

1 **Revisit the calibration errors on experimental slant total**
2 **electron content (TEC) determined with GPS**

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25 **Abstract:**

26 The calibration errors on experimental Slant Total Electron Content (STEC)
27 determined with Global Positioning System (GPS) observations is revisited. Instead
28 of the analysis of the calibration errors on the carrier phase leveled to code
29 ionospheric observable, we focus on the accuracy analysis of the undifferenced
30 ambiguity-fixed carrier phase ionospheric observable determined from a global
31 distribution of permanent receivers. The results achieved are: (1) By using data from
32 an entire month within the last Solar Cycle maximum, the undifferenced
33 ambiguity-fixed carrier phase ionospheric observable is found to be over one order of
34 magnitude more accurate than the carrier phase leveled to code ionospheric
35 observable and the raw code ionospheric observable. The observation error of the
36 undifferenced ambiguity-fixed carrier phase ionospheric observable ranges from 0.05
37 to 0.11 TECU (Total Electron Content Unit) while that of the carrier phase leveled to
38 code and the raw code ionospheric observable is from 0.65 to 1.65 TECU and 3.14 to
39 7.48 TECU, respectively. (2) The time-varying receiver DCB, which presents clear
40 Day Boundary Discontinuity and intra-day variability pattern, contributes the most
41 part of the observation error. This contribution is assessed by the short-term stability
42 of the Between-Receiver DCB, which ranges from 0.06 to 0.17 TECU in a single day.
43 (3) The remaining part of the observation errors presents a sidereal time cycle pattern,
44 indicating the effects of the multipath. Further, the magnitude of the remaining part
45 implies that the code multipath effects are much reduced. (4) The intra-day variation
46 of the Between-Receiver DCB of the collocated stations suggests that estimating
47 DCBs as a daily constant can have a mis-modeling error of at least several tenths of
48 one TECU.

49

50 **Key words:** ionospheric observable, total electron content, integer ambiguity
51 resolution, receiver DCB

52

53 **Introduction**

54 The Total Electron Content (TEC) of the ionosphere, corresponding to the
55 atmospheric layer between 60 and 2000 km in height, can be studied with a linear
56 combination of measurements from Global Navigation Satellite Systems (GNSSs).
57 This combination is known as ionospheric observable because it cancels the
58 non-frequency dependent terms: the geometric distance between the receiver and the
59 satellite, the satellite and receiver clocks, and the tropospheric delay. Thus, the
60 remaining terms are frequency-dependent: the Slant TEC (STEC) and Differential
61 Code Bias (DCB) of the receiver and of the satellite.

62 Two types of measurements are commonly used to derive the ionospheric
63 observable. On the one hand, the pseudorange measurements that are based on the
64 code delay. This raw pseudorange measurement, termed as RP4 hereafter, contains the
65 sum of STEC and DCB, but it is affected by noise up to several TECUs. For the
66 Global Positioning System (GPS) L1 observable, 1 TECU (Total Electron Content
67 Unit) corresponds to 0.162 m. On the other hand, the carrier phase measurements are
68 two orders of magnitude more precise than the code (Bossler et al. 1980; Braasch
69 1996). However, the carrier phase measurements contain an unknown term, which is
70 the so-called ambiguity, composed by an integer number of wavelengths. The value of
71 the ambiguity changes every time that the receiver locks the GNSS signal of the
72 satellite. Fortunately, it remains constant until the next tracking discontinuity occurs.

73 Several techniques are used to estimate the ambiguity, and then use the carrier
74 phase measurements as precise unambiguous pseudoranges to retrieve the sum of
75 STEC and DCB. The most widely used method is the carrier phase to code leveling
76 process (Wilson and Manucci 1993; Manucci et al. 1999). The ambiguity term is
77 estimated by averaging the difference between the carrier phase and the code per each
78 continuous arc. The accuracy of the carrier phase leveled to code ionospheric
79 observable, which is also called smoothed pseudorange geometry-free combination,
80 “SP4” for short, ranging from 1.4 to 5.3 TECU, is mainly affected by leveling errors
81 introduced from the code multipath effect (Ciraolo et al. 2007; Brunini and

82 Azpilicueta, 2009). The simplicity and effectivity of the leveling process make it
83 preferred by most of the Ionosphere Associate Analysis Centers (IAACs) belonging to
84 the International GNSS Service (IGS) (Dow et al. 2009; Hernández-Pajares et al.
85 2016).

86 As the demand for high accuracy ionospheric observable increases, the
87 ionospheric observable retrieval based on Precise Point Positioning (PPP) technique
88 (Zumberge et al. 1997) has gained interests of the ionospheric research community.
89 Zhang et al. (2012) and Zhang (2016) reported extracting the ionospheric observable
90 using the undifferenced and uncombined PPP technique. Further, Liu et al. (2017)
91 extended the retrieval of the ionospheric observable from GPS-only PPP to
92 Multi-GNSS PPP using the raw observations. Moreover, Liu et al. (2018)
93 implemented the ionospheric observable retrieval from the post-processing to the
94 real-time mode. The aforementioned results are based on the float ambiguity
95 resolution of PPP. With the development of PPP Integer Ambiguity Resolution (IAR)
96 (Laurichesse and Mercier 2007; Collins et al. 2008; Ge et al. 2008), Banville et al.
97 (2012) used the integer-leveled observation based on the decoupled clocks (Collins et
98 al. 2008) to monitor the ionosphere, while Rovira-Garcia et al. (2015, 2016a)
99 extracted the ionospheric observable based on the Fast-Precise Point Positioning
100 technique (Fast-PPP), in which the undifferenced fixed ambiguities are determined
101 from a global distribution of permanent receivers (Juan et al. 2012). In these works,
102 the fixed undifferenced ambiguity terms are substituted into the geometry-free
103 combination of carrier phases, which is usually called L4 observable, and the sum of
104 STEC and DCB can then be retrieved from the undifferenced ambiguity-fixed carrier
105 phase ionospheric observable, termed FL4 observable hereafter.

