Assisted Code Point Positioning at Sub-meter Accuracy Level with Ionospheric Corrections Estimated in a Local GNSS Permanent Network

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M. Crespi, A. Mazzoni, and C. Brunini

Abstract

It is well know that GNSS permanent networks for real-time positioning with stations spaced at few tens of kilometers in the average were mainly designed to generate and transmit products for RTK (or Network-RTK) positioning. In this context, RTK products are restricted to users equipped with geodetic-class receivers which are continuously linked to the network processing center through Internet plus mobile phone. This work is a first step toward using a local network of permanent GNSS stations to generate and make available products devoted to ionospheric delay correction that could remarkably improve positioning accuracy for C/A receiver users, without forcing them to keep a continuous link with the network. A simple experiment was carried out based on data from the RESNAP-GPS network (w3.uniroma1.it/resnap-gps), located in the Lazio Region (Central Italy) and managed by DITS-Area di Geodesia e Geomatica, University of Rome "Sapienza". C/A raw observations were processed with Bernese 5.0 CODSPP module (single point positioning based on code measurements) using IGS precise ephemeris and clocks. Further, the RINEX files were corrected for the Differential Code Biases (DCBs) according to IGS recommendations. One position per epoch (every 30 s) was estimated from C/A code; the vertical coordinate errors showed a typical signature due to the ionospheric activity: higher errors for day-time (up to 5 m) and smaller ones for night-time (around 1.5 m). In order to improve the accuracy of the solution, ionospheric corrections were estimated using the La Plata Ionospheric Model, based on the dual-frequency observations from the RESNAP-GPS network. This procedure allowed to reduce horizontal and vertical errors within 0.5 m (CE95) and 1 m (LE95) respectively. Finally, the possibility to predict the ionospheric model for few hours was preliminary checked. Our approach shows the possibility of a novel use of the measurements collected by

M. Crespi • A. Mazzoni (✉)
DITS-Area di Geodesia e Geomatica, Facoltà di Ingegneria,
Università di Roma, La Sapienza, Rome, Italy
e-mail: augusto.mazzoni@uniroma1.it

C. Brunini
Facultad de Ciencias Astronómicas y Geofísicas,
Universidad Nacional de La Plata and CONICET, La Plata,
Argentina

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GNSS permanent networks designed for real-time positioning services, which can assist and remarkably improve the C/A code real-time positioning supplying off-line predicted ionospheric corrections, acting as a local Ground Based Augmentation System.

95.1 Introduction

In the past years many efforts were dedicated to implement Augmentation Systems, mainly devoted to support real time point positioning with low-cost receivers for the extremely wide market connected to the applications requiring real-time positioning at meter and sub-meter accuracy level.

In this respect, it is well known that the ionosphere modeling is one of the crucial items, in order to reduce the positioning error remarkably below the level achievable in stand-alone point positioning.

Nevertheless, if we consider the present situation about augmentation systems such as the EGNOS in Europe and the WAAS in North America (Seynat et al. 2009; Eldredge 2009), we may realize that the positioning error is not better than few meters (horizontal error < 3 m and vertical error < 4 m, for at least 99% of the time according to Seynat et al. 2009; 3D error within 1–2 m at 95% level according to Flament and Seynat 2008), even when the augmentation correction data are available in real time, what may be difficult in many situations due to the elevation of the transmitting geostationary satellites (2 GEOs, Seynat et al. 2009), as it happens, for example, in urban canyons or in a hilly/mountainous context.

On the other hand, all over Europe, there is a wide availability of national and regional GNSS permanent networks, with permanent stations spaced at few tens of kilometers in the average, which might give a significant contribution to improve the ionosphere model at a local level. In this respects, it has to be also considered that, where these kind of networks are devoted to realize positioning services, the ionospheric model is routinely computed (together with other correction models) and delivered to the users connected by mobile phone/Internet in real-time through NTRIP protocol in RTCM 3.x format (SAPOS network in Germany, Ordnance Survey Net in UK, GPS LOMBARDIA in Italy, and many others). Nevertheless, the continuous connection with the processing center of the GNSS permanent network is required as well, whilst no assistance to non connected user is presently supplied by these well distributed GNSS permanent networks.

