 meter will contribute to an error of only 0.1024*0.2 = 0.02048 E5b cycles (i.e. 5.1 mm). As we are converting corrections from the base station, pseudorange noise is typically at the decimeter level, and the resulting noise on the converted carrier phase is well below 0.1 cycle.

The coefficient of the ionosphere term is even smaller. For example, in the E5a to E5b conversion, an ionospheric delay of 10 meters at E5a (I_{E5a} = 10m) will only contribute to an error of 0.026 cycles on $\widehat{\varphi_{E5b}}$ (i.e. 6.5mm).

When the equations of Table 1 are used by a rover to convert corrections from the base, the ionosphere term is the ionospheric delay at the base station. The baseline length does not play any role. As the base station typically transmits corrections for two frequency bands, the ionospheric delay at the base station can readily be obtained from the geometry-free combination. The accuracy is at the level of a few meters, which is more than enough considering the small coefficient. Any receiver pseudorange inter-frequency bias will contribute to a global offset and is therefore irrelevant.

Thanks to the low sensitivity to the ionosphere, it is often even possible to ignore the ionosphere term in equation (4), at least during quiet ionospheric conditions. For example, Figure 5 shows the contribution of the I_i term during a complete day for a mid-latitude station, when deriving E5b carrier phases from E5a carrier phases. The contribution increases a bit in the afternoon due to increased ionosphere activity, but remains at the level of a few hundredth of cycles all the time.

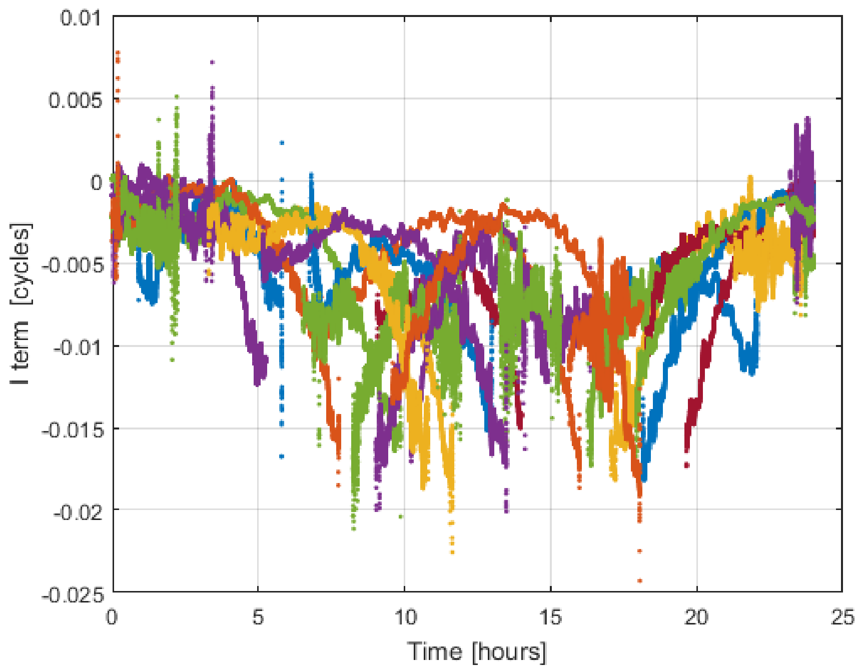

Figure 5. Ionospheric contribution as a function of the local time.

PSEUDORANGE CONVERSION

We've addressed the carrier phase so far, which is the primary measurement in high-accuracy GNSS positioning. For the pseudorange conversion, equation (3) can usually be used directly, with the δP_{ki} term being the satellite inter-frequency delay, corresponding for example to the BGD parameter in the Galileo navigation message [1].

For frequency conversions within the Galileo E5 band, the δP_{ki} term can even be neglected, as the E5a-E5b differential delay in Galileo satellites is small. In that case, the pseudorange conversion formula from frequency f_i to f_k (3) reduces to:

$$\widehat{P_k} = P_i + \left(\frac{f_i^2}{f_k^2} - 1\right) I_i \qquad (7)$$

In (7), the coefficient of the ionospheric term is small when converting between two frequencies close to each other, so that the sensitivity to the ionosphere is small.

As an illustration, Figure 6 shows the difference between the true E5b pseudorange and the E5b pseudorange converted from E5a using (7), for all Galileo satellites observed during a day (one color per satellite). The difference is noisy due to differential E5a-E5b multipath errors, but there is no noticeable satellite-dependent offset.