106 Regardless of the methods used to estimate the ambiguity, the STEC needs to be
107 separated from satellite and receiver DCBs. Typical values of -11 to 14 TECU, that is
108 -4 to 5 ns with 1 ns corresponding to 2.86 TECU on GPS L4 observable, have been
109 found for the DCB of the satellites, while the receiver DCBs range from -57 to 43
110 TECU (Hernández-Pajares et al. 2009). It is generally accepted that the satellite DCB

111 is more stable than the receiver DCB (Sardon et al. 1994; Sardon and Zarraoa 1997).
112 Taking the year 2014 as an example, satellite DCBs provided by IAAC exhibited a
113 standard deviation of 0.34 to 0.57 TECU, whereas receiver DCB stabilities at the level
114 of 0.86 to 1.43 TECU were reported (Sanz et al. 2017). Also, variations in the receiver
115 DCB ranging from 1.4 to 8.8 TECU in intervals of hours have been reported (Ciraolo
116 et al. 2007). This variation is thought to be attributed to temperature changes of the
117 receiver hardware, the chain composed by the hardware in the pre-amplifier of the
118 antenna and the cable connecting to the antenna (Coster et al. 2013; Zhang and
119 Teunissen, 2015; Zhang et al. 2017).

120 We quantify the observation errors of the RP4, SP4 and FL4 ionospheric
121 observables and then focus on the contribution of the time-varying receiver DCB to
122 the observation errors. First, the procedure to obtain the different ionospheric
123 observables is summarized, and then the method to assess the accuracy of the
124 ionospheric observable throughout an experiment with collocated stations is described.
125 After the introduction of the experimental data, the results and discussions of the
126 accuracy assessment of the ionospheric observable, as well as the contribution of the
127 receiver DCB are presented. Finally, we summarize the results and gather the
128 conclusions.

129

130 **The ionospheric observables**

131 This section reviews the different procedures to retrieve the aforementioned
132 ionospheric observables that have been used in the present study, in ascending level of
133 accuracy: RP4, SP4 and FL4. The equations used in the derivation of the observables
134 are explained in more detail than in Nie et al. (2018), emphasizing the description of
135 the strategies employed in the resolution of the carrier phase ambiguity term.

136

137 Code and carrier phase ionospheric observable (P4 and L4)

138 The raw code and carrier phase ionospheric observable are shown as below. It is

139 noted that the ionospheric range delay for code ionospheric observations P_4 has
 140 opposite sign than for carrier phase ionospheric observable L_4 ,

$$141 \quad P_4 = P_2 - P_1 = I + K_{21} + \varepsilon_{P4} \quad (1)$$

$$142 \quad L_4 = \Phi_1 - \Phi_2 = I + K_{21} + (b_1 - b_2) + (\lambda_1 N_1 - \lambda_2 N_2) + \varepsilon_{L4} \quad (2)$$

143 In the above equation, P_f and Φ_f are the pseudorange and carrier phase
 144 measurements at frequency f (m), K_{21} is the sum of the satellite and receiver code
 145 instrumental delays (or called DCB in meters), λ_f is the wavelength (m) and N_f the
 146 integer ambiguity at frequency f (cycle), b_f is a frequency-dependent bias (m), ε
 147 is the combination of the measurements noise and the multipath distinguishing the
 148 pseudorange ε_P from the carrier phase ε_L . More details can be seen in Sanz et al.
 149 (2013, Chapter 4.1).

150 Also, I is defined as the ionospheric delay in the geometry-free combination as

$$151 \quad I = (\alpha_2 - \alpha_1) \text{ STEC} = \frac{40.28(f_1^2 - f_2^2)}{f_1^2 f_2^2} 10^{16} \text{ STEC} \quad (3)$$

152 with $\alpha_f = \frac{40.28}{f^2} 10^{16} \text{ m/TECU}$, where f is the frequency in Hz.

153 Taking $b_I = b_1 - b_2$, the ionospheric bias, which is the main limiting factor that
 154 prevents the raw carrier phase measurements being treated as precise pseudoranges,
 155 can be expressed as

$$156 \quad B_I = b_I + \lambda_1 N_1 - \lambda_2 N_2 \quad (4)$$

157 Therefore, the key to using carrier phase observable in STEC retrieving resides in the
 158 ability to isolate the integer ambiguities from the estimated real parameters B_I and
 159 explicitly fix those values to integers (Collins et al. 2008). In fact, the difference of
 160 the ionospheric observables SP4 and FL4 is in the procedure to resolve the
 161 ionospheric bias in (4).

162

163 Carrier phase leveled to code ionospheric observable (SP4)

164 One of the methods to solve the ionospheric bias is to compute the ionospheric bias

165 aligning L_4 with P_4 , i.e., averaging the difference between the carrier phase and
 166 code ionospheric observable. For a continuous arc, assuming there are N epochs, the
 167 ambiguity term is computed as

$$168 \quad \langle L_4 - P_4 \rangle = \sum_{i=1}^N (L_4 - P_4) / N = B_I + \varepsilon_{\langle p \rangle} \quad (5)$$

169 Where $\langle \rangle$ stands for the average value for a period time of carrier phase
 170 measurements that belong to the same arc.

171 Combining (2) and (5), we can get the carrier phase leveled to code ionospheric
 172 observable as:

$$173 \quad SP_4 = L_4 - B_I = L_4 - \langle L_4 - P_4 \rangle = I + K_{21} + \varepsilon_{SP4} \quad (6)$$

175 where ε_{SP4} is called the leveling error, including mainly the combination of the code
 176 and carrier phase measurement noise, as well as the multipath effects (Ciraolo et al.
 177 2007; Brunini and Azpilicueta, 2009).