Overall, the goal of the paper is to demonstrate that these networks can give a significant support also to the users which cannot be continuously linked to them for several reasons (logistic, budget, . . .), by estimating, possibly predicting over few hours and then making available in advance (for example through a new dedicated web service) a local refined ionospheric model. In such a way, these permanent networks can act as local Ground Based Augmentation Systems.

In particular, the main issues related to the model estimations, the achievable point positioning accuracy level and the accuracy of the predicted ionospheric model are addressed.

In this respect, a preliminary experiment was carried out in order to establish an off-line procedure which could be used in real time.

Data from four permanent stations included into the RESNAP-GPS network (Central Italy) were used: AQUN (L'Aquila, Abruzzo), FOLI (Foligno, Umbria), M0SE (Roma, Lazio) and RIET (Rieti, Lazio) (Biagi and Sansò 2007).

For each station, three consecutive days of data at 30 s sampling rate were used in the test (year 2008, doys 167, 168 and 169) together with IGS precise orbits and clocks and CODE Earth Rotation Parameters. All stations were equipped with Leica GX1230 receivers, supplying C1 and P2 codes.

All the daily data-files, for every step of the following investigated strategy, were processed with Bernese 5.0 GPS software (Dach et al. 2007) CODSPP module (single point positioning based on code measurements) in order to obtain the epoch-by-epoch position.

95.2 Standard CODSPP Processing

At first, a standard processing was carried out with the main CODSPP parameters over three Permanent Stations (AQUN, FOLI, RIET); throughout the paper we just use the acronyms L1 to point out this processing.

All others parameters, for these processing and also for the following ones, were set to default values; in particular, Saastamoinen tropospheric model was used, with cut-off angle set at 10°.

For each processing, doy and station, kinematic coordinate errors with respect to the known station IGS05 positions (used as reference) were computed.

The standard following statistical indexes were used in order to represent the horizontal and vertical accuracy respectively:

$$CE95 = \frac{2.4477}{\sqrt{2}} \sqrt{RMSE_N^2 + RMSE_E^2} \qquad (95.1)$$

$$LE95 = 1.96 RMSE_U \qquad (95.2)$$

where $RMSE_{E,N,U}$ are computed over the mentioned errors.

In Fig. 95.1 vertical errors vs. time are shown for each station; three daily solutions are stacked in the same graph.

LE95 and CE95 respectively are at the level of 7 m and of 4 m (Table 95.1). Very strong correlations both in time and space are also clearly displayed; each station has very similar signature for different days and these signatures are very similar between different stations.

Figure 95.2 displays the errors in terms of North and East components; for each station; three daily solutions are stacked in the same graph. Also in this case remarkable space–time correlations are highlighted.

The strong space–time correlations between the errors (Fig. 95.1, Table 95.2) were hypothesized to be mainly due to satellite clocks Differential Code Biases (DCBs).