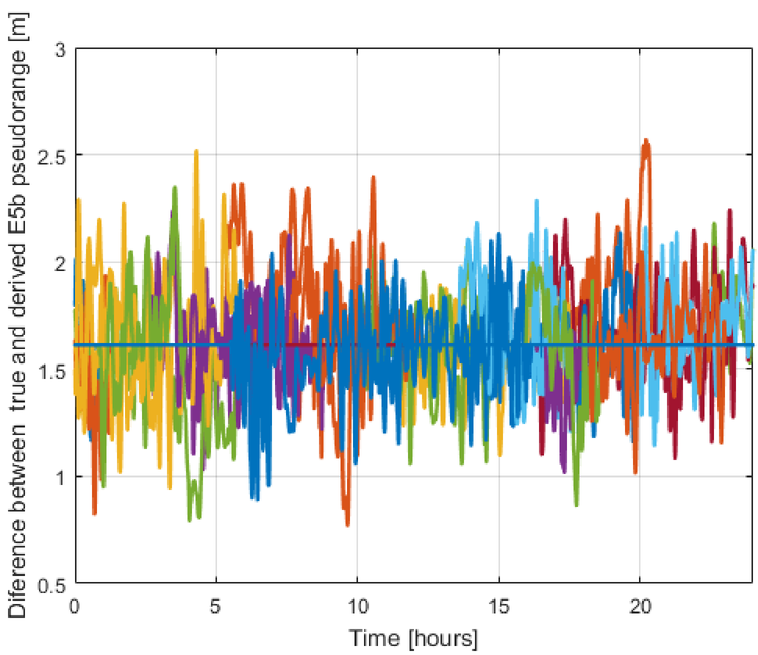

Figure 6. Difference between true E5b pseudorange and E5b pseudorange estimated from E5a using (7). Each color corresponds to a different satellite.

RTK ACCURACY TEST

To demonstrate the frequency conversion accuracy, this section presents the results of a short-baseline static RTK test in the following conditions:

- Open sky;
- Dual-constellation RTK (GPS/Galileo);
- Rover tracks GPS L1/L2 and Galileo E1/E5b;
- Base station transmits corrections for GPS L1/L2 and Galileo E1 and one of E5b, E5a or E5altboc.

Table 2 shows the 2DRMS RTK accuracy for matching and mismatching Galileo corrections, with or without correction conversion to E5b.

Table 2. Static GPS/Galileo RTK 2DRMS accuracy in different conditions

Condition	2DRMS (mm)
E5b corrections from base (nominal case of matching corrections)	5.2
E5a or E5altboc corrections from base, no conversion at rover	7.6
E5a corrections from base, converted to E5b	5.3
E5altboc corrections from base, converted to E5b	5.2

As can be seen in the first two rows, receiving mismatching corrections significantly degrades the RTK accuracy (from 5.2mm to 7.6mm in this test). This is because, in the absence of E5b corrections, the RTK engine used during the test reverts to a GPS-only mode.

The last two rows show that nominal accuracy is recovered when the rover converts the mismatching corrections to E5b using equations (4) and (7). As can be seen, conversion from E5altboc is slightly more accurate thanks to the lower noise of the AltBOC measurements.

RTK AVAILABILITY TEST

Table 3 shows the percentage of RTK with fixed ambiguities in the following conditions:

- Driving in urban environment for about 1 hour;
- Base-rover baseline of about 35km;
- Dual-constellation RTK (GPS/Galileo);
- Rover tracks GPS L1/L2 and Galileo E1/E5b;
- Base station transmits corrections for GPS L1/L2 and Galileo E1 and one of E5b, E5a or E5altboc.

Table 3. RTK availability comparison

Conditions	Percentage of RTK with fixed ambiguities
E5b corrections from base (nominal case of matching corrections)	93.6
E5a or E5altboc corrections from base, no conversion at rover	34.5
E5a corrections from base, converted to E5b	93.7

When receiving mismatching Galileo corrections from the base, the rover reverts to a GPS-only solution, and the percentage of fixed RTK drops drastically. This illustrates the advantage of multiple constellations in typical urban environments.

The last row shows that when the rover recreates E5b corrections from the E5a corrections, nominal RTK performance is recovered.

CONCLUSION

A frequent problem faced by RTK rovers is that they do not get the corrections they need from the base station. The base station may for example transmit corrections for Galileo E5a while the rover tracks E5b and needs corrections applicable to that carrier frequency.

The paper presented a patent-pending method to convert GNSS measurements or differential corrections from one frequency to another. It has been shown that this technique is particularly effective for frequency conversions within the Galileo E5 band (E5a, E5b, E5altboc) and the BeiDou B1 band (B1I and B1C). In these bands, it is possible to recreate the missing corrections with no significant loss of accuracy, only using the available corrections as input.

It has been shown that recreating the missing corrections allows rovers receiving mismatching corrections to operate at the same level of performance as if matching corrections had been received.

REFERENCES

1. “Galileo Signal In Space Interface Control Document”, OS SIS ICD, Issue 1.2, November 2015

2. Montenbruck O, Hugentobler U, Dach R, Steigenberger P, Hauschild A, “Apparent clock variations of the Block IIF-1 (SVN62) GPS satellite”, *GPS Solutions*, 2012 16(3):303-313 doi:10.1007/s10291-011-0232-x