178

179 Undifferenced ambiguity-fixed carrier phase ionospheric observable (FL4)

180 The ionospheric bias can also be solved by performing a precise geodetic data
 181 processing. As suggested by Geng et al. (2012), the narrow-lane Fractional Cycle Bias
 182 (FCB) should be determined by ambiguity-fixed network solutions. Therefore, in this
 183 work, the ionospheric bias is obtained from the undifferenced ambiguity mapped from
 184 the Double Difference (DD) ambiguities that are fixed from a network solution
 185 (Rovira-Garcia et al. 2016a). After the IAR, the fractional part of the ionospheric bias
 186 can be removed using the combination of the wide-lane and narrow-lane FCB.
 187 Therefore, the integer part of the ionospheric bias can be expressed as follow:

$$188 \quad B_I - b_I = \lambda_1 N_1 - \lambda_2 N_2 = \frac{\lambda_1 \lambda_2}{\lambda_w \lambda_n} (\lambda_w N_w - B_c) \quad (7)$$

189 where N_w is the undifferenced unambiguous wide-lane ambiguity, B_c is the
 190 undifferenced unambiguous ionospheric-free ambiguity that is reconstructed from the

191 integer wide-lane N_w and narrow-lane ambiguities N_1 , λ_w is the wavelength of the
192 wide-lane and λ_n is the wavelength of the narrow-lane.

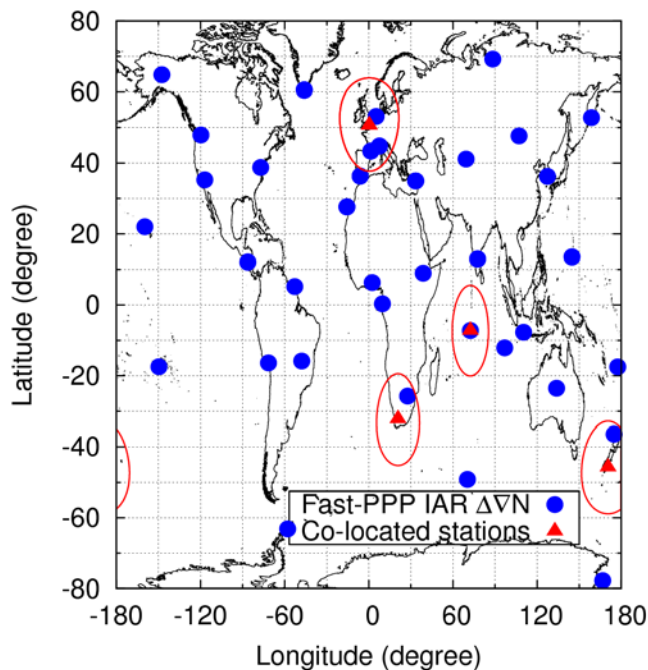
193 Thus, the undifferenced ambiguity-fixed carrier phase ionospheric observable
194 can be obtained as:

$$195 \quad \text{FL}_4 = L_4 - (B_I - b_I) = L_4 - \frac{\lambda_1 \lambda_2}{\lambda_w \lambda_n} (\lambda_w N_w - B_c) = I + K_{21} + \varepsilon_{\text{FL}_4} \quad (8)$$

196 where $\varepsilon_{\text{FL}_4}$ is the combined effect of the measurement noise, multipath and
197 mis-modeling effects during the undifferenced ambiguity-fixed carrier phase
198 ionospheric observable retrieval process.

199 In our experiment, the FL4 observable has been computed by the research group
200 of Astronomy and Geomatics (gAGE), from the Technical University of Catalonia
201 (UPC) using the Fast-PPP technique (Rovira-Garcia et al. 2016b). The Fast-PPP
202 Central Processing Facility (CPF) gathers actual dual-frequency GNSS code and
203 carrier phase measurements from 150 receivers distributed worldwide to compute the
204 FL4, the Fast-PPP ionospheric model and the DCBs. The Fast-PPP corrections
205 calculated for the year 2014 are freely available to the public for research and
206 comparison purposes at the server www.gage.upc.edu/products. The strategy
207 employed to compute the unambiguous and unbiased FL4 observable within the
208 Fast-PPP CPF follows the procedure explained hereafter. The first step of the practical
209 implementation is to fix the DD wide-lane ambiguity ΔN_w and narrow-lane
210 ambiguity ΔN_1 , thanks to the accurate estimation of the ionospheric-free ambiguity
211 ΔB_c . The second step consists in introducing these integer values as constraints in
212 the filter, which reduces the formal error of the ambiguity B_I . These computations are
213 done within a Kalman filter that processes the geodetic data, which is unaffected by
214 ionosphere, and a rough ionospheric model that allows a first but coarse estimation for
215 the DCBs, in which the DCB are assumed as a constant value for 24 h. It is worth
216 saying that the fixing of the DD carrier phase ambiguities is not done for all the
217 possible pairs of receivers, which would require an unaffordable time consumption.
218 On the contrary, DD ambiguities are computed with respect to a reduced set of

219 reference receiver, as shown in Figure 1.