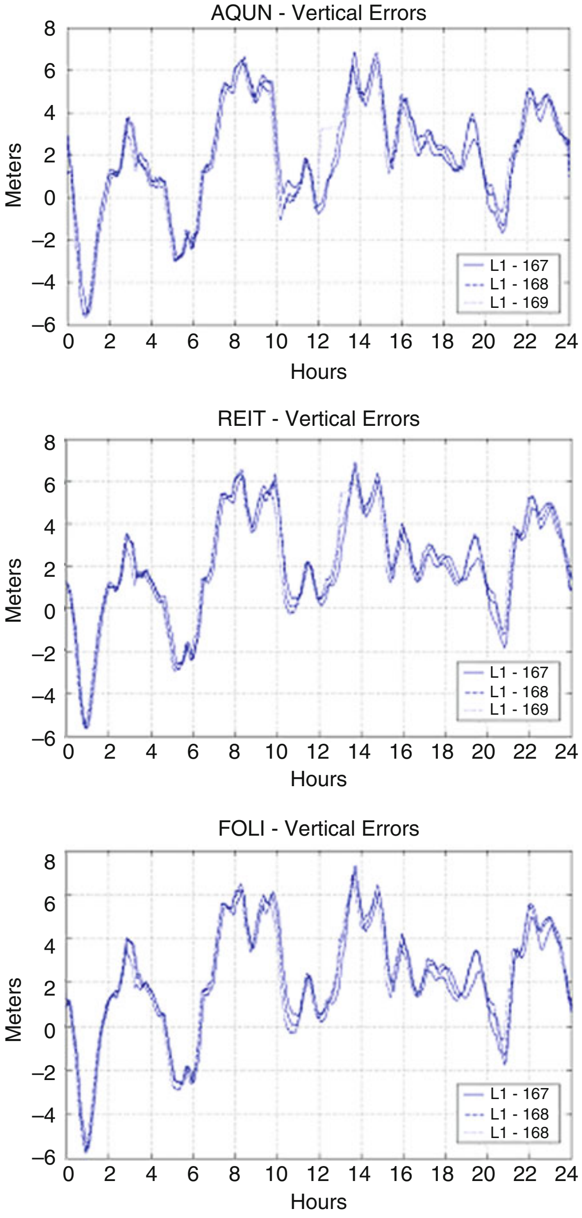

Fig. 95.1 Standard CODSPP processing – vertical errors

95.3 L1 Differential Code Biases CODSPP Processing

Matlab© routines were implemented in order to modify the native RINEX files with the CODE DCB P1C1 and P1P2 corrections (P1C10806 and P1P20806 DCB), following the recommendations reported in Schaer (2008).

Table 95.1 Standard CODSPP processing

	Linear error LE95 (meters)			Circular error CE95 (meters)		
Doy	AQUN	FOLI	RIET	AQUN	FOLI	RIET
167	6.7	6.7	6.6	3.8	3.7	3.6
168	7.0	7.0	7.0	3.7	3.7	3.6
169	6.7	6.7	6.6	3.8	3.6	3.6