220

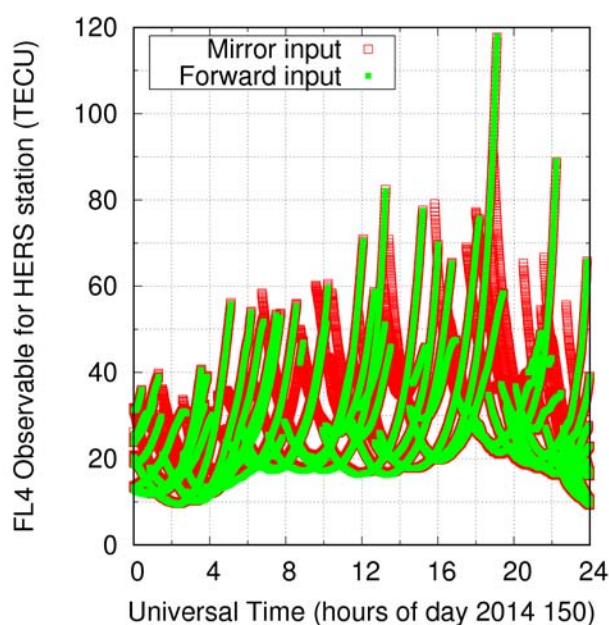
221 **Fig. 1** Distribution of stations used in the Fast-PPP to compute the DD carrier
222 phase ambiguities and perform IAR (blue points) together with the testing collocated
223 station pairs (red triangles). The solid lines enclose the projection area at 268 km
224 altitude, i.e., the height of the Fast-PPP first layer, for elevation angles higher than 7°.

225

226 A second filter runs parallel to the geodetic process; the ionospheric filter of the
227 Fast-PPP CPF, which computes the ionospheric grid-based TEC model and
228 refinement of the DCBs (Δ DCB) with respect to the coarse daily estimation into the
229 geodetic filter. The time update in the ionospheric filter is 5 minutes for the
230 ionospheric model parameters and 1 hour for the Δ DCB refinements. The estimation
231 is performed twice; as a forward and a mirror process. The forward process is
232 intended for having real-time corrections, whereas the mirror process is intended for
233 obtaining precise estimates to be used in post-process applications or in scientific
234 studies. In this sense, in the forward process, the FL4 combinations that feed the
235 ionospheric model in real-time, are obtained using the available estimation of the
236 fixed ambiguity; the ambiguity is considered fixed when the formal error is below a

237 pre-defined threshold of 0.5 TECU.

238 The mirror process estimates the DCBs and the ionospheric model in a more
239 robust way. In this process, each continuous arc of FL4 is obtained using the final
240 fixed determination of the carrier phase ambiguity and the coarse DCBs estimated
241 into the geodetic filter. Because the carrier phase ambiguities are fixed, the input data
242 for both the forward and mirror processes should be very similar except the fact that
243 the mirror process uses data that during the forward process were not used because the
244 ambiguities were still not fixed. This is illustrated in Figure 2 for the receiver HERS
245 during the day 150 in 2014. Indeed, the number of FL4s used in the mirror process,
246 which is represented by red squares, is 34% greater than that in the forward process,
247 which is represented by green squares. The greater number of backward
248 measurements is especially noticeable at the beginning of the arcs.



249

250 **Fig. 2** Example of the FL4 measurements that feed the forward filter (in green) and
251 the backward part of the mirror filter (in red)

252

253 **Methodology**

254 To assess the effects of observation error on the ionospheric observable, the so-called

255 collocated station experiment is employed (Ciraolo et al. 2007). In the set-up,
 256 permanent receivers are separated from 0 to 142 m, so that the STEC measured by
 257 each pair of receivers is assumed to be the same. Taking Single Difference (SD) of
 258 ionospheric observables between the two receivers, for every common satellite we get
 259 a series of values free from satellite DCB, and that should ideally be the measurement
 260 noise, multipath and Between-Receiver DCB (BR-DCB).

261 In this manner, the previous equations, i.e., (1), (6) and (8) can be
 262 single-differenced for two collocated stations denoted “A” and “B” and one observed
 263 satellite denoted as “S”.

264 For code ionospheric observable:

$$265 \quad \Delta P_4 = P_{4,A}^S - P_{4,B}^S = K_{21,rcv,A} - K_{21,rcv,B} + \varepsilon_{P4,AB} \quad (9)$$

266 For carrier phase leveled to code ionospheric observable:

$$267 \quad \Delta SP_4 = L_{SP4,A}^S - L_{SP4,B}^S = K_{21,rcv,A} - K_{21,rcv,B} + \varepsilon_{SP4,AB} \quad (10)$$

268 For undifferenced ambiguity-fixed carrier phase ionospheric observable:

$$269 \quad \Delta FL_4 = L_{FL4,A}^S - L_{FL4,B}^S = K_{21,rcv,A} - K_{21,rcv,B} + \varepsilon_{FL4,AB} \quad (11)$$

270 where Δ corresponds to the Single Difference operator.

271 According to (9) to (11), the SDs of ionospheric observable should be free from
 272 satellite DCB and that ideally be equal to the combination of the measurement noise,
 273 multipath and BR-DCB. The Standard Deviation (STD) of the time series
 274 corresponding to different satellites thus can be treated as a metric for inferring the
 275 observation error, as

$$276 \quad \text{Error} = \text{STD} / \sqrt{2} \quad (12)$$

277 where $\sqrt{2}$ stands for the SD operator under the assumption that the STD of the
 278 observation error on the collocated receivers is uncorrelated, once the ionospheric
 279 error is removed, and can be treated as the same.

280 The preprocessing strategy for the ionospheric observables is summarized as

281 follows: (1) an elevation cut-off angle of 7° is applied to filter the measurements
 282 with an elevated level of noise; (2) the carrier phase cycle-slip detection is based on
 283 the geometry-free combination and the Hatch–Melbourne–Wübbena (HMW)
 284 combination (Hatch 1982; Melbourne 1985; Wübbena 1985). Specifically, to reduce
 285 the leveling errors (Ciraolo et al. 2007; Brunini and Azpilicueta, 2009) of the SP4
 286 observable, only those arcs containing at least 120 epochs, which is 1 hour for
 287 30-second interval data, are retained for the retrieval of the SP4 observable.

288

289 **Experiments and results**

290 The experiment has collected GPS data from nine stations, which correspond to the
 291 red triangles depicted in Figure 1. The data campaign extends the three-day period
 292 analyzed in Nie et al. (2018), comprising the Day Of Year (DOY) 150 to 180 in 2014,
 293 which is during the last solar cycle maximum. All the GPS observations have been
 294 obtained from the IGS Global Data Center at CDDIS (Crustal Dynamics Data
 295 Information System, <ftp://cddis.gsfc.nasa.gov>) at an interval of 30 seconds. Table 1
 296 presents an overview of the experimental data sets ranked according to the latitude,
 297 including the four-character station name, receiver and antenna type, and the location
 298 in latitude and longitude of the receivers. According to their collocated situation, we
 299 group these receivers into four arrays with six pairs. One of the arrays contains three
 300 receivers that can be divided into three pairs, which are the SUTH-SUTM,
 301 SUTH-SUTV, and SUTM-SUTV station pairs. The other three arrays contain two
 302 receivers each that can be divided into separate pairs.

303

304 **Table 1** An overview of the experimental data sets collected from nine IGS stations.

Station	Receiver type	Antenna and radome type	Location	Baseline Length
HERT	LEICA	LEIAT504GG	50.7°N	136 m
	GRX1200GGPRO	NONE	0.3°E	
HERS	SEPT POLARX3ETR	LEIAR25.R3 NONE		

DGAR	ASHTECH UZ-12	ASH701945E_M NONE	7.2°S 72.4°E	0 m
DGAV	JAVAD TRE_G3TH	ASH701945E_M NONE		
SUTH	ASHTECH UZ-12	ASH701945G_M NONE	32.2°S 20.8°E	0-142 m
SUTV	JPS EGGDT	ASH701945G_M NONE		
SUTM	JAVAD TRE_G3TH	JAV_RINGANT_G3T NONE		
OUSD	TRIMBLE NETRS	TRM55971.00 NONE	45.9°S 170.5°E	3 m
OUS2	JAVAD TRE_G3TH	JAV_RINGANT_G3T NONE		

305

306 Accuracy assessment of the ionospheric observable

307 The following analysis is illustrated using one collocated station pair HERT-HERS.

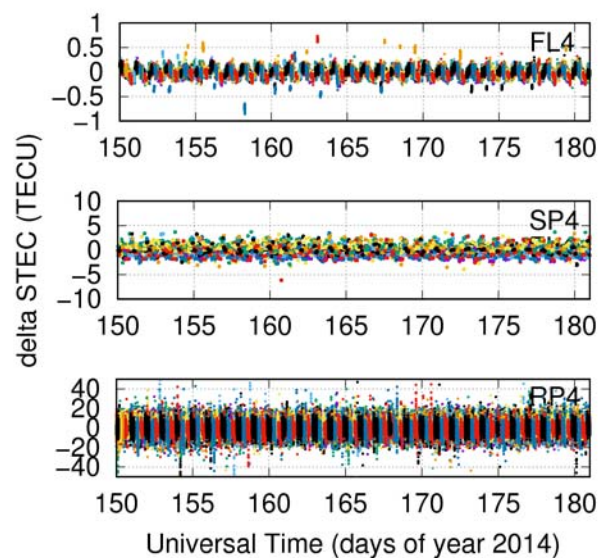
308 The results are representative of all of the other experimental pairs, summarized in
 309 what follows.

310 Figure 3 depicts the SD of the FL4, SP4 and RP4 observables between collocated
 311 stations HERT-HERS from DOY 150 to 180 in 2014. It is noted that the daily mean of
 312 the SD of the FL4, SP4 and RP4 observables is removed in Figure 3. From the top
 313 panel, a peak-to-peak value of about 0.15 TECU of the SD FL4 observable for the
 314 station pair HERT-HERS can be observed. With a 95% significance, a peak-to-peak
 315 value means almost two times the STD. The middle panel depicts the SD of the SP4
 316 observable using a y-scale ten times greater than in the top panel. It is apparent that
 317 the peak-to-peak value of the middle panel is larger than that of the top panel. The SD
 318 of the RP4 observable is presented in the bottom panel, with a peak-to-peak value of
 319 almost 10 TECU, indicating that the RP4 observable has the lowest accuracy.

320 In the top panel of Figure 3, the observed outliers, i.e., scatter points that deviate
 321 from the accumulation area are caused by the ionospheric bias B_I , which is still not
 322 perfectly fixed to an integer. This scattering occurs due to practical reasons in the
 323 implementation of the ambiguity-fixing strategy commented earlier. In addition, a

324 clear daily pattern can be observed into the SD FL4 values, which will be analyzed
325 later. Apart from these, a good agreement can be found between the results in the top
326 panel from one day to another, indicating a robust ambiguity solution.

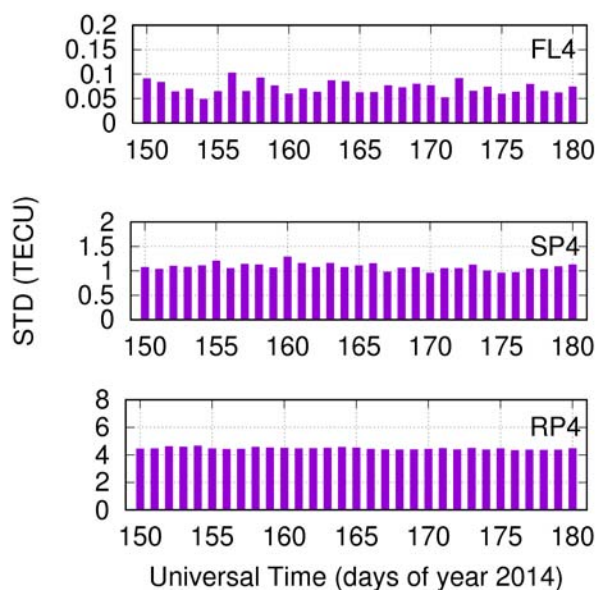
327 To quantify the reduction of the observation error, the STD of the SD FL4, SP4
328 and RP4 observable are computed every day from DOY 150 to 180 in 2014 for the
329 station pair HERS-HERT. The results are presented in Figure 4.