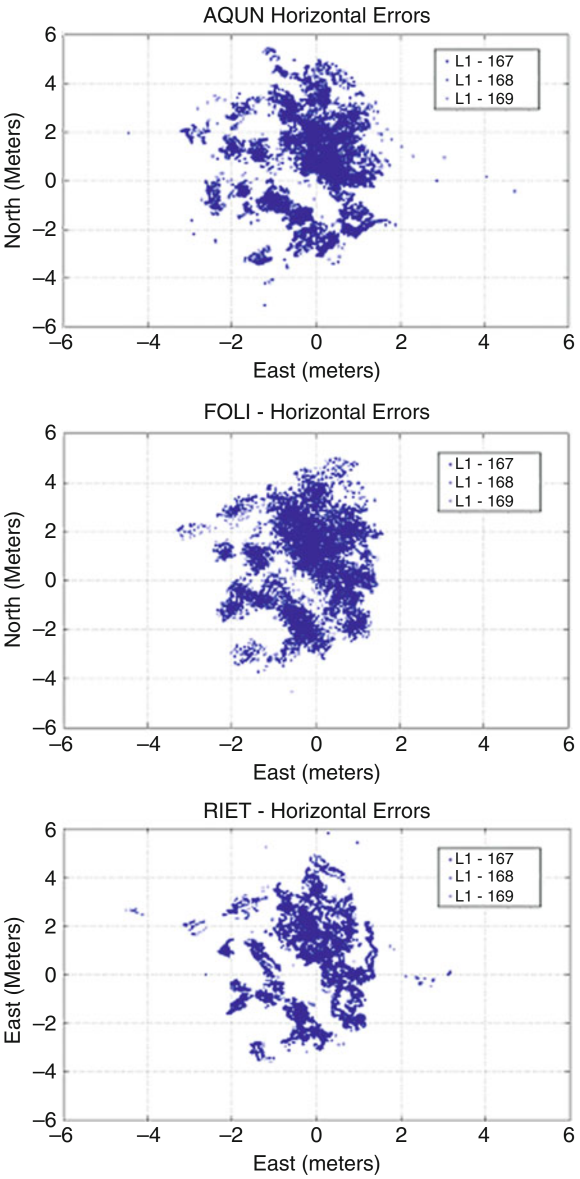

Fig. 95.2 Standard CODSPP – horizontal errors

Table 95.2 Vertical errors space–time correlations

Space correlations	167	168	169
AQUN-FOLI	0.92	0.92	0.92
AQUN-RIET	0.93	0.90	0.92
RIET-FOLI	0.97	0.96	0.97
Time correlations	AQUN	FOLI	RIET
167–168	0.84	0.87	0.86
167–169	0.74	0.74	0.74
168–169	0.86	0.85	0.87

Table 95.3 DCBs CODSPP processing

	AQUN		FOLI		RIET	
Doy	B	R	B	R	B	R
Linear error LE95 (meters)						
167	6.0	6.0	6.2	6.2	6.0	6.0
168	6.2	6.2	6.5	6.5	6.2	6.2
169	5.8	5.8	6.2	6.2	6.0	6.0
Circular error CE95 (meters)						
167	1.7	1.7	1.8	1.8	1.6	1.6
168	1.7	1.7	1.8	1.8	1.6	1.6
169	1.5	1.5	1.6	1.6	1.4	1.4

In order to test the correct DCBs implementation in the RINEX files, two processing were carried out (Table 95.3, Fig. 95.3 and 95.4) with:

- L1B – modified P1C1 RINEX (frequency L1) plus P1P20806.DCB file as input in CODSPP
- L1R – modified P1C1 and P1P2 RINEX (frequency L1) as input in CODSPP

Considering that CODSPP accepts only one DCB file a time.

The first evidence is that the two processing led to equal results (Table 95.3), what confirms that DCBs corrections were correctly implemented in the native RINEX files by the Matlab© routines.

In Fig. 95.3, the vertical component errors show, for every station and every doy, the typical signature due to the ionospheric activity: higher errors for day-time (up to 5 m) and smaller for night-time (around 1.5 m). In the same time, these signatures also indicates that the DCBs effects seem to be correctly removed from the observations; the same holds for the horizontal components (Fig. 95.4) (not so influenced by ionospheric activity effects), which are now less disperse w.r.t. the NO-DCB standard L1 processing Overall, the simple use of DCBs corrections remarkably increases the accuracies.

95.4 Ionospheric Corrections

In order to further improve L1 processing accuracy, ionospheric corrections for the considered stations were estimated using Ionos New Generation Software (Implementation of La Plata Ionospheric Model LPIM) (Azpilicueta et al. 2005) on the basis of the GNSS permanent network stations observations.

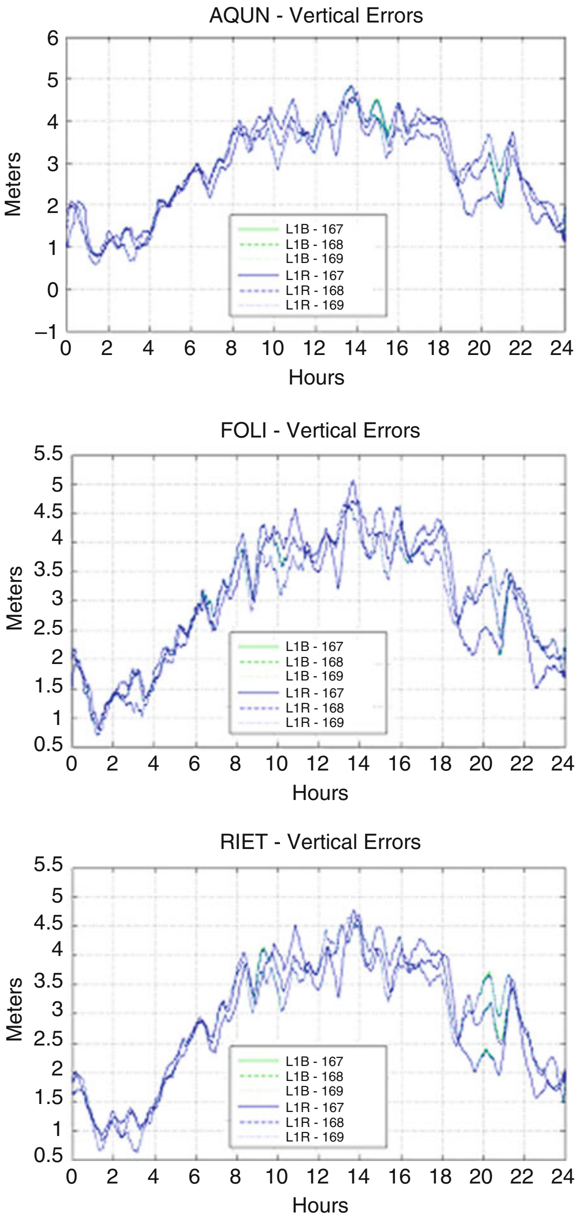

Fig. 95.3 DCBs CODSPP processing – vertical errors

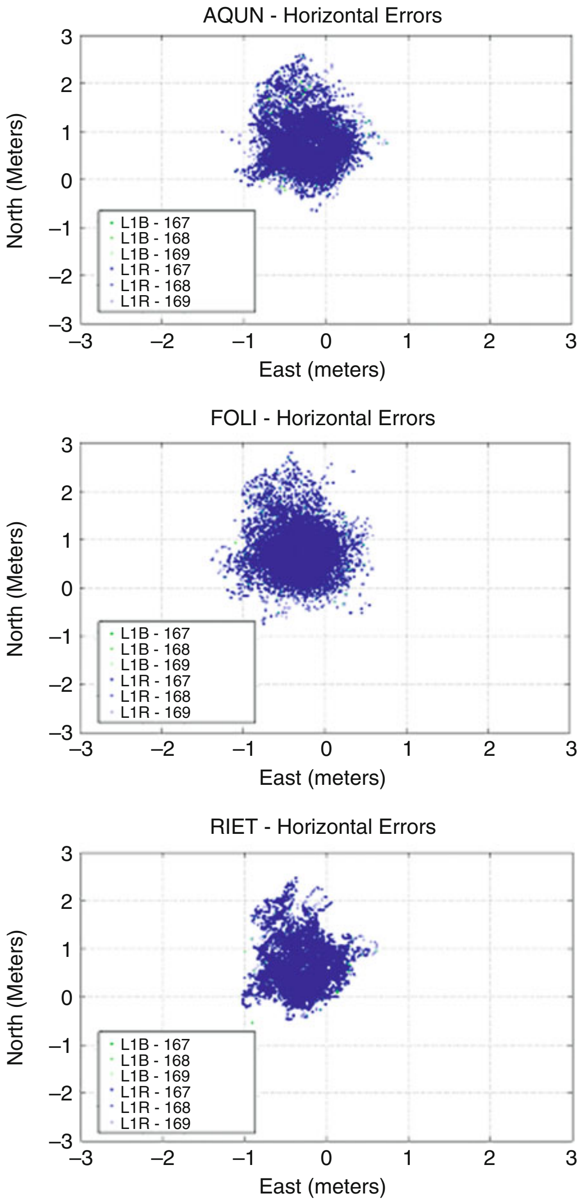

Fig. 95.4 DCBs CODSPP processing – horizontal errors

LPIM is based on the ionospheric observable:

$$L_{I,arc} = sTEC + B_R + B^S + C_{arc} + \varepsilon_L, \qquad (95.3)$$

where $L_{I,arc}$ is the carrier-phase ionospheric observable – the sub-indices *arc* refers to every continuous arc of carrier-phase observations, which is defined as a group of consecutive observations along which carrier-phase ambiguities do not change; B_R and B^s are the so-called satellite and receiver inter-frequency biases (IFB) for carrier-phase observations; C_{arc} is the bias produced by carrier-phase ambiguities in the ionospheric observable; and ε_L is the effect of noise and multi-path. All terms of (95.3) are expressed in Total Electron Content units (TECu), being 1 TECu equivalent to 10^{16} electrons per square meters.