330

331 **Fig. 3.** SD ionospheric observable retrieved from collocated stations HERT-HERS
332 during DOY 150 to 180 of 2014, using FL4, SP4 and RP4 observable presented from
333 top to bottom panel.

334



335

336 **Fig. 4.** Standard deviation computed every day from DOY 150 to 180 in 2014 for
337 station pair HERS-HERT using the SD of FL4, SP4 and RP4 observable presented
338 from top to bottom panel.

339

340 From Figure 4, we can infer that the STD of all the SD ionospheric observable
341 during the almost one-month time, which is from DOY 150 to 180 in 2014, is quite
342 stable. Taking the STD of FL4 observable as an example, it ranges from 0.05 to 0.10
343 TECU during the experiment campaign time. On the other hand, the standard
344 deviation of the SD SP4 and RP4 observable, varying at about 1 and 4.5 TECU,
345 respectively, can be found.

346 Finally, we average the STD values during the experimental time to represent the
347 accuracy of the SD ionospheric observable. The results are presented in Table 2,
348 which summarizes the mean, STD of the SD ionospheric observable, as well as the
349 error of the FL4, SP4 and RP4 observable for all the six pairs of collocated stations.

350

351 **Table 2** Mean, the standard deviation of the SD ionospheric observable and the Error
352 of the FL4, SP4 and RP4 observable for all the satellites arcs for DOY 150 to 180 in

353 2014.

Baseline name	Single difference ionospheric observable (TECU)								
	FL4			SP4			RP4		
	Mean	STD	Error	Mean	STD	Error	Mean	STD	Error
HERT-HERS	-5.27	0.07	0.05	-0.12	1.08	0.76	-0.10	4.44	3.14
DGAR-DGAV	26.15	0.15	0.11	28.97	0.96	0.68	28.96	8.52	6.02
SUTH-SUTM	34.85	0.13	0.09	34.17	2.00	1.41	34.18	10.58	7.48
SUTH-SUTV	5.99	0.14	0.10	4.88	0.92	0.65	4.86	4.47	3.16
SUTM-SUTV	28.91	0.12	0.08	29.34	2.05	1.45	29.35	9.95	7.04
OUS2-OUUSD	65.25	0.09	0.06	62.28	2.33	1.65	62.20	10.44	7.38

354

355 Table 2 represents the performance of the FL4, SP4 and RP4 observable. It can be
 356 observed that in all baselines, the FL4 observable is more accurate, followed in order
 357 by the SP4 and RP4 observables. Numerically, the observation error affecting the FL4
 358 observable ranges from 0.05 to 0.11 TECU whereas errors for the SP4 observable
 359 range from 0.65 to 1.65 TECU and those for the RP4 observable range from 3.14 to
 360 7.48 TECU. These values agree with the result presented in Ciralo et al. (2007) and
 361 Rovira-Garcia et al. (2016a), confirming that the FL4 observable is over one order of
 362 magnitude more accurate than the SP4 and RP4 observables as was reported in the
 363 three-day study period of Nie et al. (2018). Also, the dependence of the observation
 364 error on the receiver/antenna configuration of the collocated stations can be found.
 365 For example, the observation error of the RP4 and SP4 observables for station pairs
 366 DGAV-DGAR, SUTH-SUTM, SUTM-SUTV and OUS2-OUUSD are apparently larger
 367 than the for other station pairs. The reason may be attributed to that stations DGAV,
 368 SUTM and OUS2 are all equipped with *JAVAD TRE_G3TH* receivers, see Table 1.

369

370 Characterizing the time-varying receiver DCB to the observation error

371 To quantify the contribution of time-varying receiver DCB to the observation error,
 372 the hourly receiver DCB has been first estimated by the Fast-PPP ionospheric model
 373 described earlier. Sanz et al. (2017) showed that the accuracy of the receiver DCB on
 374 a daily solution for the Fast-PPP technique, which means estimating receiver DCB as
 375 a constant in one day, was 0.57 TECU, while the satellite DCB accuracy was 0.20
 376 TECU. This work has been extended to estimate the DCB on a sub-daily resolution,
 377 for example, one hour, in order to see the DCB stability in a shorter time interval. The
 378 intra-day stability, including the average, minimum and maximum STD values during
 379 DOY 150-180 of 2014, are presented in Table 3.

380

381 **Table 3** Intra-day stability of the hourly receiver DCB estimated by the Fast-PPP from
 382 DOY 150-180 of 2014.