LPIM relays on the thin-shell and the mapping function approximations. Based on those approximations, (95.3) is written in the following way:

$$L_{I,arc} = \sec(z') \cdot vTEC + \gamma_{arc} + \varepsilon_L, \tag{95.4}$$

where *sec(z')* is the mapping function, z' being the zenith distance of the satellite as seen from the point where the signal crosses the thin-shell (the so-called piercing point) that, in the case of LPIM, is located 450 km above the Earth's surface; $vTEC \equiv cos(z') \cdot sTEC$, is the equivalent vTEC at the piercing point; and $\gamma_{arc} \equiv B_R + B^s + C_{arc}$, is a calibration constant that encompasses, all together, receiver and satellite IFBs and the ambiguity term. The calibration, i.e. the estimation of γ_{arc} for every continuous arc, is performed independently for every observing receiver in the network. To accomplish this task, the equivalent vTEC is approximated by a bilinear expansion dependent on the piercing point coordinates:

$$vTEC \equiv a(t) + b(t) \cdot (\lambda_I - \lambda_0) \cdot \cos(\mu_I) + c(t) \cdot (\mu_I - \mu_0), \tag{95.5}$$

where t is the Universal Time of the observation, λ_I and the geographic longitude and the modip latitude of the piercing point and λ_0 and μ_0 the geographic longitude and the modip latitude of the observing receiver.

The dependence on time of the expansion coefficients is approximated with ladder functions:

$$\alpha(t) = \alpha_i, \quad \text{for} \quad t_i \le t < t_i + \delta t, \quad i = 1,2,..., \tag{95.6}$$

where α represents anyone of the coefficient α, or c; and δt is the interval of validity of every planar approximation (5^{m} in the case of LPIM).

Merging all together the observations gathered by a receiver in a given interval Δt ($\Delta t >> \delta t$), and arranging appropriately (95.4)–(95.6), LPIM forms an overdetermined linear system of equation of observations that contains, as unknowns, the calibration constants for all observed continuous arcs, γ_{arc} ($arc = 1,2,\ldots,n_{arc}$), and the constant coefficients of the planar fits, $a_1,\ldots,a_{\mathrm{m}}$, $b_1,\ldots,b_{\mathrm{m}}$, $c_1,\ldots,c_{\mathrm{m}}$ ($m = \Delta t/\delta t$). Since we are not interest on the coefficients, they are reduced from the system by means of a Gaussian elimination process and then, the system is solved by the Least Square methods, hence estimating the n_{arc} calibration constants. Finally, the observations are calibrated and the equivalent vTEC are estimated from (95.7):

Table 95.4 DCBs and ionospheric corrections CODSPP processing

	Linear error LE95 (meters)			Circular error CE95 (meters)		
Doy	AQUN	FOLI	RIET	AQUN	FOLI	RIET
167	0.9	1.0	0.8	0.6	0.5	0.4
168	0.7	1.0	0.8	0.5	0.5	0.4
169	0.9	1.2	1.1	0.6	0.6	0.4

$$v\hat{TEC} \equiv vTEC + \frac{\varepsilon_L}{\sec(z')} = \frac{L_{I,arc} - \hat{\gamma}_{arc}}{\sec(z')}. \tag{95.7}$$

95.5 Final CODSPP Processing

For each station, daily ionospheric corrections values (epoch-by-epoch and satellite-by-satellite) for both frequencies L1 and L2 were stacked in a correction file. Again, Matlab© routines were implemented in order to modify RINEX files adding the ionospheric correction values to the observation epoch-by-epoch.

The final CODSPP processing (Table 95.4, Figs. 95.5 and 95.6) was carried out with L1I – modified P1C1 and P1P2 RINEX and ionosperic corrections as input in CODSPP.

Results clearly evidenced the success of the procedure: the combined use of DCBs and ionospheric corrections led to horizontal and vertical accuracies at 0.5 m (CE95) and 1 m (LE95), respectively.

The space correlations between errors of different stations remarkably decrease (Table 95.5); their remaining parts might be caused by possible DCBs errors and should be investigated in the future.