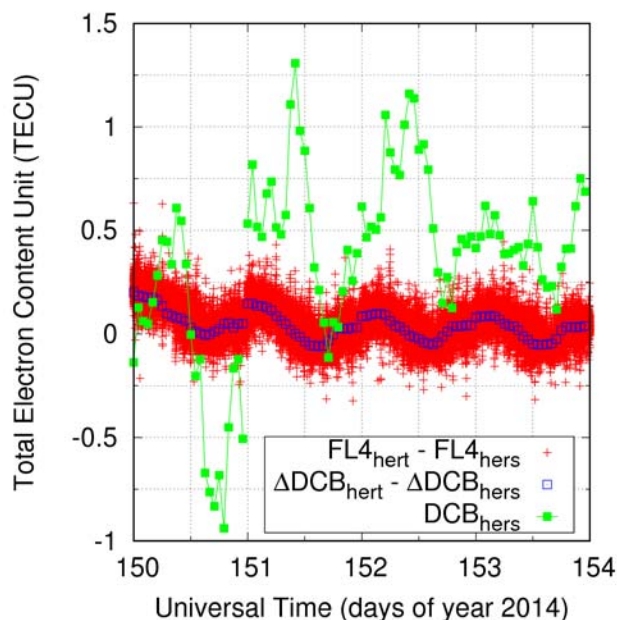
Station	Individual Receiver DCB			BR-DCB
	Min STD(TECU)	Max STD(TECU)	Mean STD(TECU/ns)	Mean STD(TECU/ns)
HERT	0.18	1.05	0.35 (0.12)	0.09 (0.03)
HERS	0.14	0.94	0.36 (0.13)	
DGAR	0.14	3.30	0.92 (0.32)	0.17 (0.06)
DGAV	0.22	3.27	0.96 (0.34)	
SUTH	0.18	0.83	0.39 (0.14)	0.10 (0.03)
SUTM	0.15	0.88	0.36 (0.13)	0.16 (0.06)
SUTV	0.15	0.94	0.40 (0.14)	0.11 (0.04)
OUS2	0.13	0.68	0.34 (0.12)	0.06 (0.02)
OUSD	0.15	0.67	0.34 (0.12)	

383

384 Table 3 presents that the mean STD of the receiver DCB during the one-month
 385 time ranges from 0.34 to 0.96 TECU, which is much larger than the FL4 observation
 386 error that ranges from 0.05 to 0.11 TECU, as presented in Table 2. However, as it is
 387 known, the accuracy of the receiver DCB is affected by the error of the ionospheric
 388 model, which depends on the time and location of the receiver and can be transferred
 389 to the receiver DCB (Sanz et al. 2017). This transference error can be eliminated by
 390 using collocated receivers where the mis-modeling on the ionospheric model can be

391 assumed to be similar, thus not affecting to the BR-DCB estimates. Therefore, the
392 mean STD of the BR-DCB is also computed and presented in Table 3, which ranges
393 from 0.06 to 0.17 TECU. Considering the STD of the SD FL4 observable, which
394 ranges from 0.07 to 0.15 TECU as indicated in Table 2, we can infer that the
395 time-varying receiver DCB contributes the most part of the observation errors of the
396 FL4 observable that feeds the ionospheric model. This conclusion can also be seen
397 from Figure 5, where the SD FL4 observable and BR-DCB for station pair
398 HERT-HERS are presented together. We limit our graphical analysis to a period of
399 four days, from DOY 150 to 153 in 2014, to present a representative result.

400



401

402 **Fig. 5.** SD FL4 observable, BR-DCB for station pair HERT-HERS as well as
403 DCB of station HERS from DOY 150 to 153 in 2014

404

405 Figure 5 depicts with red pluses the SD of the FL4 observables between HERT
406 and HERS every 30 s, as they are input into the mirror process, which is the best
407 determination that we can compute. In addition, the corresponding hourly BR-DCBs,
408 which are constructed from the individual estimates from the mirror filter, are
409 depicted with the blue rectangles. Finally, the hourly estimation of the HERS DCB, i.e.

410 the daily rough estimation into the geodetic filter plus the refinement Δ DCB
411 computed by the mirror filter, is depicted with green squares. Two main
412 characteristics can be observed in Figure 5:

413 -*A Day Boundary Discontinuity (DBD)*. These discontinuities appear because
414 carrier phase ambiguities are constrained to integer values in DD mode, whereas the
415 magnitudes depicted in Figure 5 are absolute or SD measurements. Therefore, any
416 effect that affects equally to all the satellites in view, such as a jump in the receiver
417 DCB, does not vary the value of the DD. Because carrier phase ambiguities and DCBs
418 are quite correlated, see (2), when one removes both parameters from the L4 to build
419 the FL4 measurements in (8), only small discontinuities appear in the SD
420 measurements. Thus, when common error sources, such as ionosphere, satellite orbits
421 and clock, are mitigated by building the SDs of the collocated receivers, the error of
422 the FL4, including DBD jumps, is at the level of tenths of one TECU as it can be
423 observed in Table 3 and Figure 5. Nevertheless, when undifferenced parameters are
424 considered, e.g. the DCB for the receiver HERS, the discontinuities are larger. This is
425 related with ionospheric model inaccuracies that are transferred into the parameters
426 estimation. Furthermore, due to the aforementioned correlations between carrier phase
427 ambiguities and DCBs, any error in the geodetic model is also transferred into the
428 DCBs. In any case, these discontinuities are at the level of 0.5 TECU or smaller which
429 fully agrees with the DBDs of 0.57 TECU reported in Sanz et al. (2017).

430 -*An intra-day variability pattern*. Beside the discontinuities mentioned in the
431 previous point, the absolute receiver DCB presents a clear intra-day variation that can
432 be larger than the DBDs. As it was pointed out in Sanz et al. (2017), these variations
433 can be associated to the ionospheric mis-modeling that affect the receiver DCB to a
434 greater extent than the satellite DCBs, due to the smaller ionospheric sounding region
435 of the stations. This mis-modeling effect is amplified in the hourly estimation of the
436 receiver DCB compared to the daily estimate because the hourly estimation has fewer
437 observations and thus less even distribution of the observable (Li et al. 2017).
438 Moreover, the ionosphere typically repeats on a daily basis, in such a way that the

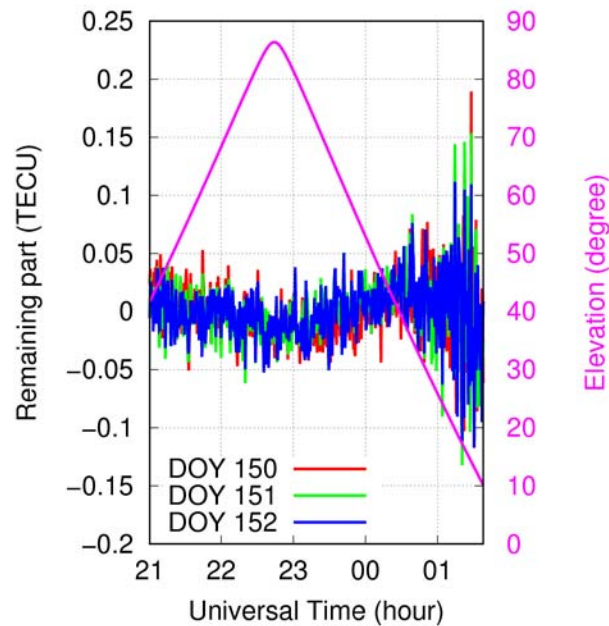
439 receiver DCB estimation absorbs the mean ionospheric errors which are similar from
440 day to day.