95.6 Spatial Interpolation Test

In order to investigate the possibility to estimate ionospheric corrections within a GNSS Network, a simple interpolation test was carried out for doy 167 the basis of three stations (M0SE, FOLI and AQUN) L1 estimated corrections, values for RIET station (approximately located in the centre of the triangle AQUN, FOLI, M0SE) were spatially linearly interpolated, neglecting the ionospheric travelling disturbances which were also detected with similar signatures but in slightly different intervals for the

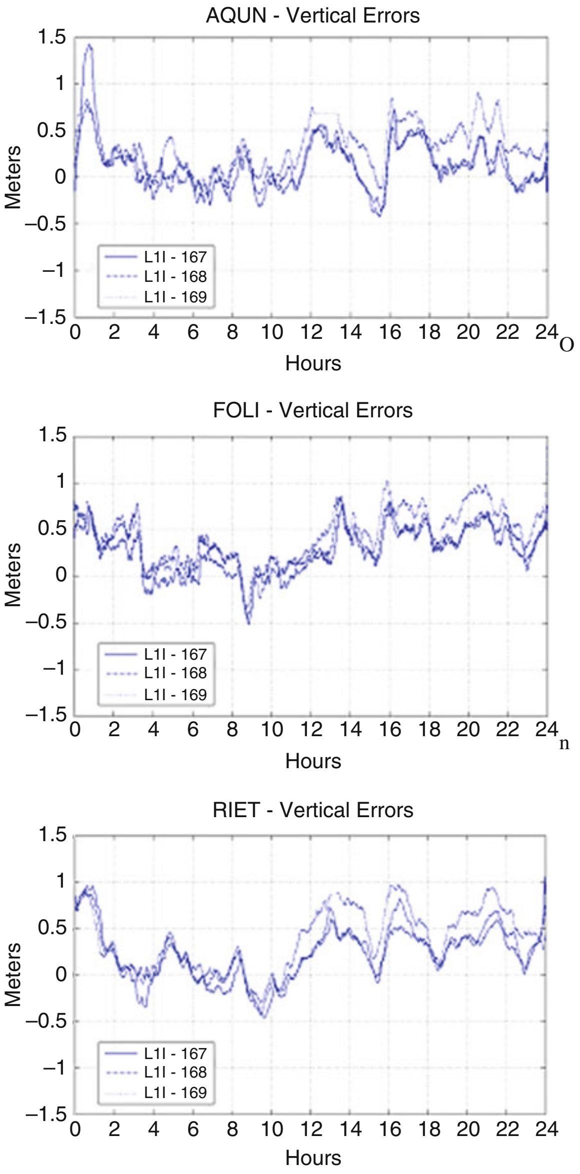

Fig. 95.5 DCBs and ionospheric corrections CODSPP processing – vertical errors

three stations. The interpolation vas carried out w.r.t. longitude and latitude, with the standard model:

$$C(t) = \begin{vmatrix} a(t) \\ b(t) \\ c(t) \end{vmatrix} = \begin{vmatrix} \lambda_{M0SE} & \phi_{M0SE} & 1 \\ \lambda_{AQUN} & \phi_{AQUN} & 1 \\ \lambda_{FOLI} & \phi_{FOLI} & 1 \end{vmatrix}^{-1} \begin{vmatrix} I(t)_{M0SE} \\ I(t)_{AQUN} \\ I(t)_{FOLI} \end{vmatrix} \qquad (95.8)$$