441 But, looking at the intra-day variation of the SD values, unaffected by
442 ionospheric errors, a remaining periodic pattern can be observed in the BR-DCBs,
443 meaning that the ionospheric model is not the only source for this intra-day variation.
444 Using the SP4 measurements, intra-day variations of several nanoseconds in the
445 BR-DCBs of collocated receivers have been reported by several authors (Coster et al.
446 2013; Zhang and Teunissen, 2015; Li et al. 2017). However, the accuracy of the FL4
447 observable allows detecting intra-day variations with higher accuracy. Indeed, Zhang
448 et al. (2017) reported intra-day variations of BR-DCBs of tenths of TECU that the
449 authors associated with temperature variations. These results agree with our results
450 depicted in Figure 5 and in Table 3 where variations of few tenths of TECU are
451 observed. Notice that we obtain these similar results without computing explicitly the
452 DD of collocated receivers, as is done in Zhang et al. (2017), i.e. it is enough to do
453 DD with respect to a reduced set of few tens of receivers distributed worldwide; see
454 Figure 1. Finally, it is worth pointing out that these intra-day variations are observed
455 in SD quantities, so they reflect the differential effect on the DCBs, but the effect on
456 the undifferenced DCBs can be still larger. In other words, considering the DCBs as a
457 constant daily parameter, as it usually assumed, can represent a mis-modeling error of
458 at least several tenths of a TECU that can be mitigated reducing the DCB refreshing
459 time.

460

461 Effects of multipath on the observation error

462 After removing the BR-DCB from the SD FL4 observable in (11), the remaining part
463 of the observation errors includes the effects of multipath, noise and the mis-modeling
464 of the receiver DCB. The evidence of the multipath effects, both phase multipath as
465 well as code multipath introduced from the HMW combination, is presented in Figure
466 6.



467

468 **Fig. 6** Remaining part of the observation errors (with mean removed to have a better
469 comparison) for PRN 11 by station pair HERT-HERS during DOY 150 to 152 in 2014.
470 The results are corrected for the 3 m 56 s sidereal shift with respect to the first day.

471

472 In Figure 6, the remaining part of the observation errors for PRN 11 by station
473 pair HERT-HERS during DOY 150 to 152 in 2014 are presented. As the multipath
474 effects for the GPS constellation repeat with a sidereal day, which is 236 s less than a
475 solar day, we shift UTC for the second solar day by 240 seconds and the third day by
476 480 seconds along the time axis to better demonstrate the sidereal day-to-day
477 repeatability. Therefore, the multipath effects are clearly presented in the remaining
478 part of the observation errors, especially when the elevation angle is small.
479 Considering the magnitude of the remaining part, with a mean STD of 0.026 TECU
480 for PRN11, which is $0.026/\sqrt{2} \times 0.162 \approx 0.003\text{m}$ for the remaining error on GPS
481 L1 observable in the three days, the code multipath effects are much reduced. Similar
482 conclusions can be presented by other satellites or other collocated receiver pairs.

483

484 **Summary and Conclusion**

485 The objective for undertaking this investigation is to quantify the accuracy of the
486 retrieved undifferenced ambiguity-fixed carrier phase ionospheric observable. First,
487 the undifferenced ambiguity-fixed carrier phase ionospheric observable, FL4, is
488 obtained through the geodetic processing to reduce the code-related multipath effect.
489 Together with the SP4 and RP4 observable, the accuracy of the FL4 observable is
490 evaluated through the collocated experiment. Second, because the receiver DCB
491 varies greatly and should be carefully accounted for the ionospheric observable, its
492 contribution to the observation errors is discussed. Also, the short-term stability of the
493 intra-day receiver DCB has been analyzed.

494 The conclusions are:

495 (1) By using data from DOY 150-180 in 2014, the observation error affecting the
496 undifferenced ambiguity-fixed carrier phase ionospheric observable, ranges
497 from 0.05 to 0.11 TECU, which is over one order of magnitude less than that
498 of the carrier phase leveled to code and the raw code ionospheric observable,
499 which are from 0.65 to 1.65 TECU and 3.14 to 7.48 TECU, respectively.

500 (2) In spite of such small error in the FL4 observables, two sources of error have
501 been identified:

502 a) It has been shown that the time-varying receiver DCB, which presents
503 clear Day Boundary Discontinuity and intra-day variability pattern,
504 contributes the most part to the observation error. This contribution is
505 assessed by the short-term stability of the BR-DCB, which ranges from 0.06
506 to 0.17 TECU in a single day.

507 b) Moreover, it has been shown that the remaining part of the
508 observation errors presents a sidereal time cycle pattern, indicating that the
509 geodetic model inaccuracies, especially the multipath, can have a small
510 impact on the FL4 observables.

511 (3) Finally, by comparing the amplitude of the receiver DCB variation with
512 respect to other error sources presented in this and in other works, we

513 conclude that estimating receiver DCB as a daily constant can have a
514 mis-modeling error of at least several tenths of one TECU.

515

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522

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628

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