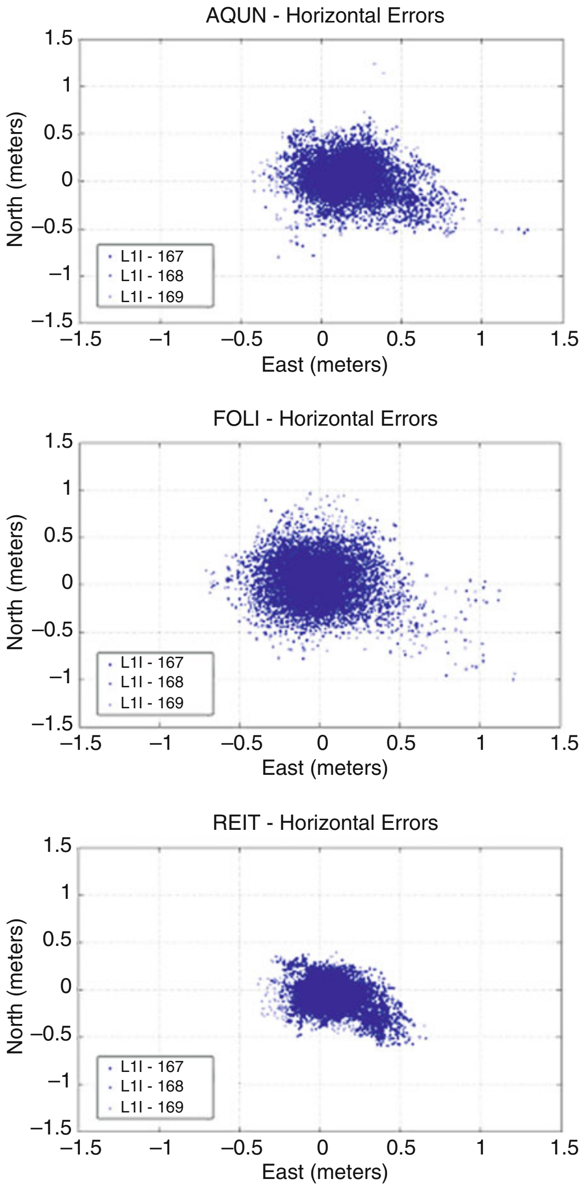

Fig. 95.6 DCBs and ionospheric corrections CODSPP processing – horizontal errors

Table 95.5 DCBs and ionosperic corrections CODSPP processing – vertical errors space–time correlations

Space correlations	167	168	169
AQUN-FOLI	0.20	0.14	0.25
AQUN-RIET	0.45	0.37	0.52
RIET-FOLI	0.39	0.34	0.46
Time correlations	AQUN	FOLI	RIET
167–168	0.34	0.68	0.27
167–169	0.28	0.55	0.27
168–169	0.25	0.63	0.28

$$I(t)_{RIET} = a(t)\lambda_{RIET} + b(t)\varphi_{RIET} + c(t) \qquad (95.9)$$

where $a(t)$, $b(t)$, $c(t)$ are the time dependent interpolation coefficients to be computed on the basis of the modeled ionospheric delay at permanent stations AQUN, FOLI, M0SE (95.8) and $I(t)_{RIET}$ is the interpolated ionospheric delay at RIET position. Interpolated values were compared to L1 ionospheric corrections estimated on the basis of the RIET station observations.

The RMSEs of the differences were computed satellite-by-satellite and their values show that spatial interpolation accuracy is generally within 15 cm.

95.7 Final Remarks

This work shows the possibility of a novel use of the measurements collected by GNSS permanent networks designed for real-time positioning services, which can assist and remarkably improve the C/A code real-time positioning supplying off-line predicted ionospheric corrections, acting as a local Ground Based Augmentation System.

Horizontal and vertical accuracies at 0.5 m (CE95) and 1 m (LE95) are respectively achievable, provided DCBs and ionospheric corrections are duly considered.

The work is still preliminary in the sense that some questions arose and have to be addressed in the next future:

- The investigation of the possible causes of the still present space–time correlations in errors time series
- The refinement of the ionospheric corrections interpolation with a space–time model, in order to account for the ionospheric travelling disturbances propagation

The replacement of the interpolation with a prediction space–time model, in order to enable the real-time implementation of the ionospheric correction and its quality assessment; in this respect a simple low degree polynomial model for satellite arc could be effective for few hours prediction at 10–20 cm level.

Finally, since at present only measurements acquired by geodetic class receivers working at permanent stations were considered, the proposed procedure should be tested over low-cost C/A receivers, in order to evaluate the overall achievable accuracy accounting also the higher noise level of such equipments.

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